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Conformal Projection Printing Method to Increase the Accuracy of 3D Printed Nails

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Synopsis

Incorporating technologies such as 3D printers and the Internet of things (IoT) can improve the nail art industry by making it more efficient, and, most importantly, safer. It eliminates the need for physical shops such as nail salons. Nail art by 3D printing technology can achieve higher resolution and accuracy than before with conformal projection printing method (CPPM). The conventional method of painting nails manually leads to acute exposure to ultraviolet (UV) light that can contribute to minor health hazards. This research illustrates the benefits of using 3D printing for nail art. This study uses the IoT system, which can be stationed in a distinct location from the customer. The product on the nail is printed at least once and up to three times within 5 μm to achieve precise resolution through laser marking and CPPM, which can increase the accuracy by repeated projection to attain the required settling ratio. The correlation between the numbers of printed layers and different incident angles of the printing head on the conformal surface is discussed. The ratio of projected weight to the ideal weight for high-definition printing condition is illustrated, and comparison studies with conventional nail art techniques are conducted to validate the results.

INTRODUCTION

The integration of artificial intelligence (AI) in the industries of the 21st century increased the efficiency of existing production and marketing processes. The amalgamation of 3D printers and Internet of things (IoT) systems puts forth the concept of digital manufacturing (DM), which enables users to enter the relevant information and produce with minimal material input. Such improvement simplifies the manufacturing processes and reduces the lead time, gaining consumer satisfaction and leading to the fourth industrial revolution (1). DM technology initiated with nano-inks where nanosized particles were dispersed in an aqueous solution through the direct injection method. This technology has drawn attention since 1990, because of not only various convergence technologies but

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also efficient and effective economic advantages that can save material and time (2). The conventional printing method has grown as a leading technology in the 3D printing industry, ranging from roll to roll, micro-dispensing deposition write, and inkjet. Furthermore, it emphasized on standardization of materials and equipment, which are used in display printing (3). In addition to plastics, ceramics, metals, food, biomaterials, and medicines have been used and developed in various industries, including architecture, automobiles, dentistry, education, medicine, dietary life, drug delivery, and fashion (4–6). Furthermore, the specific flexibility of 3D printing technology that can create unique, complex, and diverse shapes with the characteristics to be used in different materials depending on the user has gained popularity among scientists and technical workers because of its flexibility and its unique characteristics (7). Wohlers Associates and the Journal of Science Policy & Governance predicted the growth of the global 3D printing market, which supports the emergence and rapid growth of several future industrial technologies, which might increase to US$10.8 billion by 2021 (8).

Because of the future direction of the automated industries, economic growth and the development of media through modernization affect the increase of people's desire to express themselves freely and individually (9). In the beauty industry, along with the hair design and makeup sectors, the nail art industry has proliferated in recent years and has attracted attention by the fusion of material aesthetics with sophistication and smooth curves that give a smooth glossy surface from a material point of view (10). These positive changes in aesthetic perceptions are widely expressed beyond social class, genders, and ages.

The nail art market, which has been developed mainly by women, is expected to expand to the area of tattoos with the development of 3D printing technology. In recent years, tattoos widely spread and became widespread among young people as a form of art (11). Therefore, the development of the nail art and tattoo industry can realize the recent rapid growth and changes in society through the convergence of art and engineering for personal identity and the freedom of expression and aesthetic reasons. However, the nail art industry has recently received a red light in scalability as a challenge to solve the health problems caused by exposure to chemical toxic substances and UV process during gel nail formation. Nail art contains harmful chemicals such as acetone, ethyl acetic acid, toluene, and butyl acetic acid, and other various chemical dust that occur during the abrasion process, which is the essential task of smoothing nails. These can cause respiratory disorders to customers and operators (12). In California, a survey of 201 nail art workers in 74 different branches of nail shops found that 62% of workers complained of general health problems and 47% of them had skin irritation, respiratory disease, and paralysis related to the eyes and neck (13). The UV lamp rays that are used to cure acrylic gel in the nail polish process have similar properties to UV suntans that which most emit UV-A radiation (14). The UV exposure that accompanies the nail curing process has the potential of susceptible damage to the skin's epidermis, which can be caused by UV rays. Thereby, the DNA cells called "P53" that inhibit the occurrence of apoptosis or mutation of DNA cells can lose their function. This means the possibility of causing skin cancer (15). UV exposure is known to be a severe risk factor for skin cancers such as cutaneous melanoma and nonmelanoma (16).

The emotional conversation between the customer and the nail art practitioner was the impetus for the development of the nail art industry rather than technical advancement. If any error is found in the final product in the field, it can be immediately corrected, and it could lead to emotional satisfaction, which cannot be quantified. It has evolved to complement the operator's skill level, reproducibility, low levels of precision, environmental hazards, and processes that are exposed to unsanitary and health risks in a long-term requirement (17).

Recently, the introduction of technologies to eliminate health risks has begun. As one of the examples, in the field of 3D printing, it was reported that the IoT-enabled 3D printers were controlled through web-cloud (18). This telemedicine system successfully delivered medicines with food (19). This concept has been extended to the 3D nail art area and with the convergence of IoT and AI technologies in conjunction with 3D printing or additive manufacturing. The applications have extended to beauty arts and cosmetics. The food has been controlled and printed through web-cloud with a single-line design technique (20). The applications have extended to beauty arts and cosmetics. In this study, an attempt was made to transmit a nail design to a web server where the customer could monitor the proceedings of the design and make changes. Customers can observe the results on the conformal surface of nails, and they can request modification of the final design. Even though hazardous chemicals, such as volatile organic compounds, have not been exposed to equipment operators and customers in the process, there were differences in the degree of completeness in the shape desired and the printed shape.

The conformal projection printing method (CPPM) that was applied in this study demonstrated that not only high precision but also increased environmental safety level shortened the processing time and the modification and supplementation of the printing process required by consumers in the worksite. The simulation between the laser beam and nail in different numbers of printings were performed through repeated experiments with the CPPM. The technique that was introduced at the time required to print 10 nail shapes on the system, and it took 10 min from the order to the final result. Validation experiments have been carried out on a logistics system that allows the customer to order specialized nail designs directly on the web and to modify the results from anywhere in the world. The study presents the ability to print 300-4,000 dots per inch (DPI) with high definition, which is superior to the conventional manual method of nail art. It is expected that 3D printing technology, which shows high sharpness results and a three-dimensional effect, can adjust the height to more than 2–5 μm, and can be combined with nail art technology to lead contemporary markets and technologies.

METHODS

CPPM

CPPM was applied in the field of nail art. Figure 1 shows the angle of incidence (theta, θ) formed between the projected line and the surface of the nail tip. The weight of ink projected perpendicular to the surface per unit area of the nail is called the ideal weight and is denoted as W_I, whereas the weight of ink projected on the conformal surface per unit area of the nail is called the projected weight and is denoted by W_P. Overall, based on the actual projected amount per unit area, the range of theta is $0^{\circ} < \theta \leq 90^{\circ}$, and the settling ratio is $0 < \frac{W_P}{W_I} \leq 1$. According to the formula $W_P = W_I \sin\theta$, the projected quantity per unit

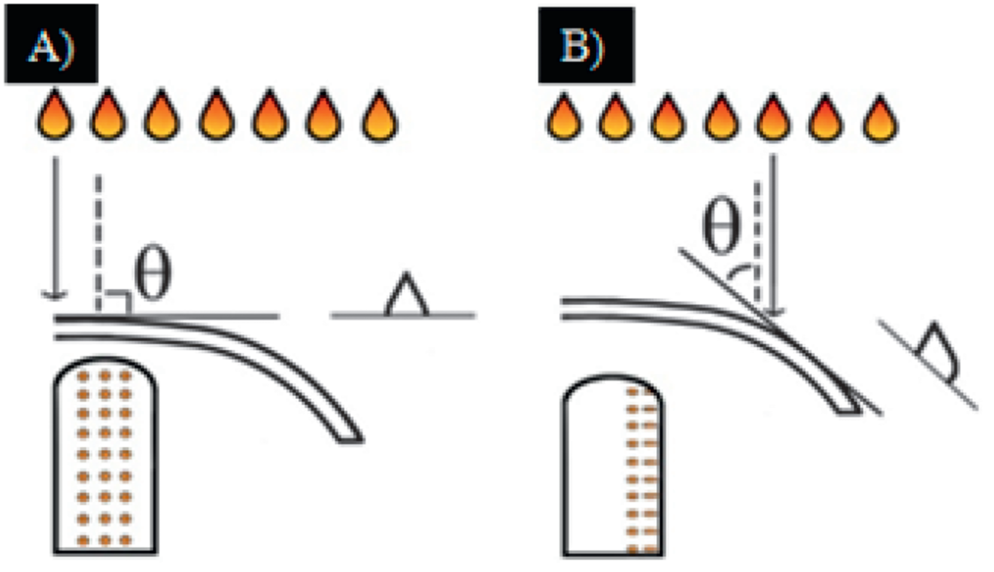

Figure 1. Different values of theta on the nail tip from the printer head.

area can be accurate and consistent. This settling ratio is close to 1 when the projected weight is the same as the ideal weight (Figure 1A), and it decreases (Figure 1B) with the theta value. The dispensing pigments contain color and solidifiers that harden under UV light, and it is observed that the density increases as the particle size is reduced to nanoscale (21).

MATERIALS AND EQUIPMENT

An oil-based UV-curable ink was used in this study (Hongkong Liyu Technology Co., Ltd., Shenzhen, China).

The monomers in the UV ink produce a building block of the ink and can devote a specific property such as hardness of the ink when it cured, as well as flexibility or elongation characteristics of the ink. And pigments are smaller than 200 nm in size to prevent agglomeration and the possibility of hindering the nozzle. The colorants of UV ink that applied in the experiment were yellow, red, black, white, and blue. The amount of ink used at a time for 10 tips is less than 10 mL, and it takes less than 10 min from order to output. UV light emitting diode has been designed to adjust the height of the product, which emits light at 3W intensity and cures the product of 5 μm height up to 1,000 μm. To obtain 4,000 DPI, the Epson head L805 model was used. (L805; Epson, Carson, CA)

Nail tips used in this study are made of both acrylonitrile butadiene styrene (ABS) and acrylic-based material, and the basic colors are natural, clear, and white. The nail tips used in the experiment were clear and white. There are 10 different tip sizes ranging from 0 to 9, and seven types were used in this experiment. (size 2: 0.46 × 1.15; size 3: 0.44 × 1.07; size 4: 0.41 × 1.05; size 5: 0.41 × 1.03; size 6: 0.37 × 0.99; size 7: 0.34 × 0.97; and size 8: 0.31 × 0.91). It is observed that an image printed from an inkjet printer had a significant impact on the printing modulation transfer function of the ink image, depending on the type of paper on the substrate (22). Thus, there have been studies to solve the problem that these factors can influence the print result by using various methods such as measuring the horizontality of output and the bed, including surface tension (23). As the degree of curvature of the conformal surface varied according to the nail tip size, the different injection frequencies were simulated and empirically tested with three zones that, according to the incidence angle (theta), range on the nonhorizontal plane. To minimize the influence of such external conditions and to increase precision, a laser treatment process was incorporated that precisely removes the hydrophilic or hydrophobic coating of the output, preventing the spread and diffusion of the ink on the surface.

It is reported that the equipment used in this study can be operated at 3W through which the energy consumption is reduced by less than 1/10 times when compared with existing UV lamps (24). The equipment used in the experiment is an A4 UV printer (A4 UV printer; Taicang Vevor Machinery Equipment Co., Taicang, China) that outputs only by XYZ movement without rotation axis, and the method of stacking is 2D–2.5D layers on the plane. Figure 2 shows the overall schematic of the mechanical processing of an order for printing. The concept of nail printing and its material chain verification experiment is explained in Figure 2D–F. By combining IoT system and AI, the operator selects the design remotely and the customer can choose by using a system that separates the space between the customer and the operator (Figure 2A). Once the data to be printed are delivered to the Raspberry Pi, which is the central processing unit for processing information (Figure 2B), ink is dispensed through the print head (Figure 2C). The surface was etched with a 3W precision laser (Figure 2D) for surface modification, and repeated printing (Figure 2E) is

Figure 2. Basic concept of nail printing and the flow of material chain.

performed to produce 2.5D and 3D shapes. UV curing process is followed after laser treatment of carbon nanotube–coated material to increase laser etching and the settling ratio of the material (25), In this iterative printing method, zig was used to set the exact position (Figure 2F) so that the printing target position was not changed.

The verification experiment was conducted for 10 months starting in January 2019, after reviewing the stability of AI and IoT. The ordering process by AI and IoT is described in detail in Figure 3. The customers can order the product using a computer or a mobile phone. They can choose the automatically recommended photos by AI or can upload their own image files with jpeg type on the website (Figure 3A). Once sent to a printing device that can apply IoT systems (Figure 3B), an image file is automatically allocated to a printer that can print (Figure 3C). The stability of the whole system was verified by repeated output with CPPM. More specifically, the overall conceptual diagram is shown as A, B, and C in Figure 3 in the following text. In this study, images were transmitted more than 300 times in a spatially isolated IoT system and tested according to three different angles of incidence settings. After images being sent to the printer at the University of Texas at El Paso Physical Science Building #411 (Figure 2C–E), where the equipment is located, the printer equipment is maintained

Figure 3. Mechanism of IoT system.

at 100 m^3/min. The focus was on setting three different ranges of angles, finding different optimized printing conditions accordingly, and printing within a certain amount of time.

RESULTS AND DISCUSSION

The microscopic phenomena of the ink deposition due to the difference in adhesion force because of the surface energy difference between materials when the ink reaches on the nail tip are shown in Figure 4 by measuring the surface tension and energy change. When droplets of water about 100 μm diameter are dropped on a nail tip made of ABS or acrylic material, the contact angle changes according to the surface energy of the tip material and the water. As shown in Figure 4A, the contact angle is close to 90°, which is seen when using hydrophobic substrates that dislike each other because of the large surface tension of the two materials. In the plane of high incidence angle, this type of material property can be used to increase the precision. However, if the angle of incidence is small, the ink flows down from the nail tip (Figure 4B). On the other hand, if the nail tip is made hydrophilic by laser treatment, then the contact angle is close to 0°. There is a disadvantage of spreading (Figure 4C), but if the angle of inclination is small, the ink does not flow down from the nail tip (Figure 4D).

In CPPM, the ratio of settling degree $\left(\frac{W_P}{W_I}\right)$ varies depending on the range of different θ (theta) values. Based on the amount of projected ink per unit area, the standard degree of theta is $0^\circ < \theta \leq 90^\circ$, and the ratio is $0 < \frac{W_P}{W_I} \leq 1$. Through the geometric simulations and repetitive experiments, the comparative analysis is conducted based on the experiments under the conditions shown in Table I. The experiments tried to find the optimal number of prints by outputting high accuracy results by repeating experiments to enable efficient and accurate printing according to the angle of incidence. The experimental method that shows the difference between the incidence angles of dripping ink and the conformal surfaces is as explained in Figure 1. The conformal surface has a steady output when the angle of incidence of the ink falling from the inkjet print head is perpendicular to the surface, so it does not flow down the surface. However, when the theta value decreases, the ink does not settle on the conformal surface and flows down. Spreading in unstable surface causes DPI decreases when the absolute amount projected per unit area is diluted. Accuracy and clarity have been increased by changing the number of print layers according to theta value changes. Table I shows the optimal number of printing layers from 1 to 3 which depends on the different theta range. There are different numbers of printing layers depending on the theta to increase accuracy. The ratio of settling degree should be greater than 1.00 to obtain accurate results.

Various sizes of nail tips are classified into different angles of incidence in three ranges. After laser marking on the substrate for improving accuracy, different layers are printed according to the theta value. In addition to the UV-curable inkjet printing method and laser treatment, the technology of printing three-dimensional shapes by ink printing is introduced. When the ink height is accumulated about 2–5 μm, the difference of accumulation in the shade gives a three-dimensional effect. A combination of printing technologies that use the color of the ink can give a visual effect and rapidly print and apply in three dimensions with other materials like ceramic or polymer. However, the experiment mainly focuses on the CPPM.

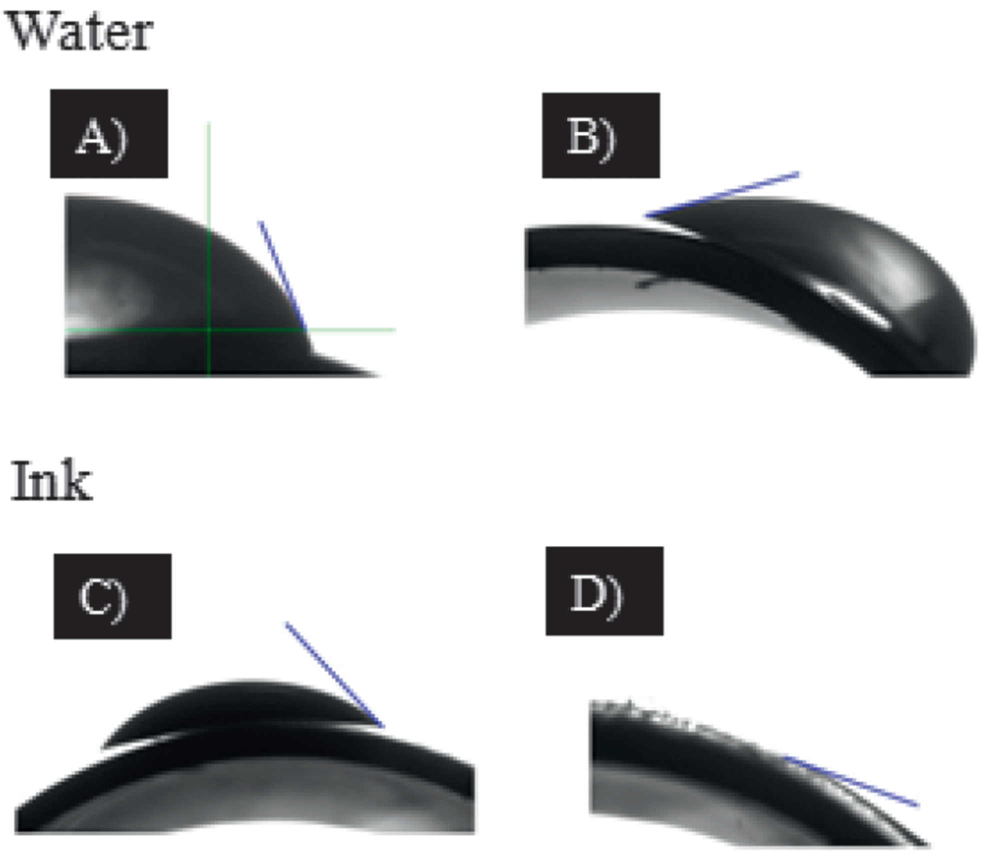

Figure 4. Distribution of water and ink per unit area.

As the angle of incidence between the nail surface and projected ink decreases, the actual projected area increases because of the flow of ink. It reduces the amount of spraying printed per unit area. The problem of decreasing the amount of projection per unit area according to the angle of incidence $\left(15^{\circ} \leq \theta \leq 30^{\circ}\right)$ can be solved by repeated printing up to three times while increasing the precision and accuracy for the projection correction. It expands up to 150% of the maximum amount of projection. Incidence angles from 30° to 70° are supposed to be projected twice in the same position to get high precision; thus, the actual projected amount increased from 114% up to 181% of the ideal projected amount of the minimum incident angle. By repeating experiments, the number

Table I
Different Numbers of Printed Layers Depend on the Angle of Incidence

θ (the angle of incidence)	$\frac{W_P}{W_I}$ (the ratio of settling)	Number of printing (layers)
70°–90°	0.94–1.00	1
30°–70°	0.50–0.94	2
15°–30°	0.26–0.50	3

of printing performed on the surface can determine the accuracy of the result. Printing one layer results in a minimum of 94% settling ratio, and printing it twice in the same position can result in a maximum of 182% settling ratio. Areas printed three times or twice have no numerical difference compared with areas printed twice or once. However, the area printed twice and one time shows a difference of up to 90% that indicate the boundary. By repeating the experiments with various designs, a result of 100% or even more of the settling ratio was obtained. These numerical results are shown in Figure 5.

The conventional printing method, in which CPPM is not applied, can print the image when the theta value is 90°. However, when the theta value is less than 90°, the ink distribution is nonuniform because of spreading. On the other hand, CPPM is a method of calculating the drop settling of ink according to the change of the angle of incidence and concentrating the amount of ink deposited in the same place with repeated printing from one to three layers to get distinct results. Figure 5 shows a graphical representation of the settling ratio of $\frac{W_P}{W_I}$ (actual projected weight/ideal projection weight) to the different values (15°–90°), as shown in Table I. As seen before, the ranges of settling ratio is $0 < \frac{W_P}{W_I} \leq 1$. To have the accuracy and clarity of the result through the CPPM, it reaches at $1 \left(\frac{W_P}{W_I}\right) = 100\%$ when $\theta = 90°$, where the actual and ideal projections are matched. But because the output is printed on the conformal nail, the theta value decreases as the curvature becomes more severe. To increase the settlement rate, the accuracy and clarity of the result are increased by the number of printed layers. This study was based on achieving 100% settling degree, regardless of the range of different theta values for the clarity and accuracy of the print.

Figure 6 shows the piston-type extrusion method that prints high viscosity materials on the boundary with a laser guide for precise 3D printing, which differs from the results of conventional printing to CPPM to show improvement in the accuracy of the print (26). The printing results from Figure 6 imply that three-dimensional sculptures can be constructed by repeated printing up to three times with CPPM. In the process of printing more than 300 image files, the results were compared with those of the CPPM applied to the conventional printing method (single layer), including the analyzed printing conditions. The result of stacking up to three times on the conformal surface by CPPM increased three-dimensional effects as it was accumulated on the Z-axis one by one. In the conventional printing method, where CPPM is not applied, it is confirmed that the amount of output per unit area is absolutely insufficient at the curvature because of

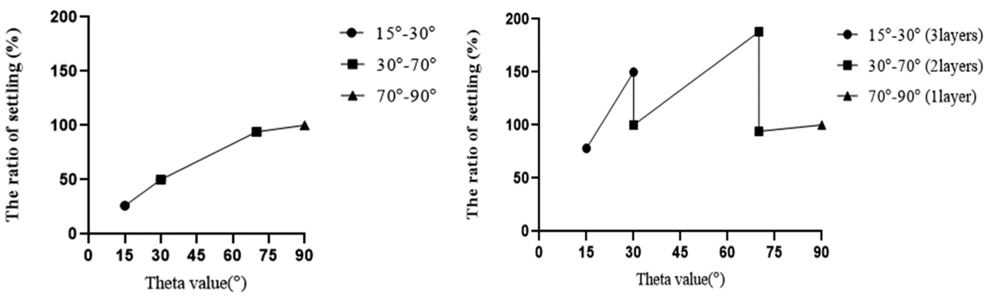

Figure 5. The comparison of the conventional single layer printing method and CPPM with W_P/W_I rate distribution graph.

the small incident angle between the ink droplets and surface. In other words, as theta becomes smaller, the discharged amount flows over the curved surface, resulting in a fading or bleeding phenomenon, and losing sharpness in which the original colors and shape of the edges do not appear. This is illustrated by the red circles comparing the same image output in Figure 6. Printing unique designs provided by the consumers on time, the demonstration of maximizing the effects of accuracy and clarity by preventing the dispersion of materials by laser treatment and increasing the adsorption power between inks has been successfully completed and verified.

CONCLUSION

The introduction of the IoT system solved the health risks in the conventional nail art process with the advantage that customers can receive services in their personal spaces without being exposed to UV radiation.

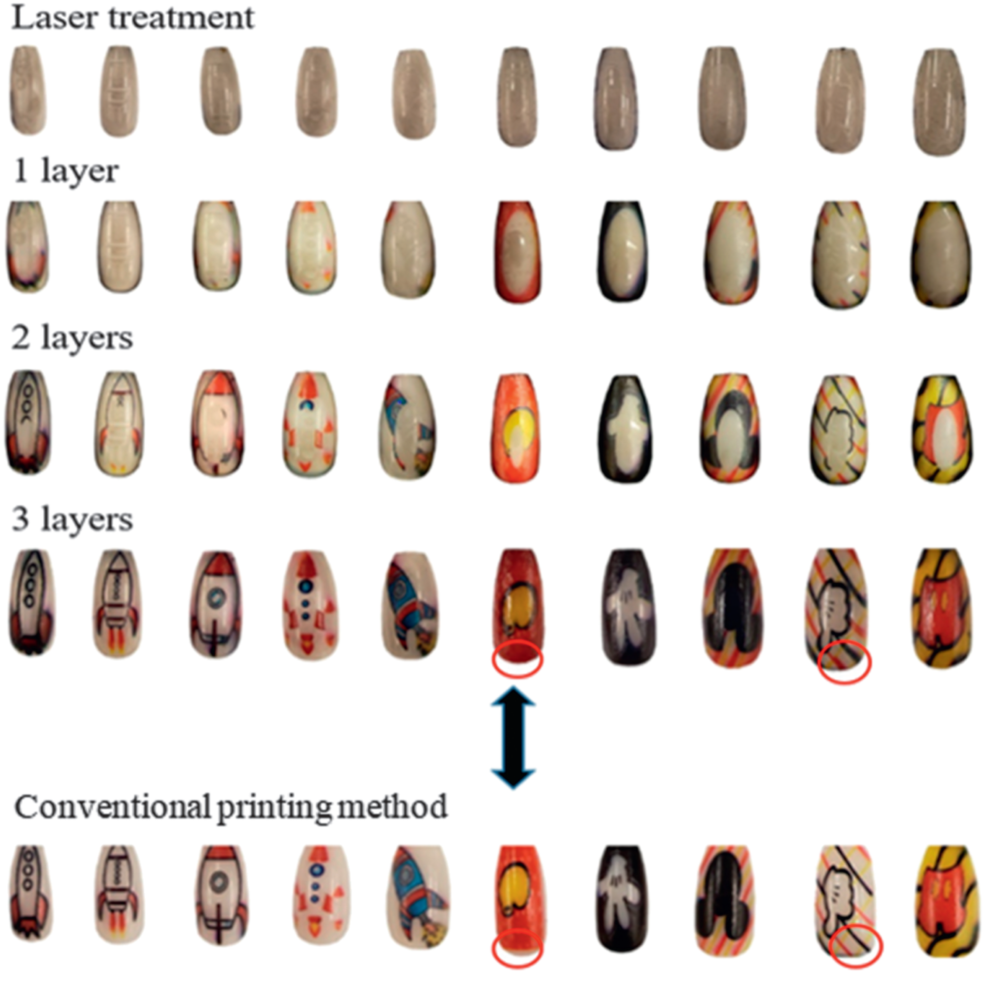

Figure 6. Comparison between conventional printing method and CPPM.

Nail art printing results have been successfully compared with conventional methods with the introduction of the CPPM, which enables printing on the conformal surfaces from the existing inkjet printing that can print the highest accuracy and detail only on a flat surface. In the conventional curved surface print, as the angle of incidence between the ink and the substrate becomes smaller, the spread of ink flows along the curved surface, which reduces the amount of output per unit area. Laser treatment was used to solve this problem by increasing the adhesion of the ink. Another method to increase the sharpness of the curved surface is divided into three ranges of theta value, and the number of printings is changed from 1 to 3 accordingly to increase the settlement ratio $\left(\frac{W_P}{W_I}\right)$ of the ink to 100% or more. The optimal number of printing layers is derived and verified to increase the accuracy of the print in three different ranges of theta from the smallest stacking area (15°–30°) to the largest stacking area (70°–90°). According to the difference in curvature of the surface to be printed, the number of layers printed depends on the theta values, and the results of each range of values increased the clarity and accuracy of print. The successful application of nail art with the CPPM can be extended to various applications requiring compact precision in the future.

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