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An Overview of 3D Thin Shell Textile Preforms

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Abstract

The automobiles, aircraft, and lightweight industries continuously demand thin near-net-shape preforms just out-of-machine as close to the final shape. This study addresses the possibilities of 3D thin shell textile preform as the solution of lightweight reinforcement in various applications. Investigation into the development of 3D thin shells has led to different manufacturing processes. However, 3D thin shell preforms are mostly made by weaving and knitting, but nonwoven, winding, and/or layup techniques have been reported for over a decade. Owing to the complex thin shell manufacturing processes, they are not similar to the conventional methods. The different 3D thin shell preforms can extend the opportunities for new applications in various technical fields. This study presents existing research gaps and a few potential issues to be solved regarding 3D thin shell preforms in the near future.

Keywords

3D Thin Shell Preform, Weaving, Knitting, Braiding, Nonwoven, Winding and/or Layup

1. Introduction

The utilization of thin shells for technical applications has been on the rise, especially as composites for engineering purposes. Textile composites can provide performance benefits, particularly in terms of high-strength ratios compared to metal counterparts, which make them suitable for automotive and aerospace industries, where reduced weight contributes to fuel efficiency and notably improves ease in handling in the manufacturing processes. The development of 3D thick textile preforms has increased over the past few decades [1]. Textile engineers are challenged to introduce lighter technical parts as composites. Therefore, 3D thin shell preforms hold great promise for automotive, aerospace, and other engineering applications.

More than one hundred years ago, people started to develop 3D textiles for technical applications. Due to their diverse fields of applications, the demands of 3D thin shell textile preforms besides the thick components in the fast-growing area of modern composite materials for different commercial industries are immense [1]. However, until today, there is no addressable definition for thin shell textile preforms. Unfortunately, there are not enough profound breakthroughs yet to imply and extend the use and value of 3D thin shells for industrial and engineering applications, which essentially require the shaping ability to maintain strength and automation. An understanding of shape geometry for design, process optimization, and production methods for 3D thin shells is still missing.

Besides, the conventional and existing techniques, design complexity, and product scalability are challenged in the progress of manufacturing. The production of 3D thin shells directly by a manufacturing process without the support of seaming, molding, or deep drawing is a challenge for researchers, which still needs precision to maneuver thin shells into the correct shape. However, different fabric manufacturing techniques are used to produce 3D thin shell preforms, which contain thickness limitations, and shape-wise irregularities. This paper addresses a few key manufacturing processes of 3D thin shells and provides an understanding of their scopes and application areas with important examples. This study also sheds light on the industrial requirements of thin shells and gaps to optimize production.

3D thin shell textile preform can be referred to as near-net-shape with a substantial diameter and shows interpolated curvature due to possible slippage between fibers, and displacement in the thickness direction. Thin shells can be regarded as shells having a much lower thickness in comparison to width and length (thickness << length, width) and a shell preform has a three-dimensional shape known as near-net-shape. For example, a helmet is a thin shell preform, exhibiting both 3D and near-net-shape of predefined thickness. However, 3D-spacer preforms are not thin shells, as they do not match near-net-shape criteria. Hu defined 3D contoured preforms, which are fully integrated fibrous (continuous) assemblies containing multiaxial in-plane and out-of-plane fiber orientation [2]. According to Bogdanovich, a 3D textile preform can be termed 'thin' when its length and width are measured in tens of centimeters or meters, but the same preform becomes thick when its length and width are measured in millimeters or a few centimeters [3].

Thickness plays a crucial role in many industrial and technical applications. Noticeably, research works have been reported on 3D textile components, which are not concentrated on 3D thin shells. Textile composites are used in automotive and other industries due to their intrinsic advantages over metal parts. Unfortunately, there are not many specialized devices and methods to make 3D thin shell textile preforms. On many occasions, fabric-manufacturing techniques have been followed to produce 3D shells. However, only a few automated methods are available to produce such preforms, mainly due to their requirements like fiber materials (carbon, glass, etc.) and deformation capabilities. The demand for lightweight automotive components is on the rise and it is correlated with the overall weight reduction of the vehicle [4]. Nonetheless, the manufacturing of 3D thin shell textile preforms is critical due to quality and seam-free creation. Processes like tailoring, deep drawing, and molding are limited by their poor reproducibility and adverse effect on shape forming. All those reasons are relevant to describe 3D thin shell textile preforms with their applications and opportunities.

2. Thin Shell Manufacturing Techniques

Different fabric manufacturing processes like weaving, knitting, nonwoven, winding, and/or layup are used to produce 3D thin shell textile preforms. All these techniques can create different 3D structures as presented in **Table 1**. This paper mentions briefly a few important technologies that create 3D thin shell preform and provides an understanding of such complex procedures with different shape possibilities. The 3D braiding technology has a unique ability to form 3D-shaped complex fiber structures integrally [5], but unfortunately, a 3D thin shell is not possible to generate with this method (**Table 1**).

Table 1. 3-D shape manufacturing methods and their types of structures.

Method	Type			
	solid	*hollow*	*shell*	*nodal*
3D weaving	yes	yes	yes	yes
3D knitting	yes	yes	yes	no
3D braiding	yes	yes	no	yes
3D nonwoven	yes	no	yes	no
3D winding and/or layup	no	yes	yes	no

Here, the nodal is referred to as a truss configuration containing strut members (in hollow or solid forms) which can be joined and/or bonded to form a node [6].

2.1. Woven 3D Shells

3D weaving is signified as a multiple-weaving method. Langer attempted to make a woven shell out of loom using a simple principle in the early part of the nineteenth century [7]. However, until today, there has been a lack of automated processes and machines for 3D-shaped shells [8]. In modern days, Computer-Aided Design (CAD) and various simulation programs have broadened new avenues for 3D shell manufacturing techniques. Buesgen introduced a revolutionary shape weaving to make 3D woven thin shells using Jacquard weaving [9]. The main idea of shape weaving is to create a fabric area having a larger spacing of weft and warp-ends than in the encircling fabric, which is achieved by mechanical devices and weave design. Shape weaving offers a programmable take-up mechanism to realize varying take-up lengths individually, which enables weft spacing variation. A Jacquard head is placed to execute shedding according to geometry requirements. The overall elements can be controlled by basic hard- and software for machine operation. **Figure 1(a)** shows a part of the loom used for shape weaving and **Figure 1(b)** illustrates a contoured shell produced by it [9].

(a) (b)

Figure 1. (a) Shape weaving loom, (b) 3D woven shell by shape weaving.

Loom is the pioneer of all weaving methods for 3D woven structures and shells. Greenwood patented a weaving loom to assist in making woven shells [10] and in the same year, Fukuta *et al.* showed a method and loom to make woven shells [11]. Talavasek and Svaty introduced a shuttle-less weaving machine [12], and Krauland Jr. presented a method and apparatus for continuous woven structures [13]. The year 1991 to 2001 was the revolutionary period of making multilayered woven 3D structures, either as woven reinforcements for composites or woven 3D shells for automotive parts [14]-[25].

Chen and Tayyar employed an add-on device (easy-to-use) to the conventional loom for making woven 3D shells [26]. They made changes in the let-off mechanism and used a profiled take-up roller. When the add-on device is removed, the loom resumes its original setup for making 2D shapes. Bhattacharya and Koranne introduced a novel method for 3D-shaped woven structures, but those are not of shell types [27].

Chen *et al.* addressed different weaving techniques for 3D-shaped shells [28]. Jetavat showed a near-net-shape structure by 3D weaving [29]. Khokar demonstrated a method and apparatus to produce woven 3D profiles, which are primarily not shell structures [30]. Lu *et al.* described a novel Origami method to make a 3D woven box [31]. Lüling and Boussu *et al.* explained a few techniques to create 3D-shaped structures and their applications in their publications [32] [33]. A Ph.D. candidate at Technical University Dresden (Germany) made complex 3D shells **Figure 2(a)** using Jacquard technology and won the AVK-Innovation Prize 2022 [34]. Harvey *et al.* made a woven shoe **Figure 2(b)** by realizing different samples of experimental 3D woven structures [35]. They divided the warp into three distinct zones for design: sole, insole, and upper. They planted materials and yarns of varied sizes to emphasize the shoe's center and bulk up the heel of the shoe so that different sizes of weft were possible to insert. They took the benefits of Jacquard weaving to finalize the traditional shoe components as part of their visual design. They employed the Weavecraft software to design 3D weaves effectively as it contains three easy-to-use windows that collectively provide the information. The task of the software is to generate a standard 2D binary file to run the Jacquard process, which converts into JC file language to run the loom [35].

Figure 2. (a) 3D woven preform, (b) woven shoe.

2.2. 3D Knitted Shells

Thin shell preforms made by knitting technology represent a group of materials with great flexibility mainly due to the advantage of having fewer process steps. Flat knitting machines are mostly used for their design variability and it offers a versatile way to produce complex 3D-shaped shells, spacers, tubes, and other forms [36]. New software design, performance modeling, and new-generation machines capable of producing complex structures can stimulate the development of 3D-knitted preforms [37].

The technologies from SHIMA SEIKI and STOLL have undertaken many important developments. Ciobanu produced a knitted shell **Figure 3(a)** using STOLL (CMS 320 TC) knitting technology and described it [37]. Dome-like structures with minimal or no seams can be produced by suspended stitches **Figure 3(b)** through WholeGarment®, referred to as WG technology from SHIMA SEIKI [38]. The way of producing 3D knitted shells by suspended stitches using SHIMA SEIKI technology is also called the Spickel process.

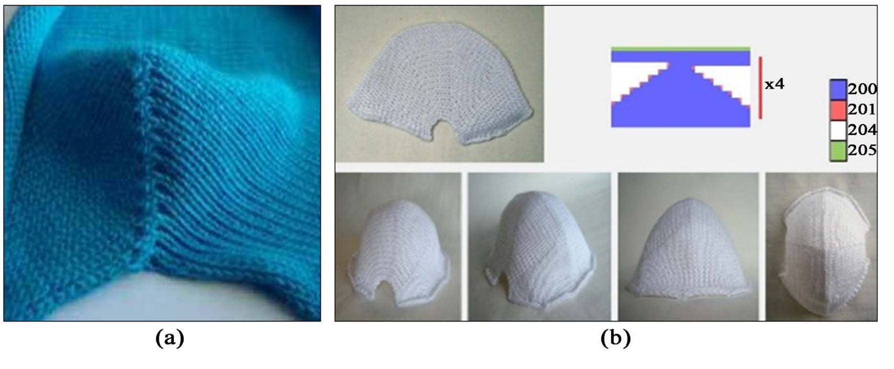


Figure 3. (a) Knitted 3D fabric preform, (b) dome shape formed by suspended stitches, where single jersey knitting = 200, front tuck stitch = 201, no needle selection = 204, cast off (jersey) = 205.

There has been a lack of consistency in the lifetime of a car seat for a long time and woven 3D shell dominates automotive sectors. However, SHIMA SEIKI launched an anatomically contoured seat **Figure 4(a)** in cooperation with two German companies Trevira and imat-uve [39]. SHIMA SEIKI showed a prototype of a multiaxial knitting machine at Techtextil Fair (Frankfurt, Germany), which can create 3D-shaped shells as shown in **Figure 4(b)** and **Figure 4(c)** [40]. Simonis *et al.* made 3D-shaped knitted shells using a large circular knitting machine **Figure 5**, where needle parking or pendulum function was not followed due to the discontinuous movement, and continuous movement was maintained throughout the process [41]. Some key innovations for knitted shells were revealed at ITMA 2019 [42].

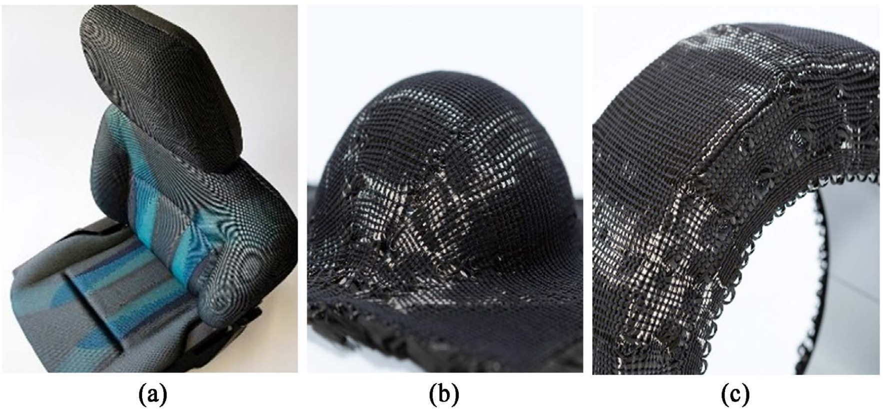


Figure 4. (a) 3D knitted car seat from ©STOLL, and SHIMA SEIKI multiaxial knitted preforms, (b) knitted helmet, (c) knitted tire.

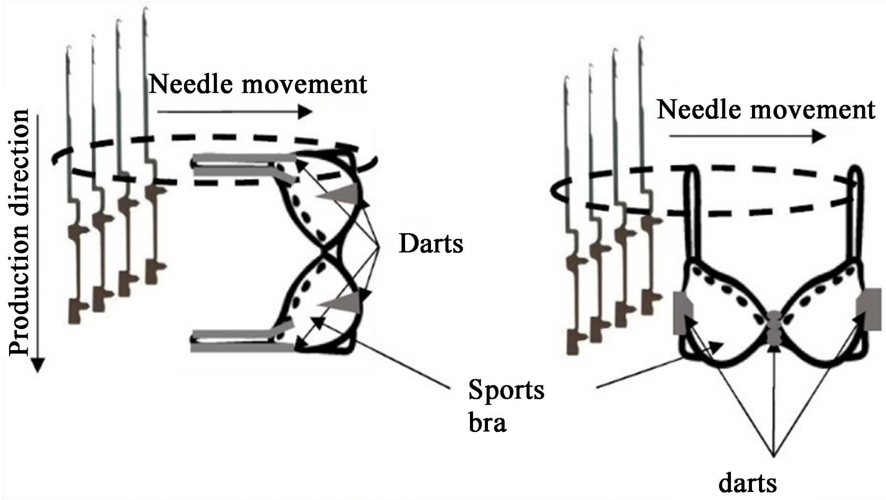


Figure 5. Sports bra using a large circular knitting machine.

2.3. 3D Nonwoven Shells

The nonwoven process to make a 3D thin shell preform is unlike 3D weaving and 3D knitting. However, this process is shorter, faster, and more economical compared with other traditional ones [43]. The maiden 3D nonwoven shell is arguably the felted hat [43]. Felting is an easy process to realize and make 3D-shape manually, but the main drawback is productivity. The German company—Freudenberg Performance Materials developed nonwoven-based Lutraflor® technology for automotive interior parts **Figure 6(a)** with excellent formability [44]. Air-laying nonwoven process is also an option to produce thin shells; the University of Manchester used a thermal-through air bonding system to make a softer shell preform **Figure 6(b)** and can be pressed by molds [43]. The engineers and researchers of ITM (Dresden, Germany) developed the net shape nonwoven (NSN) technique, where they used solid free forming (SFF) to process textile fibers into 3D nonwoven scaffolds **Figure 6(c)** without any negative mold or forging dies [45].

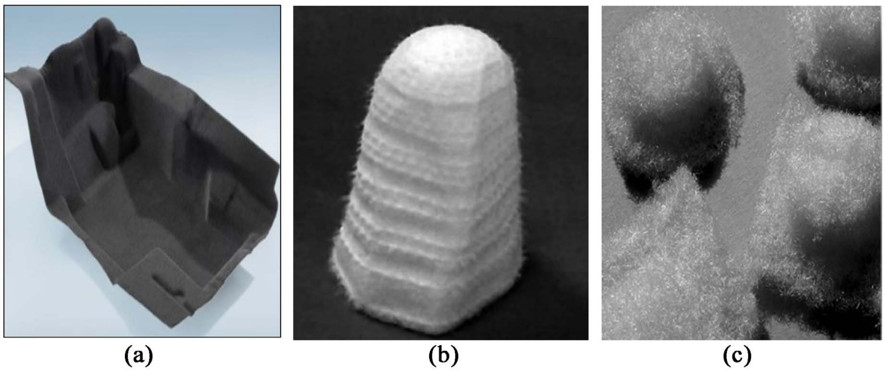
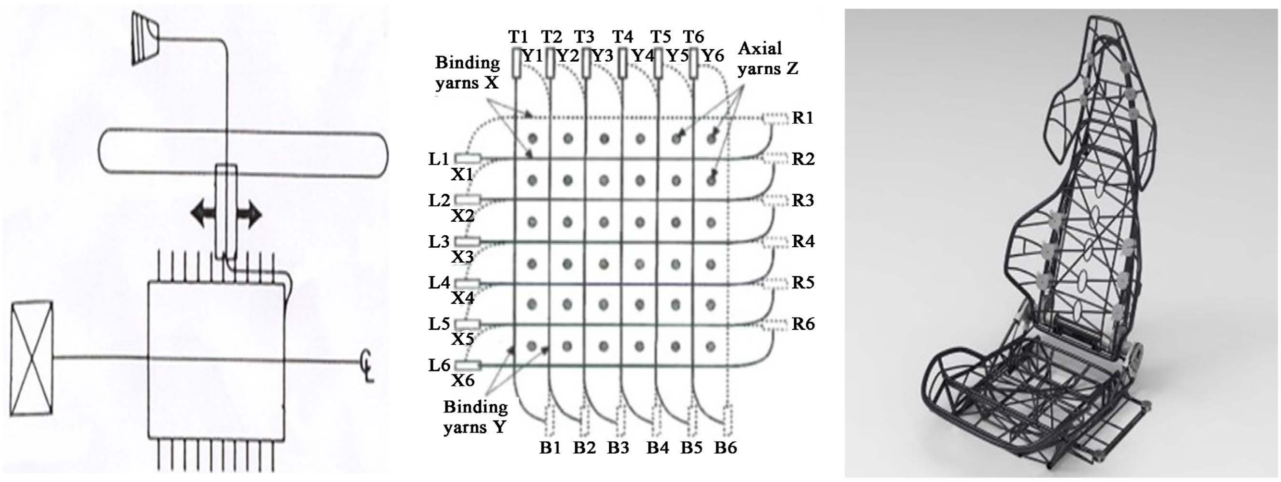


Figure 6. (a) Automotive part from Freudenberg Performance Materials (Weinheim, Germany), (b) Air-laid 3D-shaped nonwoven, (c) Net-shape-nonwoven product from ITM (Dresden, Germany).

Miura and Hosokawa showed 3D-shaped nonwovens using an electrochemical process [46]. Yin *et al.* combined melt-blown and spun bond processes to produce 3D nonwoven shells [47]. Dong described techniques and opportunities for 3D nonwoven shell preforms for the automotive industry [48]. Additionally, several informative publications have been reported on various aspects of 3D nonwoven preforms [49] [50]. However, not all these inventions and methods are suitable for technical yarns, which means depending on the product and demand one chooses the manufacturing technique.

2.4. 3D Shells by Winding and/or Layup

Few unconventional methods like winding and/or layup processes have no convincing accomplishments in 3D thin shell textile preforms. Rolincik introduced the autoweave process, which was interpreted as 3D weaving [51]. **Figure 7(a)** shows one schematic diagram of the autoweave process. However, no images of the final product of the autoweave process are available so far. Khokar invented a noobing process, where no interlacement of fibers was recorded [52]. Khokar classified noobing process as a nonwoven 3D fabric-forming process and the final product of it was termed as noobed fabric but wrongly assumed 3D woven fabric. Moreover, the author classified noobing as a layup process according to the details and graphics available for it Figure 7(b) [52]. Khokar and Peterson revealed a noobing device [53], although it is arguably not suitable for 3D thin shells. Nevertheless, a layup process like noobing can produce 3D-shaped forms [54]. Apart from autoweave and noobing, it has been reported that 3D thin shells are made using filament winding.



(a) (b) (c)

Figure 7. (a) Autoweave process, (b) Khokar's noobing process, and (c) filament wound seat frame.

Filament winding is an established simple process for producing parts like spherical, cylindrical, and other forms. Aerospace filament winding has become impressively effective for contour parts at a premium price. It can be useful for making 3D thin shell preforms as shown in Figure 7(c) [55]. However, the productivity of the process depends on machine parameters like axis speed, preform geometry, and fineness of the fiber. Hopmann *et al.* presented a new winding strategy, which offers good productivity with reasonable costs [56]. McIlhagger *et al.* described filament winding and its manufacturing processes [57].

3. Industrial 3D thin Shell Applications and Demands

The importance and impact of 3D thin shell textile preform are one of the underperformed research topics in the textile and composite industries. The important functionalities of 3D thin shells are required for industrial purposes. Shell forming is a complex action and foremost the fiber orientation. Table 2 presents the state of the art for different 3D thin shell manufacturing techniques.

Table 2. State of the art of 3D thin shell manufacturing.

Process	3D thin shell manufacturing				
	Shape	Size (mm)	Fiber orientation (degree)	Automation (fully/semi/not)	Cycle time (min)
Weaving					
1. Folded up:					

Continued

Shuttle weft insertion	doubly contour	__________	0, 90	not automatic	__________
Origami	rectangle box	__________	0, 45, 90	semi-automatic	__________
2. Variation of thread spacing:					
Koppleman's process	hemispheres	__________	0, 90	__________	__________
Shape weaving	biaxial curves	__________	0, ±45, 90	fully automatic	4:08 (e.g. indoor panel)
Knitting					
Spickel & suspended stitch:					
SHIMA SEIKI WholeGarment® (e.g. SWG-XR)	domes, spheres	1250 - 1500	__________	fully automatic	__________
STOLL (e.g. CMS 320 TC)	tube, ellipse	__________	__________	fully automatic	__________
Nonwoven					
Net-shape nonwopven (NSN)	scaffolds	__________	__________	fully automatic	__________
Airlaying	web, hat	__________	__________	fully automatic	__________
Thermal through-air bonding	complex surface contours	__________	__________	fully automatic	__________
Winding and/or **layup**					
Filament winding	car seat	__________	__________	fully automatic	__________

3.1. Comparison of Recent 3D Textile Technologies and Industrial Demands for 3D Thin Shell Preforms

The ability and advantages of 3D thin shell textile preforms contribute to reducing composite component manufacturing costs. It is possible to make suitable 3D thin shell preforms using appropriate technology with greater automation Table 3 illustrates the gaps between 3D thin shell manufacturing techniques and industrial requirements. It is not easy to discuss all limitations in one combined work to overcome the commercial hurdles. Therefore, continuous research and development are necessary to seal their place in the fields of technical textiles.

Table 3. Comparison of recent 3D textile technologies and industrial requirements for 3D thin shells.

Application areas	Fulfilled industrial requirements	Gaps between 3D textile technolgy & industrial demands	Remarks
Aerospace			
Radome	automated, available sizes	production capacity, design complexity	requires feasible method to meet design criteria
Motor Vehicles			
Bonnet	automated, organized shape geometry	range of production process	prodcution cycle timefor light weight components
Indoor panel	automated, fiber orientation	organized eco-process with less costing	cost-effectiveness with a certain quality

Continued

Machinery & equipment			
Shield	automated	limited fiber orientation, not suitable for each 3D-process	variable and controlled shape geometries
Pressure vessel	automated	all shapes are not possible directly through a 3D-process	choice of a particular technique as demand
Safety helmets	automated, standardized shape	commercial accountability, increase in the process channel	eco-process chain

3.2. Research Gaps and Future Needs

One of the most critical issues in the composite industry is to reduce weight by replacing heavy metal components. It has been reported that 50% - 75% weight reduction for some components is possible in the long term through carbon fiber-reinforced composites [4]. However, the absence of commercially available computational modeling and lack of automation in the processes are still major challenges for manufacturing 3D thin shell preforms. Three-dimensional thin shell textile preforms can be as lightweight components and they will add benefits to the automotive industries by optimizing fuel consumption. To succeed significantly with this mission, it is important to understand their long-term application requisites, replaceable opportunities with other 3D textile preforms, cost-effectiveness, the demand of consumers, and productivity. Table 4 presents a few important examples of possible 3D thin shell preforms with existing demands and requirements.

Table 4. Outlook of a few industrial thin shell applications and existing industrial requirements.

Applications	**Industrial requirements**				
	Shape	*Size* (*mm*)	*Ply orientation* (*degree*)	*Automation* (*fully/ semi/ not*)	*Cycle time* (*min*)
Aerospace					
Radome	spherical	46,000	0, 45, 60, 75, 90	fully automatic	___________
Curved indoor	oval	508 - 914	___________	fully automatic	___________
Motor vehicles					
Bonnet	heart	1100 - 1420	0, 15, 60, 75, 90	fully automatic	___________
Indoor panel	curves, diagonal	915 - 2030	0, ±45, 60, 90	fully automatic	___________
Monocoque (e.g. ZR 19 race car)	elliptical	___________	0, ±45, 90	fully automatic	___________
Wheel rim (e.g. 700C)	parabolic	622	0, ±45, 90	fully automatic	___________
Machinery & equipment					
Shield (e.g. Chuck)	ring	254 - 660	0, ±45, 90	fully automatic	___________
Pressure vessels	cylindrical	165 - 425	±45, ±55, ±65, ±75, ±85	fully automatic	___________
Safety helmets	hemispherical	510 - 630	0, ±45, 90	fully automatic	___________

Continued

Others					
Gypsum	cube	1200 - 2440	___________	fully automatic	___________
Prosthesis	limb	180 - 198	0, ±45, 90	fully automatic	___________

4. Conclusions

An overview of key manufacturing technologies, application possibilities, and existing gaps for 3D thin shell textile preforms are presented. The conventional machines and methods are still enough for producing other 3D textile preforms, but many new approaches are needed for manufacturing complex 3D thin shells. The progress in 3D nonwoven is very limited regarding thin shell preforms. However, 3D woven and 3D knitted shells offer many more versatilities than 3D shells produced by nonwoven, winding, and/or layup processes. The available machines for 3D thin shell textile preforms are only prototypes and not used for commercial production, which influences heavily the productivity and industrial demand. Although 3D shells are regarded as one important group of 3D textiles, they still require more attention and extensive studies. There are a few gaps to be filled for achieving the fullest potential of 3D thin shell textile preforms:

- Lack of automation.
- Special setup (*i.e.* weaving, knitting, nonwoven, winding, and/or layup).
- Shape discrepancies due to process variation.
- Additional downtime and setup costs for the change in shell geometry.
- Alteration of properties of the final 3D product.
- Problem in forecasting for design complexity and shape deformation.
- Damage to the high-performance fibers due to improper settings and handling.

Researchers and engineers have been working to adopt new methods to simplify the process and improve efficiency with a higher degree of automation. Therefore, a new layup process for 3D thin shell preform will be published in a separate research paper.

Alternatively, 3D printing has drawn the attention of textile engineers and manufacturers immensely for its potential [58]. The 3D printing technology assists to create mock-ups in a short period. It will be no wonder if in the future 3D printed shell preforms replace 3D woven, 3D knitted, 3D nonwoven, and other 3D shells.

Challenges and Outlooks of This Research

This paper has provided a basic definition and a few important manufacturing methods with application areas mainly in technical textiles. However, it is a challenge to convince experts from different methodologies as each process offers a particular specification with distinct parameters and a few limitations. For example, Khokar mentioned noobing as nonwoven in his research works although in this paper author classified noobing as a layup process. In relation to the definition of a 3D thin shell, a few points should be reviewed. Therefore, the manufacturing processes must be studied further for their complex design and requirements. The tooling needed for the manufacturing has to be budget-friendly with an easy assembly process, and the design should support real weight reduction.

The realization of this underperformed research topic will definitely allow textile engineers and researchers to evaluate 3D thin shell preform characteristics, as well as more practice in building prototypes using simplified design programs. A brief description of different 3D thin shell manufacturing processes in this study will assist textile engineers to fabricate and classify the newly designed preforms as 3D thin shells.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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