Fecha de recepción: septiembre 2024
Fecha de aceptación: octubre 2024
Versión final: noviembre 2024

Fabricación en un solo paso de estructuras textiles en forma 3D

Daniela Laura Rondinone (1)

Resumen: En el mercado actual de tecnología textil, hay un aumento en la demanda de productos textiles para aplicaciones técnicas como los campos médico, automotriz y de protección. Uno de los principales desafíos de producir productos técnicos de base textil para esas aplicaciones es el hecho de que se requieren estructuras 3D complejas manteniendo buenas propiedades mecánicas de manera rentable. Desafortunadamente, la mayoría de las técnicas de fabricación tradicionales de corte y costura no sólo afectan negativamente la resistencia de los productos terminados, sino que también requieren mano de obra costosa, lo que lleva a la necesidad de desarrollar nuevos métodos de fabricación textil.

Una alternativa atractiva al problema de fabricación mencionado anteriormente es el uso de innovadoras tecnologías textiles con formas 3D que permiten la creación de geometrías complejas en un solo proceso. Esta creciente categoría de productos se vuelve cada vez más atractiva debido a los diversos beneficios que presenta, como versatilidad de diseño, resistencia a la delaminación y propiedades de confección, sólo por nombrar algunos.

El propósito de esta investigación es hacer una revisión de las principales tecnologías de tejido, tricotado, trenzado y no tejidos para crear productos textiles 3D. También se cubrirán las principales aplicaciones de estos productos para las industrias médica, automotriz y de protección.

Palabras claves: Textil - 3D - tecnología - mercado - medicina - automotriz - diseño - no tejido - investigación - fabricación.

[Resúmenes en inglés y portugués en la página 94]

(*) Master of Science in Textiles. North Carolina State University. Wilson College of Textiles. Raleigh, USA. Minor in Textile Engineering. Bachelor of Design in Textile and Apparel. Palermo University. College of Fashion & Communication. Buenos Aires, Argentina. Research Assistant at North Carolina State University. Research area: Healthcare Textiles & Silver-based Antimicrobial Textiles for Infection Control Research project: Evaluation of the capability of silver-based antimicrobial textiles as infection control tools for the prevention of Healthcare-Associated Infections (HAIs). Antimicrobial Textile Testing. Biomedical Textile (BMT) Research Group - Wilson College of Textiles. January 2021 Presented: "Effectiveness and durability of Silver-based Antimicrobial Textiles.

Introduction

The emergence of three-dimensional (3D) textiles has revolutionized the technical textiles industry by introducing advanced, multi-dimensional structures that significantly enhance performance characteristics while simultaneously reducing material waste. Unlike traditional 2D fabrics, 3D textiles provide reinforcement, insulation, protection, and custom shaping across a wide range of applications. Their role in lightweight, high-performance solutions for industries like automotive and healthcare is especially noteworthy. In addition to performance benefits, 3D textiles also contribute to more sustainable manufacturing practices by reducing material waste and optimizing energy use, aligning with the growing demand for eco-friendly solutions in the market.

3D manufacturing technologies such as weaving and knitting are pivotal in this evolution. 3D weaving, in particular, led the market in 2022, accounting for over 23.45% of revenue due to its broad use in the automotive, construction, and marine industries (*Technical Textile Market Size, Share & Growth Report*, 2030, n.d.). It provides superior strength, lightweight characteristics, and design flexibility. 3D knitting, also growing rapidly, excels in creating shaped structures, particularly in construction and civil engineering (Borneman, 2012) (Cherif, 2015).

3D-shaped textile structures are widely used across the Technical Textiles group, which includes categories such as agrotech, buildtech, clothtech, geotech, hometech, medtech, protech, and sporttech. The global technical textiles market was valued at USD 188.81 billion in 2022, with an expected CAGR of 4.7% from 2023 to 2030. Key drivers of this growth include the increasing demand for durable, lightweight materials across industries like construction and medical. 3D technologies have thus become an attractive option for meeting this demand due to their efficiency and performance advantages (*Technical Textile Market Size, Share & Growth Report,* 2030, n.d.).

This review aims to analyze the current state of 3D-shaped textile technologies, their applications in medical, automotive, and protective industries, and explore future trends in this rapidly evolving field.

Technologies for developing 3D shaped textiles

3D textiles represent a significant advancement in the technical textiles industry, characterized by their ability to create multi-dimensional structures that offer enhanced performance and minimize material waste. Unlike traditional 2D fabrics, 3D textiles offer critical advantages, such as customized shaping, reinforcement, and insulation, making them essential in applications like medical devices and automotive components, where lightweight and high-performance solutions are needed.

In contemporary discussions about technical textiles, 3D weaving and 3D fabrics often refer to a rapidly expanding range of products designed primarily for high-performance

composite applications. These include everything from jet engine components and specialized engineered shapes to composite billets used in bulkheads and ballistic armor. The appeal of 3D-shaped textiles for these applications lies in their design flexibility, resistance to delamination, improved damage tolerance, and ability to tailor composite properties precisely for specific needs. They also offer near-net-shape preform capabilities and can reduce complexity in lay-up processes and handling time (Borneman, 2012).
Definitions of 3D-shaped textiles vary in the literature, but for this paper, the term will refer to volume-forming geometries—thin, two-dimensional constructions produced in a single process to create 3D structures (Cherif, 2015). A useful classification of these products is based on their geometric design, which influences the final shape. According to their geometries, textiles can be categorized as follows (Cherif, 2015):

- One-Dimension: Thin, elongated structures like monofilament or twisted yarns.
- Two-Dimension: Flat fabrics with minimal thickness compared to their surface area.
- 2.5-Dimension: Planar fabrics with minimal thickness that can be shaped into 3D forms through techniques like forming, draping, or assembly.
- Three-Dimension: True volumetric textiles, which are spatially designed constructions produced using a single forming process.

The above mentioned categorization of the different textile geometries is illustrated in Figure 1.

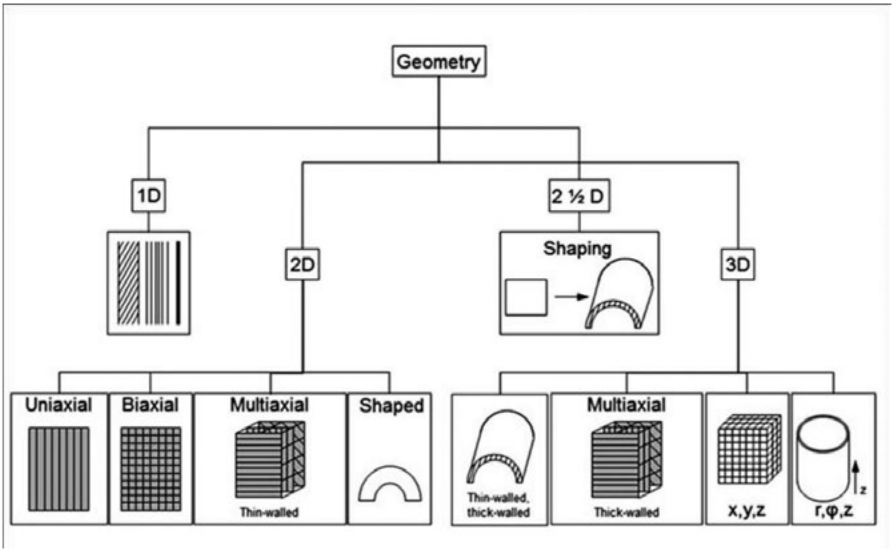

Figure 1: Shape of textiles-geometry. Source: (Cherif, 2015).

This paper focuses on 2.5D and 3D geometries as they are critical for developing shaped textiles. The shift from traditional 2D laminated textiles to 3D composites offers cost savings in both production and lifecycle, thanks to their reduced material requirements and improved structural integrity. Producing 3D textiles involves several technologies, including weaving, knitting, braiding, and nonwovens. These methods utilize specialized machines or adapted conventional machinery, allowing for the creation of complex shapes. In the following sections, the primary methods of manufacturing these advanced materials will be explored, highlighting their unique benefits and applications.

3D Weaving

To fully grasp the concept of 3D woven textiles, it is crucial to first understand the basics of 2D woven fabrics, which are prevalent across the textile industry. These fabrics consist of two perpendicular sets of yarns: warp and weft. The interlacing of these yarns, following a specific weave type and pattern, forms the fabric. Basic weave types include plain weaves for regular use, twill for denim, and satin for glossy applications, each offering unique properties (Bilisik et al., 2016).

While most woven fabrics are 2D, certain applications—especially in technical textiles—demand 3D woven structures. Traditionally, this is achieved by converting 2D fabrics into 3D shapes through tailoring, a process involving seams and manual labor. However, this method can diminish mechanical performance due to seam use and generates waste, making it less efficient for technical applications (Chen, 2015; Chen & Tayyar, 2003).

To address these challenges and meet the growing demand for 3D woven structures, advanced technologies have been developed. These methods utilize both conventional and specially designed weaving machines to create 3D structures by arranging warp yarns in three-dimensional configurations, while inserting weft yarns at various levels (Chen et al., 2011).

Chen, Taylor, and Tsai categorize 3D woven textiles based on their geometrical structures into four types: Solid, Hollow, Shell, and Nodal. Table 1 describes the architecture and shape of each of those four types of structures. Each category offers unique architectural properties, suited to different technical applications (Chen et al., 2011). This classification aids in understanding the diverse range of configurations possible within 3D weaving, and their potential for innovative textile solutions.

According to the definition of 3D-shaped textiles provided in the introduction, Shell and Nodal structures fall into this category, as they enable the creation of three-dimensional forms from a two-dimensional surface in a single process. These structures are especially valuable for their ability to streamline manufacturing while achieving complex geometries. The following sections will delve into the specific technologies used for producing shell and nodal 3D structures, highlighting their design principles, manufacturing processes, and potential applications within the realm of technical textiles.

Structure	Architecture	Shape
Solid	Multilayer	Compound structure, with regular or tapered geometry
	Orthogonal	
	Angle Interlock	
Hollow	Multilayer	Uneven surfaces, even surfaces, and tunnels on different levels in multi-directions
Shell	Single layer	Spherical shells and open box shells
	Multilayer	
Nodal	Multilayer	Tubular nodes and solid nodes
	Orthogonal	
	Angle Interlock	

Table 1. 3D textile structures and weave architecture. Source: Reproduced from (Chen et al., 2011).

Shell structures

3D shell woven fabrics are defined as textiles that form curved, three-dimensional structures while maintaining continuous fiber alignment. These fabrics are capable of creating various shapes, including spherical and cubic forms, without breaking the continuity of the fibers (Chen et al., 2011).

The manufacturing of shell 3D woven structures involves several key methods. Early approaches included shaped breast beams and curvilinear reeds for weaving contoured shapes directly on the loom. Techniques evolved with fan reeds for adjusting weft spacing and Jacquard shedding for creating flat fabrics that unfold into 3D forms. Modern methods like shape weaving allow programmable adjustments in thread spacing, enabling complex shell geometries directly during weaving. These methods support seamless designs, enhancing structural integrity for applications like airbags, helmets, and other technical textiles (Chen, 2015).

Nodal structures

A 3D nodal fabric is defined as a textile structure that forms a network by connecting multiple tubular or solid elements at specific junctions or nodes. The fabric is initially woven flat on a loom and transforms into its three-dimensional shape when removed and tension is applied (Chen et al., 2011). Manufacturing methods for nodal 3D woven structures focus on creating interconnected strut configurations with nodes that maintain structural integrity. The process involves designing hollow tubular elements within woven panels that form nodes at intersections. Methods include 2D-to-3D approximations, where a planar woven layout is translated into a 3D form, and multilayer weaving, which allows precise control over yarn orientation and density for nodes. These methods ensure a smooth transition from flat structures to three-dimensional configurations, achieving stability and flexibility in technical applications (Chen, 2015).

3D Knitting

Conventional knitted textiles are formed from intermeshed loops in a two-dimensional format, created through weft or warp knitting. These fabrics are typically shaped into 3D structures via cutting and assembly. To enhance their application in industrial settings, integrated 3D knitting processes have been developed that produce 3D forms directly, eliminating additional joining steps. This approach reduces material waste and improves structural uniformity. Advanced 3D knitted textiles exhibit properties such as lightweight design, high stiffness, strength, and stability, making them valuable in aerospace, automotive, geotechnical, marine industries, and medical implants (Chen, 2015).

Knitted fabrics are particularly adept at producing complex 3D shapes due to their high elasticity and formability, allowing for intricate designs. Existing knitting machinery can be employed with minimal modifications, and the structural parameters of the fabrics can be adjusted to influence their behavior. Both weft and warp knitted fabrics are utilized in various technical applications, including composite reinforcement, medical products, and industrial items like tanks and hoses (Ionesi et al., 2010).

The adoption of 3D knitting technologies is on the rise within the technical textiles sector, fueled by advancements in high-tech knitting machines. Various 3D knitted textiles have emerged, employing both weft and warp knitting methods. In weft knitting, yarn is looped horizontally, either using circular machines to produce tubular fabrics or flat knitting machines, which allow for advanced 3D structures like tubes and spacer fabrics. Warp knitting involves feeding multiple yarns vertically, with all needles forming loops simultaneously. Known for efficiency and structural variety, it uses machines like double-needle bar Raschel to create complex tubular and spacer fabrics efficiently (Chen, 2015).

Common 3D structures include tubular forms, net-shaped designs, spacer fabrics, and Design of Structures (DOS). These structures can be produced using a range of techniques enabled by 3D knitting technologies (Chen, 2015).

Tubular Forms

The production of 3D tubular knitted structures can be achieved using both weft and warp knitting machines. Circular weft knitting is ideal for creating single, continuous tubes by adjusting cylinder diameter and stitch density. In contrast, flat weft knitting offers greater flexibility, allowing for the creation of complex structures like single, bifurcated, and multibranched tubes. This is accomplished using techniques like tubular knitting, unconnected tubular knitting, and the integration of multiple yarn carriers. Advanced methods enable the creation of various tube shapes and joints, including C, L, T, and Y configurations, by adjusting knitting patterns and yarn carrier arrangements (Chen, 2015).

Net-shaped Designs

Computerized flat knitting machines have also been used to produce complex 3D textile shapes, such as domes, spheres, and box-like forms, by adjusting the number of active needles. Dome structures are created by gradually increasing and decreasing the number of needles, with the shape and angle depending on the shaping segments used. By modifying the shaping segments from elliptical to triangular, box-like structures can be produced. This ability to vary needle use provides significant flexibility, allowing for a range of intricate 3D shapes through different knitting techniques (Chen, 2015).

Spacer Fabrics

Sandwich or spacer knitted fabrics consist of two separate layers connected by yarns or knitted layers. Warp-knitted spacer fabrics use yarns for connection, allowing open or closed structures with thicknesses exceeding 5 cm, and offer good bending recovery, making them suitable for items like backpacks and mattresses. Weft-knitted sandwich fabrics can be connected with either yarns or more complex knitted layers, offering diverse shapes like rectangular or trapezoidal forms. These structures are mainly used as preforms for advanced composites, especially with glass or carbon fibers (Ionesi et al., 2010).

Design of Structures (DOS)

Directionally Oriented Structures (DOS) are specialized multi-layered fabrics where non-crimped, parallel yarns are inserted at various angles, allowing the material's properties to be optimized in specific orientations for enhanced mechanical performance. DOS can include mono-, bi-, tri-, and multiaxial designs and are produced using both weft and warp knitting technologies. In weft knitting, yarns can be inserted in different directions (walewise and coursewise) to create biaxial or multiaxial structures. Warp knitting utilizes systems like Multiaxial Warp Knitting (MWK), which integrates multiple yarn layers, offering high structural integrity and damage tolerance (Chen, 2015).

Braiding

3D braiding is a versatile and advanced technique used to create complex 3D textile structures, offering significant advantages in technical applications where durability and structural integrity are critical. Unlike traditional 2D braiding, which is typically limited to flat or tubular designs, 3D braiding allows for the production of intricate shapes such as T, I, and J cross-sections, as well as various tubes—rectangular, circular, and triangular (Boisse, 2015). These structures are particularly beneficial in industries like aerospace, automotive, and medical devices, where lightweight solutions with enhanced strength are required.

A key feature of 3D braiding is its ability to orient yarns in all three spatial directions, which results in structures with high stiffness, strength, and reduced mass, making them ideal for applications needing robust yet lightweight materials (Gries et al., 2021). This process is especially useful for components subjected to stress or impact, as the continuous fiber alignment enhances damage tolerance. Despite its many advantages, 3D braiding has some limitations, particularly in the size of the structures it can produce. Current technologies can achieve a maximum cross-sectional size of about 100 mm, which restricts their use to smaller components, such as automotive parts, aerospace elements, and certain medical devices (Boisse, 2015).

Rotary braiding

One prominent method within this field is rotary braiding, which involves moving bobbins along two concentric circular paths with opposite rotations. The process uses 180° phase-shifted oscillations, allowing the bobbins to switch between inner and outer paths at crossing points, thus interweaving the yarns into complex 3D shapes. This method enables the creation of reinforced tubular structures, such as overbraided cores, which are built layer by layer to form a 3D preform (Gries et al., 2021).

Hexagonal braiding

This method is particularly effective for creating medical devices and specialized industrial components. Hexagonal braiding is known for its tightly packed machine bed, which allows for more precise control of yarn placement, making it suitable for fine materials. It was developed through collaboration with the University of British Columbia and has undergone multiple iterations to optimize performance. This technology is especially well-suited for producing near-net shape tubular structures, enabling precise customization of cross-sectional shapes during the manufacturing process (Gries et al., 2021).

Nonwovens

Nonwoven fabrics are textile materials made by bonding or interlocking fibers through mechanical, thermal, or chemical processes, rather than by traditional weaving or knitting methods. This creates a fabric with a more randomized structure, allowing for properties like breathability, durability, and flexibility. In recent years, the development of 3D nonwoven structures has advanced the capabilities of these materials even further, allowing for deeper, three-dimensional forms that enhance their performance in various technical applications. The creation of 3D shapes through molding processes enables nonwovens to take on complex geometries that can meet the demands of diverse industries (Clemens, 2015).

The production of 3D nonwoven textile structures involves creating materials with significant depth and three-dimensional contours, which extend beyond simple flat fabrics. These 3D textiles are often made using a process known as deep molding, where heat, pressure, and time are applied to a thermoplastic nonwoven substrate to shape it into intricate forms. Key methods include the use of male/female molds and interdigitated molds, each offering different characteristics in the final product. The male/female mold creates structures with distinct protrusions on one side, while the interdigitated approach results in symmetric features on both sides. The choice of mold, alongside factors like fiber type and orientation, significantly influences the final properties, such as thickness and stiffness, which are crucial for various applications (Clemens, 2015).

Nonwoven substrates used in this process are often made of thermoplastic materials like polyester or polypropylene, and the use of finer denier fibers (less than 100 microns) has improved the molding capabilities. For optimal results, fibers are typically not fully drawn before molding, which allows them to stretch and form more effectively during the process. This technique is especially useful for creating materials that maintain a lightweight, textile-like feel while offering increased structural resilience (Clemens, 2015).

Deep molded nonwoven fabrics offer a range of benefits compared to traditional materials like foam, including better air permeability, reduced weight, enhanced moisture management, and recyclability. These characteristics make them valuable for applications such as medical bedding, filtration, impact-resistant protective gear, and advanced seating solutions. For example, in automotive seating, the structured air channels provide enhanced comfort and easier integration of electronic components. The technology thus represents a versatile, sustainable option for industries seeking efficient and high-performance materials (Clemens, 2015).

Technical applications of 3D shaped textiles

3D-shaped textiles have emerged as a critical innovation in the technical textiles industry, offering unique structural advantages and flexibility for various applications. Their ability to form complex shapes while maintaining strength and lightweight characteristics makes them ideal for diverse sectors, including medical, automotive, aerospace, and protective gear. This section explores the practical uses of 3D-shaped textiles, highlighting how their specialized properties meet the demanding requirements of modern industries and contribute to advanced product development.

Medical Applications

Medical textiles are specialized fabrics used in healthcare settings for applications such as wound dressings, implants, surgical gowns, and prosthetics. These products require high performance in terms of strength, flexibility, and patient comfort.

Traditional methods, like cutting and sewing, have limitations when used for producing medical textiles. This process is labor-intensive, requiring skilled manual work, and often introduces imperfections. Needle holes created during sewing can damage fibers and compromise the fabric's integrity, leading to weakened strength and reduced performance.

Additionally, seams concentrate stress, which can cause premature failure in medical products. Bulkiness at seams can also cause discomfort for users, which is undesirable in applications such as wearable medical devices (Anderson & Seyam, 2004).

As the demand for advanced medical textiles grows, the need for seamless, shape-specific solutions has become more critical. The key methods for creating seamless, shape-specific medical textiles include advanced 3D weaving and knitting. These approaches allow manufacturers to design fabrics that precisely match the desired shape, reducing production costs while maintaining high quality. Innovations in programming and modern weaving equipment have made it possible to automate these processes, facilitating the rapid production of complex shapes (Anderson & Seyam, 2004). These advancements support the development of next-generation medical textiles, offering improved comfort, functionality, and safety for patients and healthcare professionals. The following subsections will highlight some of the latest innovations in 3D technologies for medical applications

Compression garments

Compression garments are specialized clothing designed to apply controlled pressure to specific body areas. These garments are commonly used in medical applications to improve blood circulation, reduce swelling, and support the recovery process after surgeries or injuries.

Recent innovations in 3D textiles for compression garments in medical applications are focusing on enhancing comfort, efficacy, and integration of smart technologies. One key advancement is the use of computerized flat knitting and circular weft knitting to create more tailored compression profiles. These technologies enable the production of seamless, custom-fit garments with precise pressure gradients, which are especially beneficial for medical conditions like lymphedema and chronic venous disorders. Additionally, smart textile integration has enabled real-time monitoring of pressure levels through embedded sensors, making these garments particularly beneficial for rehabilitation and post-operative care (Xiong & Tao, 2018). Innovations also focus on improving the elastic properties and durability of the fabrics to maintain consistent compression over time, ensuring that therapeutic effects remain effective throughout prolonged use (Velu et al., 2024).

A commercially available product that exemplifies the above mentioned innovations can be found through the compression garments created by LympheDIVAs, illustrated on Figure 2. LympheDIVAs was founded by breast cancer survivors Rachel Troxell and Robin Miller in response to their own experiences with lymphedema, a common side effect of breast cancer treatment. Frustrated by the limited options for compression sleeves, which were often uncomfortable and unattractive, they collaborated with a designer to create stylish, comfortable alternatives. After Robin left the company and Rachel passed away in 2008, her family took over, continuing her vision of creating products that help others feel confident during their recovery (*LympheDIVAs Garment Features, n.d.*). The brand specializes in compression garments like arm sleeves, gauntlets, and gloves, designed to manage lymphedema by promoting circulation and reducing swelling. Their products are known for their technical features, including a seamless design that prevents irritation, four-way stretch for comfort, and moisture-wicking properties that keep the wearer cool and dry throughout the day. The compression levels are medically graduated, ensuring effective pressure for mild to moderate lymphedema while also offering a range of styles and patterns to make patients feel empowered and fashionable during their treatment (LympheDIVAs Garment Features, n.d.).

Figure 2: Sleeve and Glove for patients with Lymphedema.
Source: (LympheDIVAs Garment Features, n.d.)

Vascular Implants

Vascular implants are medical devices designed to support or replace damaged blood vessels in the body. They are essential in treating conditions like aneurysms or blockages, helping to restore normal blood flow and improve patient outcomes.

Recent advancements in 3D woven textiles, particularly tubular woven conduits, have revolutionized vascular implants. These woven conduits are engineered to provide adjustable pore sizes, making them suitable for patients with complex vascular anatomies, such as narrowed or angulated vessels. The innovation lies in the use of ultra-fine medical-grade multifilament yarns (≤ 20 dtex) to create thin-walled woven conduits. This design minimizes the folded profile of woven stent grafts, allowing for better access through complicated femoral vessels (Gries et al., 2021).

The tightly woven structure of these conduits ensures impermeability against blood leakage, enhancing the safety and reliability of the implants. Moreover, the woven conduits exhibit excellent tensile strength in all directions, contributing to their durability. To address the typical limitations on this product such as a lack of elasticity and low kink-resistance, the fabric is pleated in an accordion-like fashion. This modification provides the necessary flexibility and kink-resistance, crucial for the functionality of vascular grafts. Additionally, metal stent structures are sewn onto the woven conduits to maintain the lumen's openness during movement (Gries et al., 2021).

Automotive Applications

The aerospace and automotive industries are increasingly adopting 3D textiles in their manufacturing processes to enhance efficiency and reduce weight. Traditional materials, such as steel and aluminum, can be cumbersome and time-consuming to transport, particularly when dealing with complex components needed for aircraft and automobiles. By utilizing 3D textiles, manufacturers can achieve significant weight reductions without compromising on strength or functionality. This shift not only enhances flexibility in design but also allows for innovative applications across various sectors.

In automotive applications, 3D textiles are being integrated into components such as interior panels, seats, and structural reinforcements, contributing to a lighter overall vehicle weight, which can lead to improved fuel efficiency. For example, the use of 3D woven fabrics in seat structures and headliners provides not only aesthetic flexibility but also enhanced durability and comfort. Additionally, the ability to customize the properties of these textiles—such as incorporating sound-dampening features—further optimizes their performance for specific automotive needs . Moreover, the aerospace sector has historically leveraged 3D textiles for parts like stiffeners and stringers in aircraft wings. These lightweight materials contribute to overall structural integrity while facilitating more streamlined manufacturing processes (Velu et al., 2024).

Seat Covers

One of the latest innovations in automotive applications using 3D textile technology comes from Ford, which is revolutionizing the way seat covers are produced. Traditionally, making seat covers involved stitching together numerous small pieces of upholstery, a process that has remained largely unchanged for decades. Ford's introduction of 3D knitting technology allows for the creation of a single, seamless seat cover that fits perfectly over the seat's frame and foam components. This innovative process begins with precise measurements of the seat dimensions, which are input into a specialized software that controls a 3D knitting machine. This machine uses the exact amount of thread needed for production, eliminating fabric waste associated with traditional cutting methods. The time required to produce a seat cover is significantly reduced—from nearly a full day of manual labor to just about one hour. This efficiency not only streamlines production but also contributes to a cleaner, more aesthetically pleasing product (Glon, 2019).

The importance of this advancement for the automotive industry lies in its potential to enhance customization options for consumers. Ford envisions offering unique design elements, such as specialized shapes or decorative features that can be integrated directly into the seat covers. This capability aligns with the industry's move towards more personalized vehicle interiors and could provide an exciting opportunity for differentiation in a competitive market. Looking ahead, Ford's 3D knitting technology is set to enable further innovations in material experimentation and design flexibility. Future developments may include the introduction of new materials that enhance comfort and functionality, as well as expanded customization options that cater to individual preferences (Glon, 2019).

Protective Applications

3D textiles are also increasingly used in protective equipment due to their ability to offer a balance between impact resistance, flexibility, and comfort. Traditional protective gear often relies on hard or semi-hard materials that, while effective at providing impact resistance, can be bulky and restrict movement. In contrast, 3D textile structures provide a more adaptive approach, using advanced materials like shear thickening gels (STGs) integrated into woven fabrics to create protective layers that respond dynamically to impacts. These materials are particularly valuable in applications such as sports, industrial safety, and personal protective gear for high-heat environments. For example, in sports, athletes benefit from gear that can absorb impacts during falls or collisions while remaining lightweight and comfortable. Similarly, industrial workers, like those in construction or manufacturing, require protection from accidental impacts without sacrificing mobility and comfort during extended wear (Tan et al., 2024).

Recent innovations in this field include the use of flock-reinforced STG (FRSTG) in 3D woven fabric composites. This combination allows for the creation of textiles that maintain flexibility under normal conditions but become rigid upon impact, offering superior protection. The FRSTG is incorporated into a specialized 3D woven fabric with a folded structure, produced using advanced air-jet weaving techniques. This design allows for a stable, breathable, and highly durable material that can withstand repeated stress while maintaining comfort. With air permeability rates of up to 79.473 mm/s, these materials are particularly suited for applications where breathability and moisture management are critical. The resulting 3D textile-based protective equipment is not only capable of better impact absorption but also provides improved comfort compared to traditional options. By allowing moisture to escape and reducing bulkiness, these advanced fabrics help users remain comfortable during prolonged use, which is crucial in both high-intensity sports and industrial work environments. This advancement signifies a shift towards more user-friendly protective solutions, merging safety with the flexibility needed for a wide range of physical activities. The future of 3D textiles in protective applications looks promising, as research continues to explore new ways to enhance material properties and tailor them to specific needs (Tan et al., 2024).

Functionalized undergarments

The HEATex project is an innovative development by a research team in Germany, focused on enhancing protective clothing for workers exposed to extreme heat. This project specifically addresses the risks faced by individuals in high-temperature environments, such as those in metalworking, glass production, and firefighting. Traditional protective gear often relies on outer layers to shield against heat, but HEATex introduces a novel approach with 3D functionalized undergarments. The innovation centers on the use of 3D spacer fabrics, which create layers that prevent direct skin contact with heat-absorbing outer clothing. These fabrics use pile yarns of varying stiffness to maintain distance and ensure moisture removal, thus minimizing the risk of scalding from trapped sweat. The system also includes a circumferential splicer module, which allows for quick changes between different yarn types during the knitting process, ensuring precise reinforcement in areas like elbows or knees that are subject to pressure (Lechthaler et al., 2018).

This approach to 3D textile structures for protective applications represents a significant advance, as it not only improves worker safety by reducing the risks of heat-related injuries but also enhances comfort through better moisture management. It highlights the potential of 3D textiles to provide tailored solutions for specific challenges, paving the way for future developments in high-performance protective wear. As the industry continues to focus on safety and efficiency, such innovations are likely to become more widespread across various sectors (Lechthaler et al., 2018).

Future trends

3D fabrics offer significant advantages such as breathability, durability, and customizability, making them ideal for technical applications. Future trends in this field focus on integrating advanced functionalities like thermal resistance and moisture management, while emphasizing sustainability through eco-friendly materials and optimized processes. Research is also aimed at enhancing recyclability and incorporating sustainable practices, positioning 3D textiles for growth in sectors like healthcare, sports, and automotive (Dejene & Gudayu, 2024).

Sustainability has become a strong trend at the forefront of manufacturing innovation. For example, Norafin Industries, a German company, has developed an innovative process called "Hydro-Shape," which earned them the Techtextil Innovation Award in the category of 'New Technologies on Sustainability & Recycling.' This process uses high-pressure water jets to bond fibers into 3D shapes in a single stage, directly from fibers to finished products. Unlike traditional methods that often require multiple stages and generate waste, Hydro-Shape optimizes resource use by applying energy and materials only where necessary. The technology enables the production of 3D textile structures with reduced waste and can incorporate biodegradable natural fibers, making it particularly eco-friendly. Developed in response to the EU's Single-Use Plastics Directive of 2021, Hydro-Shape supports a shift towards more sustainable manufacturing practices in the textile industry (Messe Frankfurt Exhibition GmbH, 2024).

Sustainability efforts also extend to recycling. The Belgian textile research institute Centexbel has developed an innovative process to enhance the recycling of aircraft components made from thermoplastic fiber composites. These materials, which are lighter and more flexible than metals, play a crucial role in modern aviation, with many aircraft comprising over 50% of these lightweight composites. Centexbel's award-winning process uses induction heating to separate welded thermoplastic, textile-reinforced composite materials, enabling easier disassembly and reuse of critical components like stringers and wing parts. This breakthrough not only promises more efficient recycling but also aligns with broader efforts in sustainability and circular economy practices in aerospace (Messe Frankfurt Exhibition GmbH, 2024).

Another area of future development for 3D textiles is in space applications. Bally Ribbon Mills (BRM) is leading this innovation with advanced woven fabrics, including 3D orthogonally woven materials like their 3DMAT Quartz. This material, developed for NASA's Orion Multi-Purpose Crew Vehicle (MPCV), is designed for compression pads, offering durability, resilience, and a high strength-to-weight ratio. It was recognized as the NASA Government Invention of the Year in 2023. Future work in this area includes increased collaboration between industry and academia for R&D, along with prototyping and testing materials in space environments (Bally Ribbon Mills (BRM), 2024).

Despite these promising advancements, several challenges need to be addressed in 3D textile technologies. These include the need for specialized equipment, higher initial costs, and the requirement for skilled operators. Additionally, integrating these advanced materials into existing manufacturing processes may require significant adjustments to supply chains and quality control measures.

Conclusions

The advancements in 3D-shaped textile technologies have significantly impacted various industries, offering innovative solutions to complex challenges. This review has highlighted the diverse applications of 3D textiles in medical, automotive, and protective sectors, demonstrating their potential to revolutionize product design and performance. The ability to create seamless, complex geometries while maintaining or enhancing material properties has opened new avenues for customization and functionality. As the field continues to evolve, sustainability and recyclability are becoming increasingly important, driving research towards more eco-friendly production methods and materials. The integration of smart technologies and the development of multi-functional textiles present exciting opportunities for future innovations. While challenges remain, particularly in scaling production and reducing costs, the trajectory of 3D textile technologies suggests a promising future. Their continued development will likely lead to more efficient, sustainable, and high-performance products across a wide range of applications, ultimately contributing to advancements in healthcare, transportation, and personal protection.

References

Anderson, K., & Seyam, A. M. (2004, June). Developing seamless shaped woven medical products. *Journal of Medical Engineering & Technology,* 23(3), 110-116. 10.1080/0309190042000193874

Bally Ribbon Mills (BRM). (2024, September 3). *Bally Ribbon Mills To Highlight High-Performance Webbing At The 2024 Advanced Textiles Expo.* Textile World. Retrieved October 16, 2024, from https://www.textileworld.com/textile-world/nonwovens-technical-textiles/2024/09/bally-ribbon-mills-to-highlight-high-performance-webbing-at-the-2024-advanced-textiles-expo/

Bilisik, K., Karaduman, N. S., & Bilisik, N. E. (2016). *3D Fabrics for Technical Textile Applications.* In Non-woven Fabrics (p. 326). Han-Yong Jeon. 10.5772/61224

Boisse, P. (Ed.). (2015). *Advances in Composites Manufacturing and Process Design.* Elsevier Science.

Borneman, J. (2012, July 24). *An Introduction To 3-D Weaving. Textile World. Retrieved October 3,* 2024, from https://www.textileworld.com/textile-world/features/2012/07/an-introduction-to-3-d-weaving/

Chen, X. (Ed.). (2015). *Advances in 3D Textiles (*1st ed.). Elsevier Science.

Chen, X., Taylor, L. W., & Tsai, L.-J. (2011). *An overview on fabrication of three-dimensional woven textile preforms for composites.* Textile Research Journal, 81(9), 932-944. 10.1177/0040517510392471

Chen, X., & Tayyar, A. E. (2003). *Engineering, Manufacturing, and Measuring 3D Domed Woven Fabrics.* Textile Research Journal, 73(5), 375-380. 10.1177/004051750307300501

Cherif, C. (Ed.). (2015). *Textile Materials for Lightweight Constructions: Technologies - Methods - Materials - Properties.* Springer Berlin Heidelberg.

Clemens, C. (2015, January). *Creation and Application of 3D Nonwoven Structures. Freudenberg Nonwovens.* https://www.inda.org/papers/enhancements2005/Clemens.pdf

Dejene, B. K., & Gudayu, A. D. (2024, May). *Exploring the potential of 3D woven and knitted spacer fabrics in technical textiles: A critical review. Journal of Industrial Textiles, 54.* 10.1177/15280837241253614

Glon, R. (2019, November 14). *Ford's 3D knitting tech ensures your seats won't burst at the seams.* Digital Trends. Retrieved October 3, 2024, from https://www.digitaltrends.com/cars/ford-3d-knitting-technology-is-the-future-of-car-upholstery/

Gries, T., Bettermann, I., Blaurock, C., Bündgens, A., Dittel, G., Emonts, C., Gesché, V., Glimpel, N., Grigat, N., Löcken, H., Löwen, A., Jacobsen, J.-L., Kimm, M., Koch, H., Kröger, H., Kuo, K.-C., Peiner, C., Sackmann, J., & Schwab, M. (2021, April). *Technology Overview of 3D Textile Materials and Recent Innovation and Applications.* Proceedings of the 9th World Conference in 3D Fabrics and Their Applications.

Ionesi, D., Ciobanu, R., & Ciobanu, L. (2010, November). *Developments of 3D knitted fabrics. 17th International Conference, Structure and Structural Mechanics of Textiles.*

Lechthaler, L., Peiner, C., Popzyk, M.-I., & Gries, T. (2018, December 14). 3*D Functionalized Protective Clothing To Cope With Extreme Heat Stress.* Textile World. Retrieved October 16, 2024, from https://www.textileworld.com/textile-world/nonwovens-technical-textiles/2018/12/3d-functionalized-protective-clothing-to-cope-with-extreme-heat-stress/

LymphеDIVAs Garment Features. (n.d.). *LymphеDIVAs. R*etrieved October 3, 2024, from https://www.lymphedivas.com/garment-features

Messe Frankfurt Exhibition GmbH. (2024, April 16). *Techtextil & Texprocess Innovation Awards: Changing The World With Textile Innovations*. Textile World. Retrieved October 16, 2024, from https://www.textileworld.com/textile-world/2024/04/techtextil-texprocess-innovation-awards-changing-the-world-with-textile-innovations/

Tan, Y., Ma, Y., Liu, J., Wu, F., & Li, Y. (2024, February). *Breathable and impact-resistant shear thickening gel based three-dimensional woven fabric composites constructed by an efficient weaving strategy for wearable protective equipment.* Composites Part A, 177, 1-13. https://www.sciencedirect.com/science/article/pii/S1359835X23004621

Technical Textile Market Size, Share & Growth Report, 2030. (n.d.). *Grand View Research.* Retrieved October 3, 2024, from https://www.grandviewresearch.com/industry-analysis/technical-textiles-market

Velu, R., Subburaj, K., & Subramaniyan, A. K. (Eds.). (2024). *Digital Design and Manufacturing of Medical Devices and Systems*. Springer Nature Singapore.

Xiong, Y., & Tao, X. (2018, June). Compression Garments for Medical Therapy and Sports. Polymers, 10(6), 2-19. 10.3390/polym10060663

Abstract: In today's textile technology market, there is an increase in the demand of textile products for technical applications such as medical, automotive, and protective fields. One of the main challenges of producing textile-based technical products for those applications, is the fact that complex 3D structures are required while maintaining good mechanical properties in a cost effective manner. Unfortunately, most of the traditional manufacturing techniques of cutting and sewing not only negatively impact the strength of finished products, but also require costly manual labour, thus, leading to the need for developing new textile manufacturing methods.
An attractive alternative to the above mentioned manufacturing issue is the use of innovative 3D shaped textile technologies that allow the creation of complex geometries in a single process. This growing category of products is becoming increasingly attractive due to the various benefits that it presents, like design versatility, resistance to delamination, and tailoring properties, just to name a few.
The purpose of this paper is to do a review of the main weaving, knitting, braiding and nonwoven technologies to create 3D textile products. The main applications of these products for medical, automotive and protective industries will be covered as well.

Keywords: Textile, 3D, technology, market, medicine, automotive, design, nonwoven, research, manufacturing.

Resumo: No mercado atual de tecnologia têxtil, há um aumento na demanda por produtos têxteis para aplicações técnicas, como áreas médicas, automotivas e de proteção. Um dos principais desafios da produção de produtos técnicos de base têxtil para tais aplicações é o facto de serem necessárias estruturas 3D complexas, mantendo boas propriedades mecânicas de uma forma económica. Infelizmente, a maioria das técnicas tradicionais de fabrico de corte e costura não só afectam negativamente a resistência dos produtos acabados, mas também requerem mão-de-obra dispendiosa, levando à necessidade de desenvolver novos métodos de fabrico têxtil.
Uma alternativa atraente para o problema de fabricação mencionado acima é a utilização de tecnologias têxteis inovadoras com formas 3D que permitem a criação de geometrias complexas em um único processo. Esta crescente categoria de produtos está se tornando cada vez mais atrativa devido aos diversos benefícios que apresenta, como versatilidade de design, resistência à delaminação e propriedades de fabricação, apenas para citar alguns.
O objetivo deste artigo é revisar as principais tecnologias de tecelagem, tricô, trançado e não tecido para criação de produtos têxteis 3D. Serão também abordadas as principais aplicações destes produtos para as indústrias médica, automotiva e de proteção.

Palavras-chave: Têxtil - 3D - tecnologia - mercado - medicina - automotivo - design - não tecido - pesquisa - manufatura.

[Las traducciones de los abstracts fueron supervisadas por el autor de cada artículo.]