Design and Fabrication for Dynamic Color-Changing on Curved 3D-Printed Surfaces

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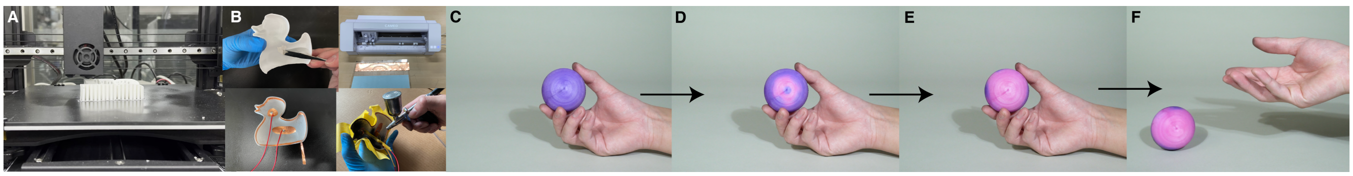

Figure 1: A novel dynamic and rapid color-changing method designed for curved 3D-printed surfaces. (A, B) A design and fabrication process combining specialized paint application, electrode layouts, and base material preconditioning for effective color transformation. (C, D, E, F) Design example, which changes the color of a curved surface.

ABSTRACT

Recent studies have presented various methods for changing the color of objects using thermochromic materials. However, many methods face challenges related to heat sources, leading to limitations in object shape, size, and the speed of color change. In this paper, we propose a novel dynamic and rapid color-changing method designed for curved 3D-printed surfaces. We explored the use of Carbo e-Therm, a carbon-based electrically-conductive heating paint, as a novel means of joule heating for color change. We developed a design and fabrication method for color change that integrates specific paint application techniques, electrode configurations, and pretreatment of base materials. This approach enables rapid color changes using thermochromic materials, across diverse 3D-printed substrates and curved surfaces. Furthermore, this work operates as a self-contained system, eliminating the need for bulky external equipment and allowing the object itself to change color. This paper details the proposed method and presents several design examples.

CCS CONCEPTS

• **Human-centered computing** → *Interaction devices.*

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KEYWORDS

Programmable Materials, Color-changing, Personal Fabrication, Heating Paint, Carbo e-Therm

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1 INTRODUCTION

In recent years, the discussion of programmable matter [4, 20], which refers to matter with the ability to change the physical properties of objects, such as shape, color, and size, has attracted attention. This concept is also advancing in the field of Human-Computer Interaction (HCI). There are emerging proposals to dynamically change the form and function of objects by leveraging material science technologies and applying them to computer interfaces. One of the dynamically controllable physical properties is color. Changes in color are intuitively comprehensible as visual information and their practicality extends well in everyday life.

In the field of HCI, research has been conducted on enabling objects to change their color without the need for external heat sources such as hot water or dryers. A commonly used method for achieving color change involves thermochromic materials, which change color in response to temperature. However, this approach comes with several challenges related to heat sources. Techniques using Peltier elements [12, 16, 24] offer rapid color changes but are limited to two-dimensional surfaces. Approaches that use conductive ink [7, 8, 11, 15, 22, 23] allow paper and other thin materials to function as heaters, but they restrict the shape flexibility and choice of substrates. Methods employing conductive threads [2, 3, 9, 25] can adapt to curved surfaces by weaving the threads along them. However, these methods tend to have limited heat distribution and thermal capacity. On the other hand, using off-the-shelf resistive heaters often results in uneven heating and compatibility issues with thermochromic materials in terms of temperature range. As a result of these challenges related to heat sources, the use of thermochromic materials imposes some constraints on the shape, size, and speed of objects' color change.

Changing the color of objects with highly curved surfaces is particularly challenging, especially when the objects are intended to operate as self-contained systems. Methods using thermochromic materials face difficulties changing the color of such curved surfaces due to issues with heat sources, as previously mentioned. While there is an approach that feeds cold and hot water into the object to achieve color change, it requires an external large-scale and complicated fluid system [28]. Methods employing photochromic materials have been proposed to dynamically change the color of curved surfaces [6, 17, 27]. However, these methods require a projector or UV light source, making the overall system cumbersome and requiring a long duration for the color change. Thus, rapidly changing the color of objects with highly curved surfaces while maintaining them as self-contained systems remains a major challenge.

To address these challenges, in this paper, we propose a novel dynamic and rapid color-changing method designed for curved 3D-printed surfaces. We explored the use of Carbo e-Therm [13], a carbon-based electrically-conductive heating paint, as a novel means of joule heating for color change. We developed a corresponding design and fabrication method that integrates specific paint application techniques, electrode placement, and pretreatment of base materials. This approach enables rapid color changes using thermochromic materials across diverse 3D-printed substrates and various curved surfaces. Additionally, utilizing paint as a heat source allows the heating size to be freely adjusted to suit specific applications without size restriction defined by electronic components. Furthermore, DynaColor operates as a self-contained system, eliminating the need for bulky and large external equipment and allowing the object itself to change color.

In this study, we present the design and fabrication methods and show several design examples. The core novelty of this paper in relation to the HCI field lies in its pioneering exploration of the self-contained color-changing approach that integrates various curved shapes, versatile color-changing dimensions, and dynamic, rapid-changing speeds. In summary, we contributed:

(1) A novel approach, to make a self-contained system capable of versatile and dynamic color changes across a range of curved surfaces.
(2) A pioneering utilization proposal introducing Carbon e-Therm coating for color transformation within the realm of HCI
(3) A design and fabrication process combining specialized paint application, electrode layouts, and base material preconditioning for effective color transformation.
(4) Design examples of electrode placement based on different types of curved surfaces.

2 RELATED WORK

This section describes Carbo e-Therm, a heating paint adopted by this work. Carbo e-Therm is a highly efficient, electrically conductive coating that can be used in a non-hazardous low voltage range [13]. This coating consists of a binder matrix and a specially matched carbon formulation. Due to its excellent conductivity, it can achieve high heating capabilities at a safe low voltage.

As shown in Fig. 2, conventional resistive heating methods require serpentine patterns. In contrast, Carbo e-Therm can distribute heat uniformly without creating hot spots. The heating temperature is determined by the Joule heat generated when current flows through the applied Carbo e-Therm coating. The lower the resistance value of the applied Carbo e-Therm, the easier it is for current to flow when voltage is applied, resulting in easier and quicker heating to higher temperatures. This resistance value R_{total} can be calculated by the following formula, taking into account the thickness of the coating layer R_s (sheet resistance), the distance between the electrodes to which the voltage is applied L, and the length of the electrodes W.

$$R_{total} = R_s \frac{L}{W} \quad (1)$$

The applications of Carbo e-Therm are still in the developing stage. Several proposals have been made primarily in the aerospace field [5, 10, 19, 26], specifically for de-icing and anti-icing on the leading edges of Unmanned Aerial Vehicles (UAVs) [19]. Other applications include its use in heating systems for the preservation of art [1, 13] where it is generally employed as a large-scale heater using Carbo e-Therm. In the field of HCI, Stiff-switch [21] has been proposed, which utilizes Carbo e-Therm as a heating paint for thermal stiffness control. However, to date, there is little use of Carbo e-Therm in the field of HCI. To the best of our knowledge, no prior research exists on its use as a heat source for color change.

In this way, we propose a pioneering exploration to adapt Carbo e-Therm for color changes. By utilizing Carbo e-Therm as a heating source, we can flexibly set the size and shape of the heating surface area to suit various applications. Furthermore, Carbo e-Therm exhibits a faster temperature rise compared to other conductive inks such as silver conductive ink, making it superior in heating performance [21]. Leveraging these characteristics, we introduce a novel design and fabrication process for color changes on curved surfaces as a self-contained system.

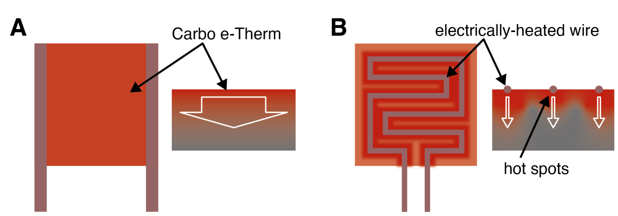

Figure 2: Comparison of heating characteristics between Carbo e-Therm and conventional resistive heating methods. (A) Carbo e-Therm: Uniform heating without hot spots. (B) Conventional resistive heating methods: Heating only in the serpentine pattern of the conductive area.

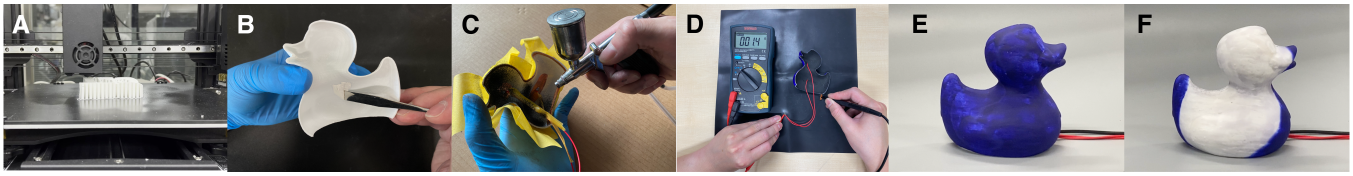

Figure 3: Overview: (A) print 3D-print model, (B) pre-treat on the 3D-printed surface to facilitate the application of paint, (C) install electrodes on the backside of the pre-treated object and coat it with Carbo e-Therm, (D) measure the resistance value of the applied Carbo e-Therm, (E, F) apply voltage to the electrodes. The color of the object's surface begins to change.

3 DESIGN FOR DYNAMIC COLOR-CHANGING ON CURVED 3D-PRINTED SURFACES

3.1 Overview

We introduce the basic operation of this work using a simple example. The flow of operations is illustrated in Fig. 3. First, (A) we create data for a 3D model with a surface thickness of 1mm and then print it using an FDM 3D printer. Next, (B) we perform a pretreatment on the 3D-printed surface to facilitate paint application. Subsequently, (C) we install electrodes on the backside of the pretreated object and coat the entire backside with Carbo e-Therm. The object's front surface is then coated with thermochromic ink. Details about the steps in (B) and (C) will be elaborated in the Fabrication section. After that, (D) we use a tester to measure the resistance value of the applied Carbo e-Therm, which will determine the voltage to be applied. Finally, (E, F) we apply voltage to the electrodes, which heats the Carbo e-Therm coating on the backside of the object. This induces color changes even in objects with curved surfaces and perforations. As a self-contained system, a compact electronic system smaller than the size of a palm is implemented, and voltage of about 4 V to 12 V is controlled by this system.

3.2 Mechanism and Structure

The fundamental working mechanism and structure is as follows. The backside of the 3D-printed object is heated, allowing the heat to transfer to the front surface. Thermochromic ink applied to the front surface of the 3D-printed object induces color transformation due to temperature shift. The structure of this work consists of five major layers, as shown in Fig. 4. Each layer has multiple properties that can be configured to achieve different functions, which will be outlined below.

This proposal features a thin shell structure to enable faster heat transfer between the layers. Additionally, while the shell structure is suitable for use not only with 3D-printed surfaces but also with other insulating thin-shell objects, the speed of color change depends on the thermal conductivity of the material.

3.2.1 Thermochromic ink layer. The thermochromic ink layer is where the surface of the 3D-printed object undergoes the actual color change. Commercially available thermochromic ink is applied to the surface of the object by brush or airbrush.

3.2.2 3D-printed surface layer. The 3D-printed surface layer is the surface of an object output by an FDM 3D printer. To enhance thermal conductivity, all parts are printed with an outer wall thickness of around 1 mm. This value of 1mm is configured because 3D-printed surface at this thickness can normally be printed stably while being able to pass heat sufficiently. Stereolithography is generally sensitive to heat and may cause the object to deform during heating. Therefore, as the temperature of the heated surface is around 40 to 60°C, FDM 3D printers are primarily used (because the temperature of the heated surface is around 40 to 60°C.) with a rich choice of generically used filament material. Additionally, the commercially available thermochromic filaments can be used as an alternative to the thermochromic ink layer described in Section 3.2.1.

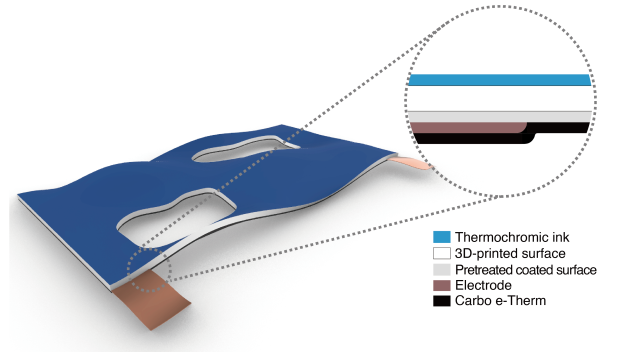

Figure 4: The structure consists of five major layers: Thermochromic ink layer, 3D-printed surface layer, Pretreated coated layer, Electrode layer and Carbo e-Therm layer

3.2.3 Pretreated coated layer. The pretreated coated layer is a layer to facilitate the later application of Carbo e-Therm to the backside of the object. 3D-printed objects created with FDM 3D printers have visible laminated striations. If these striations are left untreated, the application of Carbo e-Therm may be uneven or even impossible.

3.2.4 Electrode layer. The electrode layer prepares the electrodes for applying voltage. Copper tape, which is easy to work with, is used as the material for the electrodes. This layer plays a significant role, as ensuring a proper electrical connection between the electrodes and the applied Carbo e-Therm is essential for heating.

3.2.5 Carbo e-Therm layer. The Carbo e-Therm layer functions as the heating surface. Uneven application of Carbo e-Therm can result in varying heating temperatures or the creation of hotspots. Therefore, it is uniformly applied using an airbrush.

3.3 Resistance Value of Curved Surfaces Coated with Carbo e-Therm for Operation

The voltage to be applied is determined by the resistance value of the applied Carbo e-Therm. This subsection explains how the resistance value is determined for the curved shapes. As shown in Equation (1) described in 2, the resistance value of Carbo e-Therm applied to a flat surface is determined by base sheet resistance R_s (the thickness of the coating), the distance between the electrodes to which voltage is applied L, and the length of the electrodes W. The sheet resistance R_s is around $30\Omega/sq$ across any painted surface between electrodes [13, 18]. Therefore, the resistance value of the plane surface is determined by the aspect ratio of the distance L and the length W of the electrodes, as shown in Fig. 5. Compared to other conductive, sprayable, resistive-heating materials, this leads to a unique feature that allows the heating size to be easily customized for different applications. For this reason, our proposal has adopted Carbo e-Therm as the flexible heating source. However, based on our experimental experience, the resistance value can vary depending on the coating condition. Furthermore, since this paper focuses on curved surfaces, it is challenging to predefine precise resistance values. Consequently, the resistance is measured in advance by connecting a tester to the electrodes to estimate the required voltage.

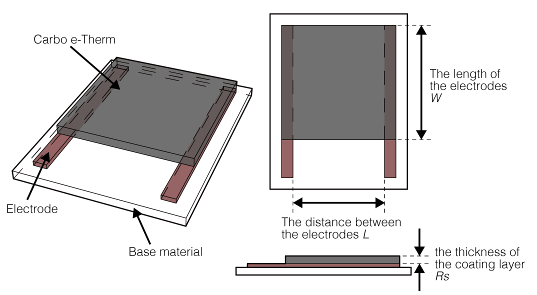

Figure 5: Theoretical resistance value of plane surfaces. (Illustrated by the authors according to the datasheet of Carbo e-Therm [18])

3.4 Electrode Structure and Layout for curved Surfaces

The layout and structure of the electrodes must be carefully considered depending on the target's curved surface. Ideally, the distance between the positive and negative electrodes should be consistent across all points. In the case of flat surfaces, as shown in Fig. 8 (A), it's most appropriate to place linear electrodes at both ends. When dealing with curved surfaces, as shown in Fig. 7 (A), line-shaped electrodes should be placed on the edges of the curved surface and circular electrodes should be placed inside the curved surface, in such a configuration that the distance between electrodes is as constant as possible for any location.

4 FABRICATION PIPELINE

This work can be fabricated through a five-step pipeline, as shown in Fig. 6, which outlines the overall fabrication process. Simply applying heating paint is not sufficient to achieve surface heating on curved surfaces. There are several significant steps involved, which will be described in this section.

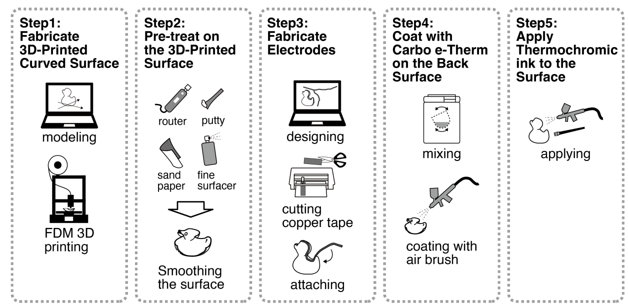

Figure 6: Overall fabrication pipeline in five steps.

4.1 Step1: Fabricate 3D-Printed Curved Surface

First, generate curved surface data with a thickness of less than 1 mm as the model to be FDM 3D printed. The model is divided to facilitate the application of the Carbo e-Therm before exporting the data. At this stage, it is recommended to output the model in a direction that minimizes the use of support material on the backside, which is the eventual heat-generating surface. Additionally, we set the layer height to 0.1 mm and performed ironing to achieve a smoother surface. While various filament materials like PLA, ABS, and ASA are generally suitable, we primarily opted for ABS for its ease of processing and high heat resistance.

4.2 Step2: Pretreat the 3D-Printed Surface

The back surface of the 3D-printed object undergoes pretreatment to ensure easy and stable paint application. First, any large protrusions, bumps, or burrs on the 3D-printed object are removed using a die grinder. Next, any areas with rough layering, overhangs, and any indentations or gaps are filled using modeling putty. After drying, the entire back surface where the putty has been applied is sanded. Finally, a fine surfacer is applied to the back surface. This surfacer is a commercially available product commonly used as a primer for painting plastic and metal models. Through this series of steps, the Carbo e-Therm can be stably applied to the back surface.

4.3 Step3: Fabricate Electrodes

Electrode fabrication plays a vital role in the process as it is essential to establish a robust electrical connection for effective heating. Copper tape was opted as the electrode material for its ease of processing. Electrodes to be placed on the edges of curved surfaces of hemispherical three-dimensional shapes have complex shapes. They cannot be easily cut by hand with scissors because the path varies depending on the target curvature. The surface of the area where the electrode is to be placed is extracted from the curved surface data and developed into a planar surface to create the electrode shape data. The electrodes is cut by a cutting plotter.

4.4 Step4: Coat with Carbo e-Therm on the Back Surface

Before applying Carbo e-Therm, it is essential to mix the material thoroughly, or else it leads to an exceptionally high resistance value, causing insufficient heating. A planetary centrifugal mixer (AR100, Thinky) is used for mixing before application. Then, an airbrush with a 0.5 mm nozzle diameter is used to uniformly coat the back surface of the object with Carbo e-Therm in a well-ventilated environment.

4.5 Step5: Apply Thermochromic ink to the Surface

Finally, thermochromic ink is applied to the front surface of the object. In this case, we use thermochromic paint with a color-changing temperature of around 40 degrees, applied with either a brush or an airbrush.

5 DESIGN EXAMPLES

This proposal is primarily based on two fundamental surface types. These are combined to fit surfaces in more complex shapes, which in turn determine the corresponding design of electrode placement. We present design examples that utilize the features.

5.1 Basic Design

This proposal's basic electrode configurations primarily depend on two types of surfaces: hemispherical surfaces and rectangular flat surfaces. We describe the color changes observed in these fundamental designs.

5.1.1 The design of color change on a curved surface derived from a hemispherical surface. Fig. 7 shows the electrode layout design and the observed color changes when using a curved surface based on a hemispherical shape. The color at the center of the hemisphere changed towards the end, which is explained in Section 6.1.

5.1.2 The design of color change on a curved surface derived from a rectangular flat surface. Fig. 8 shows the electrode layout design and the observed color changes when using a curved surface based on a rectangular flat plane. Color change of areas with electrodes attached is dependent on thermal conduction condition, which is later discussed in Section 6.1.

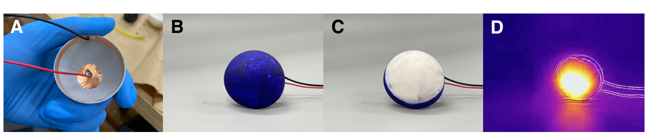

Figure 7: Color change of a surfaced based on a hemispherical surface. (A) Surface with electrodes placed on the center and along the edges. (B) Surface prior to voltage application. (C) Color changes with voltage application. (D) Heat generated between electrodes and visualized through thermal camera.

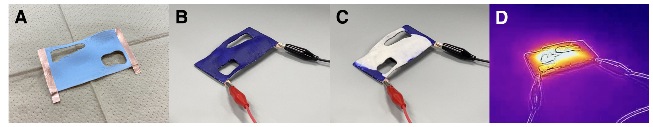

Figure 8: Color change of a surfaced based on a rectangular flat surface. (A) Planar curved surface with linear electrodes placed on both ends. (B) Surface prior to voltage application. (C) Color changes with voltage application. (D) Heat generated between linear electrodes and visualized through thermal camera.

5.2 Duck: The Design of Color Change on Highly Curved Surface

Fig. 9 shows a design example, Duck, which changes the color of a highly curved surface. This shape is based on hemispherical surfaces for determining electrode placement; electrodes are placed in the center and along the edge of each hemispherical-like surface. Regarding the color change process, it initiates from areas with closer electrode distances.

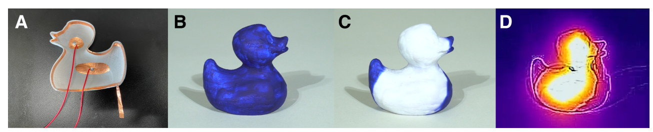

Figure 9: Color change of Duck. (A) Surface with electrodes placed on the center of two hemisphere-like shapes and along the edges. (B) Surface prior to voltage application. (C) Color changes with voltage application. (D) Heat generated between electrodes and around the center.

5.3 Butterfly: The Design of Color Change on Perforated Surface

Fig. 10 shows a design example, Butterfly, which changes the color of a perforated surfaces. This shape is derived from rectangular planes with electrodes placed on each wing. Similar to other design examples, areas with closer electrode distances change color first.

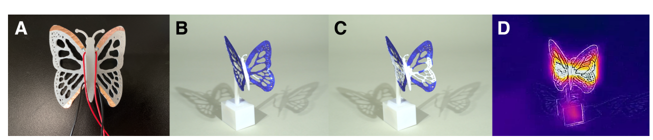

Figure 10: Color change of Butterfly. (A) Perforated surface with linear electrodes placed on the ends of each wing. (B) Surface prior to voltage application. (C) Color changes in the areas between electrodes. (D) Heat generated between the upper and lower edges of the wings.

6 DISCUSSION AND FUTURE WORK

6.1 Surface with Electrodes Attached

As the current flows between the bounds of the electrodes and not on the electrode medium itself, neither the current nor the heat is generated in the area where electrodes are adhered to. This phenomenon is visible in design examples shown in Fig. 8 (C) and Fig. 10 (C). Though the color of the area is not directly altered by thermal changes, it can undergo a gradual transformation with a delay as its temperature increases through thermal conduction from the surrounding areas, which is dependent on the location of the electrode. For hemispherical surfaces, the center of the hemisphere receives heat transferred from all directions, inducing delayed yet satisfying color transformation. Conversely, it is more difficult for heat to propagate toward the edges of both hemispherical and planar surfaces, leading to an incomplete color change along the edges. In the future, we aim to enhance the layout design by increasing the number of electrodes to facilitate faster and more efficient thermal conduction across the surface, ensuring uniform heat distribution throughout. Additionally, we would like to consider the use of thermally-conductive filament [14] to enhance heat transfer and uniform heat distribution.

6.2 Heat Transfer to Curved Surfaces

Carbo e-Therm generates heat uniformly when applied to a flat surface with a constant distance between electrodes. However, when considering its use on a curved surface, neglecting thoughtful electrode placement during the coating application can lead to predominant heating in areas where the electrode is closely spaced. This can result in uneven or incomplete heating across the object's surface or the creation of extreme hot spots. To address this, proposed method combines two basic designs based on a rectangular plane and a hemisphere, designing reasonable electrode layouts and taking into account the surface heat conduction of the object, to enable heating across various curved surfaces. Looking ahead, we believe that mathematically determining electrode layouts dynamically based on the structure would allow for more generalized application to various curved surfaces.

6.3 Evaluation and Design Space

We examined the heat generated as the curvature of the surface increases. The experimental materials were prepared at five different bending angles of 0°, 54°, 90°, 126°, and 162° for a rectangular plane 40 mm long, 80 mm wide, and 1 mm thick. As a result, even surfaces with different curvatures generated heat to about the same temperature for each. To be precise, the 3D printed samples are heated to around 40 °C with 24 V applied voltage and about 500 mA current flow. Under these conditions, the temperature reached about 40 °C in about 10 seconds after the voltage is applied. Additionally, the ABS used in the experiment has a high heat resistance, and no softening or deformation of the 3D-printed object occurred at the applied temperature. Therefore, we conclude that as long as the shape permits coating application, there is minimal variation in heating performance due to curvature. In the next step, it will be necessary to evaluate the heat distribution on the surfaces of various complex curved surfaces as well. Furthermore, object geometry, time taken for color change, and power consumption should also be further evaluated as factors.

In this study, some design examples of color change on curved 3D-printed surfaces are presented. As a next step, we will further explore applications that benefit from this new contribution that cannot be realized with existing methods. Specifically, we aim to further expand the design space by exploring stencil patterns for the heated surface areas in combination with different electrode layouts, and by creating animations using thermochromic inks with varying color-changing temperature ranges.

7 CONCLUSION

In this paper, we proposed a novel method for dynamically changing colors on curved and perforated 3D-printed surfaces as a self-contained system. As a heat source, we explored methods of heating curved surfaces using Carbo e-Therm, which offers superior conductivity and high heating capability at low voltages. By combining two basic designs based on a rectangular flat surface and a hemisphere, we outlined a design and fabrication process that enables color change on surface shapes previously unattainable with existing heat sources. This work could represent a significant advancement in the utilization of heating technology. Through the contributions of this paper, we hope to pave the way for various color-changing products to become an part of our daily lives in the future.

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