Study on creating the three-dimensional shape of apparel by thermal bonding of thermoplastic polyurethane film and vacuum forming molding

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Abstract
The shape of apparel is one of the most important elements in fashion design, for example, the three-dimensional shape of apparel can be quite creative and fashionable. The current technologies for creating the three-dimensional shape of apparel are many, but have their limitations in dealing with various fabrics, particularly light and soft fabrics. This article presents a new method to rapidly create three-dimensional shape of apparel for avoiding the aforementioned disadvantages. The method combines thermal bonding of thermoplastic polyurethane film and vacuum forming. In this study, 12 kinds of commercial fabrics were selected and then tested. All these fabrics were first bonded to thermoplastic polyurethane film and then rapidly applied to the vacuum forming machine to form the three-dimensional mold-like shape. This research analyzed the factors of molding a fabric to a good three-dimensional shape of apparel and the relative tests to be carried out for validating its stability for the selected fabric samples. There are two main contributions of this study. The first is to propose a more effective method for three-dimensional shape of apparel in fashion design. The second is to provide useful information for fabric selection and determination of bonding temperature in molding.

Keywords
Three-dimensional shape, thermal bonding, thermoplastic polyurethane film, vacuum forming, rapid-formed

Introduction
Fashion is regarded to be artistic and creative.¹,² How to create an interesting and aesthetic three-dimensional (3D) shape becomes a crucial issue in fashion design.³–⁷ Generally, there are two types of methods for creating 3D shape of apparel (SA), namely, physical-based method and thermal-based method. There are five common physical-based methods to create 3D SA, namely, (1) pattern making,⁷ (2) 3D knitting technique,⁸,⁹ (3) crinoline technique,¹⁰ (4) padding technique,¹¹ and the recent popular (5) 3D printing.¹²–¹⁴ These methods use a series of physical practices, such as conventional cutting
and sewing, designing darts or pleats of the pattern, depositing materials into layers, applying additional structural material, or using the virtual simulation software (e.g. computer-aided design (CAD)), to build the 3D SA.

Unlike the physical methods, the principle of the thermal-based method is to transform two-dimensional (2D) fabric into a 3D shape by stretching and compressing the fabric under heat. It includes the molding and forming technologies. Ng demonstrated that these technologies have been widely applied by fashion designers since 1887. For example, for making the traditional men’s bespoke suit and the 3D-shaped felt millinery (Figure 1(b)), mold and heat (e.g. the wood mold (Figure 1(a)) and hot iron) are essentially needed. Meanwhile, hand stretch and pressure are also applied all along the process to change the fabrics into a mold-like structure. However, according to the studies from Nordheim, Ng, Carr and Tyler, Blanco et al., molding and forming technologies still have limitations, including (1) not all fabrics can be molded, as molding requires that the fabrics have specific content and structure. For example, cotton, silk, and several synthetic fiber fabrics cannot be stably molded into a 3D shape. (2) The traditional molding process for 3D SA is time-consuming or complex by providing repeated heat, pressure, and hand-stretching. With the industrial revolution and the invention of thermosetting materials, molding and forming technologies have been developed. The most typical case is the rapid production of seamless bra. The primary hand-making practice has been replaced by the industrial contour-molding machine (Figure 1(c)), which can provide high efficiency and standard production in molding and forming the fit breast shape. The traditional molding choice of material was limited to wool or wool-rich fabric. New thermosetting materials, such as polyurethane foam sheets and 3D spacer fabrics, extended the range of materials for molding and forming. In Figure 1(c), the 2D thermosetting material is placed in the space between the heated male and female molds, and then it is heated and compressed by the contour-molding machine. The whole process is quite rapid, lasting for about 1 min. It has been found from these studies that (1) the contour-molding machine requires more than one mold as mentioned, which increases the complexity and cost of production, and (2) this industrial technology still cannot apply on all fabrics.

In order to overcome the aforementioned issues, in this article, a new process for rapid creation of 3D SA by applying thermal bonding and vacuum forming technology is proposed. Thermal bonding is a popular and high-producing method for bonding used in textile manufacture, which has been discussed by Dharmadhikary et al. This technology can bond the fabric to a thermoplastic component, such as fiber, powder, or film, and create the new composite fabric with extra functions. Vacuum forming is widely applied in the rapid prototyping and industrial fabrication phase. Its principle is that the heated thermoplastic material can be molded into the desired shape by mechanical and pneumatic stretching of the rapid vacuum. This technology requires only one convex mold, which is placed on the machine’s vacuum bed. The rest of the article is organized as follows: the second section describes the use of thermal bonding the thermoplastic polyurethane (TPU) film and vacuum forming technology to rapidly create 3D SA. Further experiments are proposed to validate the stability of the formation of 3D shapes and the differences in wrinkle recovery angle (WRA) between different fabrics with TPU film and without TPU film. The third section presents the results and discussion. The final section is the conclusion and further perspectives.

**Experiment**

**Material**

In this experiment, 12 kinds of commercial fabrics with different structures and fiber contents were investigated to create 3D shape. Table 1 provides the basic information of the fabrics, and Figure 2 provides their visual details.

Twelve kinds of commercial fabrics are thermal bonded with the TPU film by the heat-press machine (XIHONG, XY-013A) and the fabric is molded to the desired 3D shape with the vacuum forming machine (Shang Yu SHANGYU, TWDE-009) (Figure 4). The reason for using TPU is its flexibility, with good mechanical properties. Moreover, the TPU film can be easily bonded under heat and it is widely...
Table 1. The characteristics of 12 kinds of commercial fabrics.

| Item | Fabric (structure)       | Fiber content          | Density of weft picks/10 cm | Density of warp picks/10 cm | Thickness (mm) | Weight (g/m²) |
|------|--------------------------|------------------------|-----------------------------|-----------------------------|----------------|---------------|
| 1    | Cotton 1 (weave)         | 100% cotton            | 480                         | 440                         | 0.19           | 134           |
| 2    | Cotton 2 (weave)         | 80% cotton, 20% polyester | 480                       | 260                         | 0.21           | 100           |
| 3    | Ramie fabric (weave)     | 100% ramie             | 200                         | 120                         | 0.59           | 170           |
| 4    | Wool 1 (weave)           | 100% wool              | 190                         | 240                         | 0.82           | 291           |
| 5    | Wool 2 (weave)           | 70% wool, 30% polyester | 212                         | 212                         | 0.31           | 154           |
| 6    | Chiffon (weave)          | 100% polyester         | 320                         | 600                         | 0.18           | 25            |
| 7    | Silk (weave)             | 100% silk              | 480                         | 1380                        | 0.15           | 55            |
| 8    | Satin (satin weave)      | 100% silk              | 260                         | 760                         | 0.35           | 200           |
| 9    | Mash (warp knitted)      | 100% polyester         | –                           | –                           | 0.18           | 145           |
| 10   | Lace 1 fabric with smooth surface | 100% rayon polyester | –                           | –                           | 0.29           | 41            |
| 11   | Lace 2 fabric with uneven surface | 100% rayon polyester | –                           | –                           | 0.58           | 155           |
| 12   | Velvet (3D woven tufted)  | 100% rayon             | –                           | –                           | 0.82           | 225           |

3D: three-dimensional.

Figure 2. Visual details of 12 kinds of commercial fabrics.
used in the fabric coating phase.\textsuperscript{28–30} In this experiment, the thickness of the TPU film is 0.2 mm and the density is 330 g/yard, and hundreds of TPU films and fabric samples were prepared. They were cut into sizes of 130 mm × 130 mm (the size is slightly bigger than that of the vacuum bed, which is 100 mm × 100 mm), 40 mm (wrap) × 15 mm, and 40 mm (weft) × 15 mm, respectively.

**Experimental phases**

**Pre-molding test.** The pre-molding test aims to check whether those 12 kinds of commercial fabrics alone can be molded into a 3D shape. If the fabric is not able to be molded into a 3D shape, it will be retained in the experiment, otherwise it will be eliminated. Step 2 in Figure 3 can be seen as the pre-molding test process, except the removal of the TPU film. The fabric was located on the top of the mold block, and by being heated and with 5 s of vacuum forming, it can be verified whether the fabric can be molded into a 3D shape. The heat temperature in this pre-molding test was set as 160°C, 170°C, and 180°C, respectively.\textsuperscript{31–35} Each selected fabric sample was horizontally placed on the top of the TPU film (Figure 4). During each thermal bonding process, a Teflon sheet (0.13 mm thick) was applied to cover the fabric and the TPU film. This is to avoid the melting TPU film from sticking to the heat-press machine. In this phase, each kind of selected fabric was bonded to the TPU film 10 times under three different bonding temperatures.

**Molding composite fabric.** The composite fabrics (bonding to TPU) obtained from section “Thermal bonding between the fabric and the TPU film” were then molded into a 3D shape using the vacuum forming machine. Figure 5 shows the molding process of the composite fabric. The designed mold block (36.6 mm × 32.0 mm × 14.8 mm) was set on the top of the vacuum bed. It is noted that the molding process has to be conducted right after the bonding process, and so the heater of the vacuum forming machine does not need to reheat the composite fabrics during the molding phase, as the high temperature from the thermal bonding phase is enough for subsequent molding. The reason for avoiding reheating is that reheating may be uneven and can result in bubbles on the surface of the TPU film.\textsuperscript{30} It is noted that only mechanical and pneumatic stretch was applied by the vacuum forming machine in this phase. The dwell time of vacuum forming was set to 5 s. All composite fabrics thermal bonded in section “Thermal bonding between the fabric and the TPU film” were transferred immediately for rapid molding.

**Visual examination and height measurement of 3D-shaped composite fabric.** After the molding process, features of the 3D-shaped composite fabrics, including the appearance and TPU bubbling, peeling, yellowing, or melting on fabrics’ back, were visually checked by the experimenter. Meanwhile, the height of the 3D-shaped composite fabric was measured by vernier caliper. There were two height measurements. The first measurement was conducted right after molding, and the second one was conducted after 24 h. All pieces of the 3D-shaped composite fabrics were measured, and then the average of the height for each 3D-shaped composite fabric was calculated. Moreover, the shrinkage of height between the 3D-shaped composite fabric right after molding and after 24 h was recorded.

**WRA analysis.** The WRA aims to check whether the composite fabrics have better capability in retaining the shape than that without bonding to the TPU film. In this phase, the AATCC 66-2008 method was applied. The selected
fabrics and their composite fabrics were prepared under the three bonding temperatures. All samples were folded along their diagonal. Same load weight (500 g) was given on the top of the folded fabrics for 5 min ± 5 s, and then the weight was removed and the two recovery angles (warp and weft directions) of each piece were recorded after 5 min ± 5 s. This wrinkle recovery experiment was repeated 10 times for each fabric, and their average angles were obtained in the end.

**Results and discussion**

*Pre-molding test results*

Based on the results of the pre-molding test on 12 kinds of commercial fabrics, all of them did not show the possibility of being molded into the 3D shape. Thus, they were all selected for further investigation.

*Visual feature of the composite fabrics after molding*

Thirty-six groups (12 × 3) of visual feature after molding are reported in Table 2, including the 3D shape performance and incidence of TPU bubbling, peeling, yellowing, or melting on composite fabrics’ back. It is found that most composite fabrics appeared good in their molded 3D shapes. Most 3D-shaped composite fabrics bonded well without bubbles, peeling, and yellowing in all three temperatures, except that several of them showed slight problems after molding in some cases. More detailed analyses are as follows:

1. At 160°C, bubbles occurred at composite fabric 2 (80% cotton and 20% polyester) and composite fabric 5 (70% wool and 30% polyester). Particularly, composite fabric 5 showed a very severe peeling-off problem. These issues were avoided when the temperatures were set at 170°C and 180°C. The reason may be that an applied temperature of 160°C cannot provide sufficient strength to bond the fabric and TPU, and temperatures of 170°C and 180°C are more favorable for sufficient bonding.

2. However, molding at high temperatures still triggers several issues, such as fabric yellowing or TPU melting. For example, when the temperature reached 180°C, composite fabric 4 (100% wool), composite fabric 7 (100% silk), and composite fabric 8 (stain, 100% silk) mostly showed the yellowing issue. When the temperature decreased to 160°C or 170°C, the incidence of yellowing issue decreased or did not show up. Therefore, it can be inferred that the temperature of 180°C exceeds the heat resistance of these three composite fabrics. The heat resistance of fabrics should be considered in the thermal bonding process.

3. At 180°C, the TPU film bonded with fabric 10 (lace 1, 100% rayon polyester) and fabric 11 (lace 2, 100% rayon polyester) melted. While, the TPU film did not turn yellow or melting problem at 160°C or 170°C. Except the reason of their lower heat resistance. It may lie in the structures of these two lace fabrics. The problem was yellowing instead of melting for composite fabric 4, composite fabric 7, and composite fabric 8 at 180°C. The structures of these four fabrics are tight and flat. However, the two lace fabrics are loose with obvious hollow area. It is reasonable to assume that the TPU on the hollow area was directly heated during the thermal bonding process under 180°C and thus led to the melting issue. In addition, for further comparison of the structures between fabric 10 and fabric 11, refer to Table 2. Composite fabric 11 showed the bubble problem at all temperatures, and composite fabric 10 did not. This problem may due to fabric 11 being an uneven lace structure with a bigger hollow area, the TPU film cannot sufficiently bind to it. Therefore, the TPU partly peeled off and bubbles occurred during the molding process.

Figure 6 (more pictures in Cloud™) shows good cases of the 3D-shaped composite fabrics. Fabrics, such as composite fabric 9 (mesh) and composite fabric 12 (velvet), show better 3D shapes than others. These fabrics which can be molded with more conformity have been found to have knitting structure and 3D woven tufted.
And others, such as fabric 1 and fabric 2, are a plain weave structure. These two different structures have an impact on molding a fabric to 3D shape, and the reason may be that knitting and 3D woven tufted structures are flexible, and it can be easily shaped along with the mold. However, the plain weave structure is generally stable, and its mechanical stretching limits the fabric’s 3D shape capability.
**Height difference comparison among composite fabrics**

Figure 7 shows two main height measurements of composite fabrics (more details of data in Cloud 36), namely, the height of the molded 3D shape right after molding and the height after 24 h under three temperatures. It is noted that the mold itself has a height of 14.80 mm, and the good molded composite fabrics should have the same height or more (the composite fabric has its own thickness).

It can be found from Figure 7 that the height of only composite fabric 12 was more than 14.8 mm at a temperature of 160°C. With the temperature increasing, several composite fabrics, such as composite fabric 3, composite fabric 4, composite fabric 8, composite fabric 9, composite fabric 11, and composite fabric 12, could reach or exceed the height of 14.80 mm right after molding. However, there were some composite fabrics whose height was lower than 14.80 mm after 24 h. For example, composite fabric 7, composite fabric 8, composite fabric 9, and composite fabric 11 had fairly good height right after molding. But their heights fell to 14.54, 14.42, 14.70, and 14.75 mm, respectively, after 24 h of cooling. There may be many reasons, such as the heavy weight of composite fabrics themselves, the structure of the composite fabrics, the improper thermal bonding temperature, and the insufficient pressure from the vacuum forming machine.

In addition, from Figure 7, the height of most composite fabrics generally shows positive ascent as the temperature rises from 160°C to 180°C. For example, composite fabric 5 gradually improved its shape-molding capacity with the increase in thermal bonding temperature and finally exceeded the height of 14.80 mm at 180°C. However, there were some fabrics not showing a positive ascent yet, such as composite fabric 4, composite fabric 7, and composite fabric 8, which reached their peak heights at 170°C and reduced as the temperature increased. Refer to the features mentioned in Table 2, these three fabrics had yellowing problem at 180°C. It indicates that the highest thermal bonding temperature was beyond their heat resistance, which may negatively affect their shape-molding capacity.

Figure 8 shows each 3D-shaped composite fabric’s height shrinkage, which is the height difference between the height of the molded composite fabric right after molding and the height after 24 h. In Figure 8, fabric 9 had the smallest shrinkage hitting at 0.17 mm at both 170°C and 180°C, and it showed the best stability of 3D shape. However, composite fabric 5 and composite fabric 8 showed quite poor stability of 3D shape almost under temperatures of 160°C and 170°C. In particular, the largest shrinkage appears in the case of fabric 8, which hit at 0.77 mm under the temperature of 160°C. The height shrinkage of fabric 8 was gradually falling (more stable) with the thermal bonding temperature increasing. The second biggest shrinkage (0.61 mm) happened in composite fabric 5, the reason being occurrence of bubbles and the TPU peeling off (features in Table 2). These problems accelerated larger height shrinkage. It is interesting to find that, except composite fabric 3, fabric 1 to fabric 9 showed their lowest shrinkage at 180°C. It seemed that the tendency of the shrinkages was more stable in 3D shape at 180°C. However, in the case of composite fabric 11, its stability of 3D shape seemed to be worse with the temperature rising. It may due to fabric 11’s significant uneven surface of texture and hollow structure. In addition, refer to the features in Table 2, there are bubble problems at each temperature and even melting surface problems at 180°C, which may negatively affect the stability of 3D shape.

**Winkle recovery between the selected fabrics and their composite fabrics**

Figure 9 demonstrates the average WRA results of the 12 kinds of selected fabrics and their compound after thermal bonding with TPU film in three different temperatures. It showed that most composite fabrics had significant increase in their WRAs. These increasing WRAs indicate that the composite fabrics have better elastic recovery
power and shape-keeping capacity than their original fabrics (without TPU). For example, the original WRAs of fabric 1 and fabric 3 are relatively low. After thermal bonding with TPU, these three composite fabrics’ WRAs rapidly increased to approximately 300°. The composite fabric by thermal bonding with TPU can generally reinforce the shape-keeping capacity and, at the same time, improve some of the features of the composite material.

Conclusion

In this article, the practical possibility of vacuum forming molding under thermal composite conditions to obtain 3D SA has been studied. Through the experiment, 12 kinds of commercial fabrics were selected for the analysis. The main experimental steps include a thermal bonding phase, which bonds the fabric and the TPU film, and a molding phase, which molds the composite fabric into the desired 3D shape by the vacuum’s mechanical and pneumatic stretching. The following conclusions can be drawn from the results. (1) The TPU film is a promising material for bonding with fabrics. Composite TPU film can cause light and soft fabrics (e.g. chiffon and silk) to be easily molded into 3D SA. (2) Even though the method can rapidly create the 3D SA (whole progress within 60 s), each fabric has various performances. In order to achieve the best modeling effect, it is necessary to consider various aspects, including the fiber content, fabric structure, thickness, heat resistance, and so on; fabric 4, fabric 7, and fabric 8 should be treated under lower temperature during further investigation. In addition, this method cannot be applied to fabrics with an uneven surface or big hollow structure. (3) In this study, it is further found that TPU has the potential to restore good shape memory under heating induction. This makes it possible to provide reusable 3D clothing models in the future.

Regarding the referred conditions that have already been provided in the study, there are other variable factors for improving the quality of the 3D SA, which can be further investigated—for example, the new temperature range after adjusting and optimizing, the pressure from the heatpress machine, and the thickness of bonded fabrics. In addition, further study will be extended to more fabrics, which is to effectively demonstrate the potential of this method as the general thermoplastic method for creating 3D SA.

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