textiles

Article

Manufacturing and Characterization of Customizable Flexible Carbon Nanotube Fabrics for Smart Wearable Applications

Ashley Kubley [1,†], Megha Chitranshi [2,3,*,†], Xiaoda Hou [2,3] and Mark Schulz [2,3,*]

1 College of Design, Architecture, Art and Planning, University of Cincinnati, Cincinnati, OH 45221, USA; kubleyay@ucmail.uc.edu
2 College of Engineering and Applied Sciences, University of Cincinnati, Cincinnati, OH 45221, USA; houxa@mail.uc.edu
3 Nanoworld Laboratories, University of Cincinnati, Cincinnati, OH 45221, USA
* Correspondence: chitrama@mail.uc.edu (M.C.); schulzmk@ucmail.uc.edu (M.S.)
† These authors contributed equally to this manuscript.

Abstract: The integration of carbon nanotube fabric into textiles is paving its way into smart materials and wearable applications. Potential novel applications of carbon nanotube hybrid (CNTH) materials and fabric composites span across a range of market levels from high-level PPE appropriate for military and industrial applications down to consumer products that can be used in everyday scenarios. The high-level performance properties of CNTH materials and their ability to be customized provide new possibilities for constructing fabrics with properties that are made to order. Furthermore, CNTH in combination with advanced textile compositing and construction methods allows the CNTH material to further leverage material customization aspects to meet specific requirements. The unique synthesis process for nanotube fabric allows for modification of the physical properties of the CNTH itself. The CNTH fabric combined with the customizability of standard textile composite materials and with the use of apparel design features allows for the design of materials with new combinations of physical properties. These unique properties offer high potential for developing families of smart wearable garments that can be scaled for industrial production. This article discusses the synthesis of carbon nanotube hybrid fabric, the process of hybrid fabric and textile integration, properties of the hybrid textile, and potential applications. The paper also provides an outlook towards large scale production of the hybrid textile material.

Keywords: carbon nanotube hybrid material; smart textile; flexible fabric

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1. Introduction

The combination of nanomaterials with textiles is an emerging field of study that offers new materials with fascinating properties and useful applications. The integration of the Carbon Nanotubes (CNTs) with textiles is paving its way into wearable technology field [1–4]. Novel approaches for synthesizing CNT hybrid materials, blended materials, and CNTs as additives are emerging in the textile sector. New customization methods integrate CNT materials into sandwich structures and fabrics at the nano and macro scales.

The customization of CNT fabric has resulted in improved properties as compared to the traditional textiles such as physical, electrical, thermal, and mechanical properties. Customized CNT hybrid (CNTH) fabric can be used in military personal protective equipment, healthcare, and fashion. Carbon nanotubes have been used to conduct electricity [5], store energy [6,7], in filtering air and water [8,9], and many other applications. The advantage of this nanoengineered fabric is the ability to exploit and combine the exceptional properties of this CNT nanomaterial within one material without compromising the flexibility and comfort of the fabric.

These combinations introduce opportunities for Customizable CNT Hybrid fabrics that span industry applications for new wearable tech, smart garments, and personal protective equipment (PPE). This paper discusses the synthesis process for customized carbon nanotube fabric, CNT fabric and textile integration approaches, and scalable manufacturing to produce flexible carbon nanotube fabric and its potential applications in technical and smart textiles. The development of these materials offers novel approaches for CNT hybridization, and altogether new kinds of blended materials and CNT additives that are emerging in the sector. The aim of this research is to use customizable CNTH materials with textiles in the applications of wearable technology, personal protective equipment (PPE), and smart and technical textiles (TT). There are various methods to integrate NPs into textile materials. NPs are dispersed in the liquid phase as additives to polymers [10,11]. In this method, particles do not form a strong interface with the material which limits the properties of the material [12–14]. This method may not be useful with flexible substrate such as fabric, where strong interface between the particles and the material is required [15]. In another method, to integrate NPs, a CNT-solvent is filtered under suction to form buckypaper. The problem with this method is that the material has low strength due to the insufficient densification and entanglement of the nanotubes [10]. The other method which faces the similar problem is spraying a solution of NPs to form a thin coating, due to the insufficient entanglement and densification, coatings are not strong enough. A direct approach of dry drawing/spinning to form sheet/yarn from nanotube forests [10,15] is used. It is an expensive batch processing method, but it produces very pure material. Another method is to produce a CNT sock using the floating catalyst method and later the sock is drawn/twisted to form sheet/yarn [15–17]. The process has limited throughput.

Large scale commercialization of nanoscale materials [18] with desired properties to satisfy wide applications is under development [19–26]. CNT have many advantages over other nano materials used in textile applications: (a) excellent properties compared to the electro spun polymer nanofibers, (b) carbon nanofibers, due to their discontinuous nature need to be spun with other fibers or mixed into a polymer), (c) forest spun nanotube yarn is expensive and long process to produce, and (d) particulate nanotubes have limited effect on mechanical and electrical properties due to their discontinuous nature and problems with shedding.

CNT integration into textiles has been slow due to issues with conventional carbon materials that include high cost, low throughput, complicated methods of application, limited strength of bulk materials, inconsistent or low conductivity, and fiber shedding during washing. There is an opportunity to address these challenges with Carbon Nanotube Hybrid (CNTH) textiles using our method which combines CNT sheets made using gas phase synthesis and textile compositing methods using fusing and adhesion.

This article discusses the synthesis of carbon nanotube and carbon nanotube hybrid fabric, the process of hybrid fabric and textile integration, properties of the hybrid textile, and its potential application in an active textile firefighter glove.

2. Background and Definitions

To fully explain CNTH materials, we must first define carbon nanotubes, nanoscale fibers and the components that make up macro scale textiles and fabrics. CNTs are tubes made of carbon with diameters typically measured in nanometers. CNTs themselves can be customized: they can be grown to custom lengths and diameters, may be created as single or double walled, and are conventionally available in either powder (which are often used as additives to polymer materials), or bulk CNT materials (like tapes, yarn, and sheets). CNTs have emerged alongside wearable tech and smart fabrics research. Expanding markets for smart textiles in medical, aerospace, personal protective equipment, and functional textiles have driven the push for new CNT integrated smart textiles.

A fiber is a natural or manufactured filament that is significantly longer than it is wide (more than 10:1 length to width ratio). A textile is any flexible material made through the interlacing of a network of yarns, threads, or fibers. Textiles take on the properties of those materials from which they are comprised. This includes properties that affect performance, like thermal resistance or conductivity, absorbency, hydrophobicity, etc. Fibers are the foundational unit making up textiles and fabrics. A fabric is made up of textile components form a flexible planar (flat) sheet material. Fabrics are used to manufacture materials and products like apparel or soft goods. In general, fabrics are organized into three structural categories: knit, woven, or nonwoven. The categorization of a fabric is dictated by the organization of the yarns or fiber that form the planar structure. Knitting is characterized by inter-looping yarns; woven fabrics are characterized by two or more interlacing sets of yarns. Nonwovens are characterized by fiber webs that are not made up of yarns. Instead, independent fibers and strands of fibers are either adhered, entangled, or fused together. The structure of the fabric determines properties such as strength, stretch, stability, and comfort. Consequently, the unique combination of the fiber content and the structural composition of a fabric define the material properties and enable customizing the fabric for appropriate end-use applications. In some cases, fabric properties depend on the finish applied to the fabric. Compositing methods, including coating, lamination, and layering methods, provide another distinct material category, which combines fabrics, often from various categories, together into one. Combining multiple materials into one provides the opportunity for customization. Now, with the inclusion of CNT as a component part of the material system, conventional fabrics can become unique multi-functional fabrics.

3. Designing CNTH Fabrics and Textiles

Traditionally, the specifications of a textile's performance, properties, and aesthetics delineate a suitable end use, but our approach begins with an end-use and user in mind. We reverse-engineer the material to include optimal performance properties for custom applications by making decisions at various levels of product development, from fiber to fabric selection, to method of assembly and final form. We carefully consider and test how differing materials will optimally work together as a system. The user-centered approach combined with textile technology and compositing equipment allows for flexible design of custom smart textiles for the wearables market. CNTs offer many advantages over existing textiles materials by reducing the weight, adding integrated non-electronic body temperature regulation, waterless self-cleaning, and other properties. In addition, the ability of the material to withstand the rigors of apparel production is a major consideration. CNT materials alone cannot withstand industrial manufacturing processes. Therefore, it is critical to combine them with veil layers to protect the CNT material from contact with metal machine parts, provide stabilization to the very thin and light material that sticks to itself, and to provide a barrier between the CNT and the skin on the inside, as well as a barrier layer to the outer environment. Selection of these veil materials, fabric structure, thickness, fiber type, layer order, application methods and machine and tool capabilities all contribute to the design of the CNT textile composite.

3.1. CNT Sheet Fabrication Process

Nanocomposite research has become increasingly important in the present decade because of the range of material properties that can be achieved through forming hybrid fabric by incorporating nanoparticles (NPs) into the fabric. As it is for textile blends, nanoblends also provide the best (and the limitations) of both materials in one composite material through this combination process. Furthermore, CNT in combination with advanced textile compositing and construction methods allows the CNTH material to further leverage material customization aspects to meet specific requirements. The unique synthesis process for nanotube fabric allows for modification of the physical properties of the CNTH itself. The integration of NPs can improve conventional fabrics without altering the fabric properties like flexibility and weight. They form fabrics that are hydrophobic, antimicrobial, filter toxic particulates/contaminants, are electrically conductive, that provide electromagnetic shielding, can harness and store energy, wick water, heat resistant and spread heat, and provide lightweight and good strength.

CNT fabric is synthesized using the floating catalyst chemical deposition (FC-CVD) method. The floating catalyst method is a continuous process and can produce industrial scale carbon nanotube material. A combination of carbon precursor, sulfur as a promoter, and catalyst is injected into a high-temperature furnace. The temperature of the heating zone in the furnace is 1400 °C. The fuel is injected into the reactor using a syringe pump which is then connected into the atomizer and then to a mixer where it mixes with the carrier gases. The carrier gas flow can vary depending on the synthesis process. Usually, the hydrogen gas flow is 100 SCCM and argon gas flow varies from 1000 to 2000 SCCM. The CNT sock aerosol is collected at the end of the reactor and collected onto a rotating drum to make a planar sheet (Figure 1A). The synthesized CNT sheet is shown in Figure 1B,C. The flow rate of the carrier gases, furnace temperature, fuel injection rate and other parameters can help in customizing CNT fabric. Close attention must be paid to the safety of the manufacturing process. Hydrogen gas is produced from the vaporization of alcohol fuel. Oxygen and hydrogen sensors are used in the harvest box to monitor the gas levels. Pre-purified argon gas is used to dilute the exhaust gas containing hydrogen in the harvest box. Typically, 20 L/min of argon gas is used for the dilution. Two exhaust tubes from the glove box are used for redundancy. Positive pressure is maintained in the glove box. Exhaust is passed through a water bubbler and is exhausted from the system using a suction fan system in the building. The harvest box has a pressure relief switch and a vacuum shut-off switch. The system is purged six times with argon and further diluted to remove oxygen (to 0.1% or less) before synthesis. Minimal hydrogen gas is used in the inlet of the reactor for safety. Particles also exhaust into the harvest box. A careful procedure is used to clean the system after each synthesis experiment. Temperature at three points in the reactor and pressure at the inlet and outlet are also monitored for safety and to understand and optimize the synthesis process. The multi-sensors are very important to monitor safe operation of the reactor. Further details about our synthesis process can be found in our previous work [27–32].

(**A**) (**B**) (**C**)

Figure 1. Synthesis process of CNT sock (the sock is a cylindrical web of CNT). (**A**) sock collection process; (**B**) obtained sheet from the drum after synthesis; (**C**) unfolded CNT sheet.

3.2. Characterization Methods

The surface morphology of the synthesized material was characterized using scanning electron microscopy (SEM) (FEI SCIOS, Waltham, MA, USA) equipped with energy dispersive X-ray analysis (EDX). The electrical conductivity of the sheet was measured using a four-probe technique (Jandel RM3000).

3.3. Carbon Naotube Hybrid (CNTH) Fabric

We call this new material Carbon nanotube hybrid (CNTH) fabric. It is formed by the integration of NPs in the pristine CNT sheet during synthesis process. The type and size of the nanoparticles can be selected based on the specific application. The advantage of this multifunctional fabric is that it can be produced in a single-step synthesis process and be customized according to the application. The properties of CNTH sheet can elevate the performance of a conventional textile to a “smart” level when included as an additive layer in a textile composite. Because of this, CNTH fabrics are uniquely positioned for smart apparel. CNTH fabric is flexible and thin. It is formed at the macro-scale and is a tailorable sheet that can be combined with conventional or high-performance planar fabrics. We use a layering method where CNTH materials are superimposed with other fabric layers to form the composite. The fabric layers are carefully selected based on their own autonomous properties, as well as their ability to interact with the CNTH sheet as part of the system. Lastly, the materials selected must be appropriate for the end-use application and be acceptable for consumer use in terms of both aesthetics (weight, handling ability, comfort) and performance (durability, strength, flexibility/stretch, safety, care). CNTs have electronic and communication capabilities, can be used for haptic sensors, filtration, and as a vehicle to spread heat and moisture rapidly.

The CNTH material was synthesized by incorporating silver and zinc nanoparticles in a high-temperature gas phase pyrolysis synthesis process. The SEM image of the CNTH material with silver and zinc nanoparticles is shown in Figure 2A. To confirm the presence of the nanoparticles in the CNTH sheet, EDX was performed on different positions. The EDX in Figure 2B shows the concentration for silver and zinc nanoparticles. The electrical conductivity of the pristine CNT and CNTH material was measured using a four-point probe method. As we can see in Figure 2C, the CNTH material has better electrical conductivity as compared to the pristine CNT. The increase in conductivity is due to the presence of silver and zinc nanoparticles in the hybrid material. The voltage–temperature relationship for the hybrid material was investigated (Figure 2D). The CNTH material showed good heating performance and reached up to 120 °C at a very low voltage. This flexible, lightweight CNTH material with good electrical conductivity and heating performance can be used in wearables’ applications.

The goal of our research using the floating catalyst method to form a CNT sock which can be collected on to a rotating drum to form a sheet. The process avoids liquid dispersion [33], which uses large volumes of liquid to disperse a small percent of nanotubes, different NPs such as single and multiwall carbon and boron nitride [34,35] nanotubes, and C60 [18] can be integrated in the high-temperature gas phase pyrolysis synthesis process so that the NPs are not oxidized [36]. The significance of the research is to create the large scale of nanoscale materials; to design and improve the properties of CNTH materials; and to incorporate manufacturing and post processing of the materials. The aim here is to synthesize a new hybrid material that surpasses the properties and manufacturing barriers of CNT materials by integration of NPs that can be used to customize the material. Large-scale manufacturing methods must also be developed that are suitable for manufacturing textiles and apparel for various applications.

Hybrid materials containing SWCNT, metals, and/or ceramics in variable combinations can be synthesized. Metal ceramic or other high heat resistant particles can also be integrated with CNTs during the high temperature gas phase pyrolysis synthesis process, offering a plethora of new customization options for building CNTH sheets from the bottom up. The additive NPs decorate the nanotubes. The amount of NPs can be integrated into the material depends upon the specific application. Hydrogen gas released from the fuel decomposition reduces the chance of CuxOy phase materials. The post-processing steps that can be applied to fabric are a) use a rolling mill to apply high pressure to densify the fabric; and b) thermal annealing in air to remove amorphous carbon and other deposits. These hybrid materials can be produced on a large-scale in a single-step with high quality, thus increasing the potential for CNTH materials to be manufactured, overcoming the limitations of high cost and production throughput for textile and apparel manufacturing [37]. CNTH material synthesis process integrates NPs during nanotube growth. This hybrid process improves fabric properties and promotes industrialization of the technology. With this process, new fabrics can be created that may perform more effectively than existing textiles.

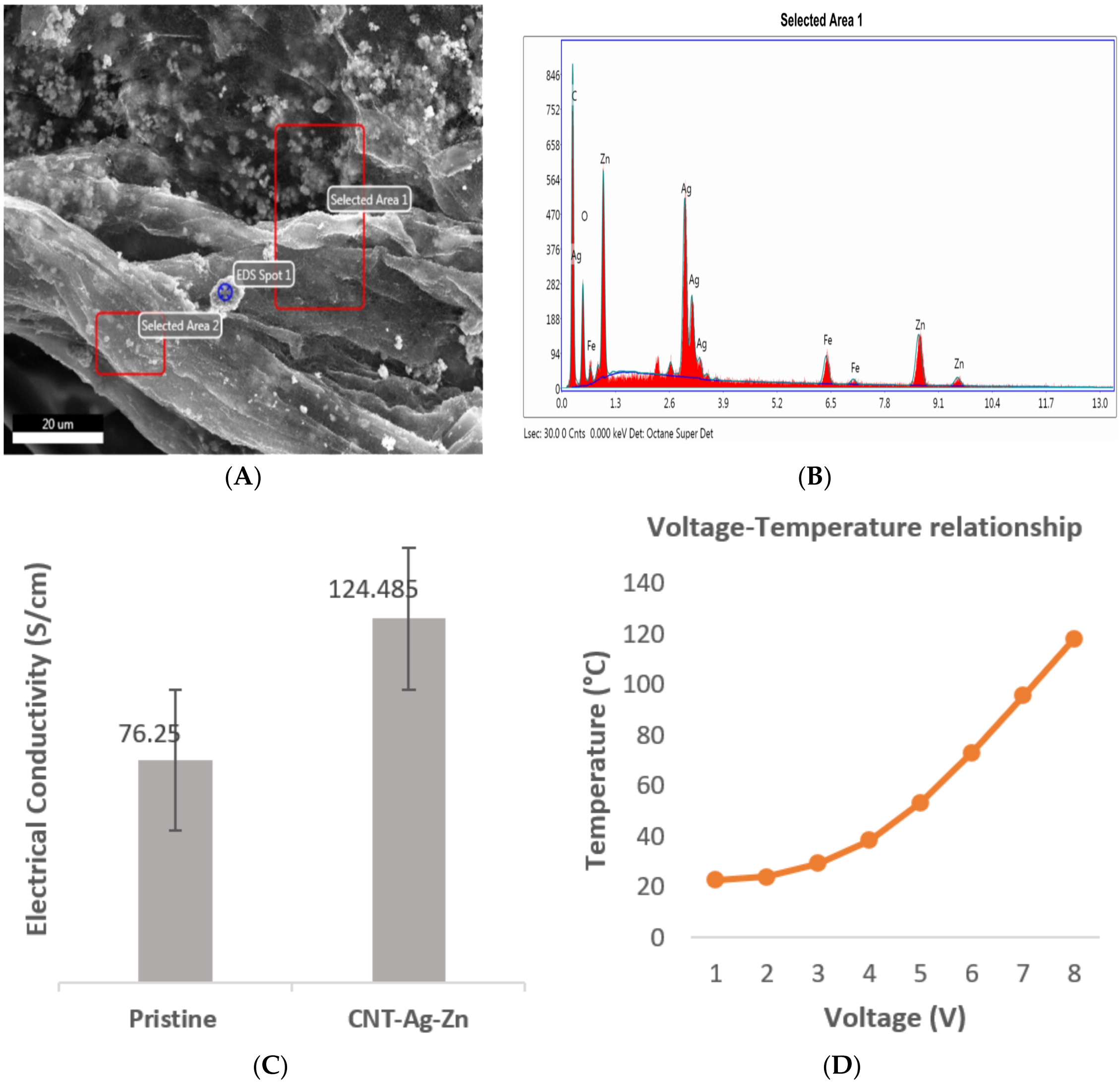


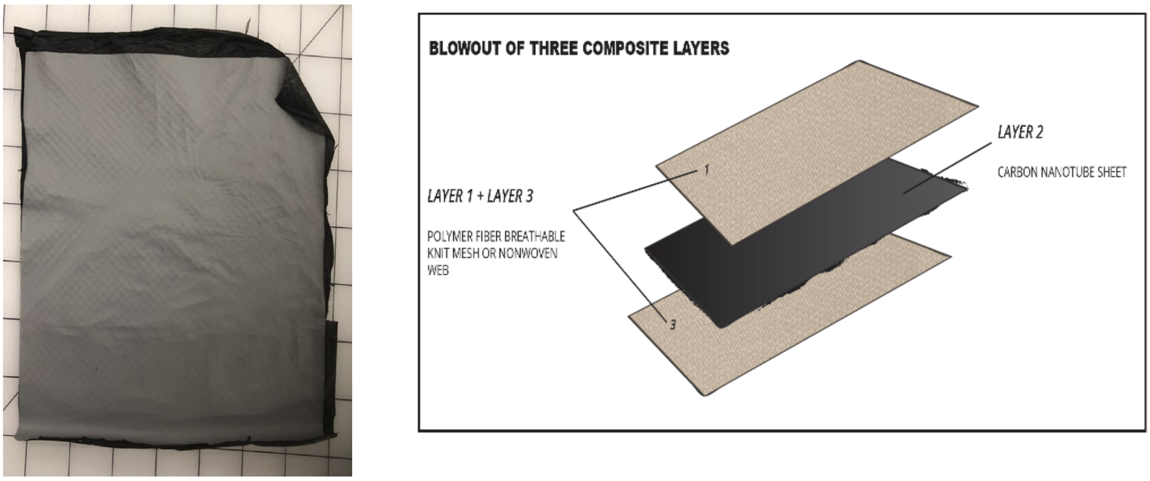
Figure 2. Properties of Carbon Nanotube Hybrid fabric. (**A**) microscopic image of the CNTH material-CNT-Ag-Zn; (**B**) EDX for CNTH material; (**C**) electrical conductivity of Pristine CNT and CNTH material-CNT-Ag-Zn; (**D**) voltage–temperature relationship of CNTH fabric material.

CNT fabric has a relatively low specific heat which makes it an excellent material for piping and distributing heat. CNT fabric is easy to handle and is light in weight (typically 30 microns thick sheets have a density of 0.5 g/cc). The fabric is cool to the touch when placed on a cold surface due to its high thermal conductivity. The materials are inherently anti-static and anti-microbial, and the hybrid material is flexible and soft and can have good electrical conductivity. Researchers have been working to improve tensile strength and lower the production cost of CNT materials to increase the possibilities for use of CNT fabric in apparel and soft goods applications. Increasing the strength and reducing the cost are issues that persist in the manufacturing of CNT continuous fiber and yarn.

3.4. Textile Composting + Construction

The integration of CNTs in composite and blended materials offers many advantages due to their combination of good strength and modulus combined with low density [38]. Several methods of combining CNTH sheet with conventional textiles have been tested as part of this study. These methods include stitching (quilting/embroidery), adhesives (liquid, spray, powder, or heat activated), coating/lamination (wet treatment) as shown in Figure 3A, and heat fusing (dry or steam embossing or calendaring) as shown in Figure 3B.

Each method offers its own set of benefits and drawbacks, which are directly dependent upon the fabric and CNTH properties, and appropriateness for the end use.



(A) (B)

Figure 3. (**A**) Pristine CNT laminated; (**B**) layout for a three layer composite.

Stitching is the most conventional method of compositing fabric materials into layers. This is often called quilting. This can be done using a conventional sewing machine but can also be done by hand, or surface stitching patterns can be engineered using automated embroidery. Industrial machines used for scaled production can damage or reduce the performance of the CNT sheet during the production process. Through testing, our team found that piercing the CNT sheet with a needle reduces its performance and causes instability in the material; therefore, our team explored alternate methods for attaching layers together. This can be optimized with variation of stitch length or localized perforation of the CNT material prior to layering. Other effective alternatives to sewing include fusing, embossing, and adhesive joining methods.

Adhesives and heat fusing work well for bonding CNTH to conventional fabrics with available glues; however, we noticed that an overall adhesive coating creates a barrier layer between the CNT and the fabric layer, preventing moisture or heat spreading to occur as it passes from the outer environment/skin through the fabric to the inner CNT layer where the heat and moisture can spread. To combat this issue, we tried laser perforating a fusible nonwoven layer before attaching it to the CNT with heat. We also silkscreen printed liquid adhesive onto the surface of the fabric to create a custom adhesive pattern, in this case a dot matrix. This allowed moisture and heat to pass around the local adhesive connections' points. For some custom applications, like protective apparel, where high heat is present in the environment, the adhesives or low melting point fibers did not produce a safe or effective solution because of the potential release of combustible or carcinogenic chemicals or melting to the skin in high-heat or fire scenarios.

4. CNTH Wearable Applications

The high-level performance properties of CNTH materials and their ability to be customized provides new possibilities for constructing garments with properties that are made to order. Wearable Technology (WT) encompasses all forms of integrated functionally, embedded products with improved performance, and spans products from eyewear, accessories, footwear, jewelry, and, in our case, apparel. Functional Apparel (FA) is a subsector of the wearables industry, and smart textiles play an important role in development process of WT. Textiles optimally engineered for their end-use applications are referred as Technical Textiles (TT). TT materials have been widely used in many areas, from medical applications [39], transportation and aerospace [40], to high-performance sports apparel [41].

Although they exhibit high performance, TTs do not have the abilities that smart textiles (STs) do. STs have the capability to react either in a passive or programmed way. STs often utilize advanced materials that are conductivity, reactive, or have embedded electronic and computation systems that can elicit state change, remote communication or other performance enhancing functions. Early experimental smart textiles used rigid components that were not appropriate for apparel or soft goods applications. Resilience is a foundational property of successful smart fabrics because of the necessity of these materials to flex and recover with the movement of the wearer, while also withstanding abrasion, washing and regular, repeated use. These unique properties offer high potential for developing families of smart wearable applications that can be scaled for industrial production.

Novel applications of CNTH fabric span a range of wearable markets, from high-tech personal protective equipment appropriate for high-performance military and specialty industrial applications, to medical applications, athletic performance wearables and garments, down to more subtle tech applications in consumer products like casual sportswear intended for everyday applications. CNTH textiles are customizable for this range of applications because each aspect of the material composite can be engineered; first, the combination of nanomaterials integrated into the CNTH sheet, the selection of the composite materials, the layering order, and finally the attachment method. The placement and direction of the CNT sheet can also improve the properties based on the performance needs of the end use application. For instance, a filtration composite may include more CNT layers than a system that is designed to spread heat and moisture in a linear way. These directional considerations will affect the design of the product.

Active Textile Firefighter Glove

Firefighters (FFs) work in difficult settings, requiring high physical activity in high temperature conditions. This working environment causes heat stress which can cause several health problems for FFs. FFs generate a significant amount of metabolic heat from physical activity. At the same time, their firefighting apparel is constructed with insulating material. The thermal insulation will protect the FF from the hot working environment. However, the insulation traps metabolic heat generated from the human body. Therefore, active textiles (ATs) are considered to remove environmental and metabolic heat from the body. ATs incorporate carbon nanotube (CNT) fabric with directional thermal conductivity into garments. An FF glove using AT material was designed as an example garment. CNT fabric has high thermal conductivity in the plane of the fabric and low thermal conductivity in the transverse direction (through the thickness). Therefore, the FF glove designed with CNT material can insulate against environmental heat entering the garment and spread heat laterally in the garment to reduce hot areas. Heat conduction depends on the thermal conductivity of the material, the area of heat conduction, thickness of the material, and temperature difference. Thus, increasing the thickness of the fabric will increase heat insulation through the thickness and increase heat spreading in-plane. There should be a cool area in the garment (glove) to transfer the in-plane heat quickly. A cold area can be designed in the glove with low temperature. This can be realized by providing an ice pack area in the glove and/or by using a fan to provide forced convection to cool the fabric. The fabric with CNT material for heat spreading and a fan for forced convection cooling is an example of an Active Textile.

A 1D heat transfer model of an FF AT glove was constructed in MATLAB to simulate the thermal performance of the glove, Figure 4. The simulation model is mainly designed to determine if the design of AT glove is practical. A two-layer fabric was simulated: the outer layer is a highly thermally insulating material; the inner layer is a CNT fabric layer. The CNT fabric layer will contact the hand skin surface. There also exists an air gap between the outer layer and the CNT fabric layer. A key factor in the simulation model is modeling air flow supplied by an air pump assumed to be integrated into the glove to provide air flow inside the air gap. A severe condition was simulated [42]. The external temperature at the glove location was set at 60 °C (140 °F). The air flow velocity is 2 m/s. The air flow comes from a cooler area away from the hand. The temperature of the air pumped into the glove is assumed to be 29 °C (84 °F). The metabolic heat generated from the human body was not considered in this case. For these conditions, the simulated steady-state temperature of the hand skin surface was 33 °C (92 °F). The temperature of the hand without the AT layer (no CNT layer and no forced convection air flow) was 58 °C (136 °F). The AT fabric thus provides an approximately 40% decrease in temperature compared to the standard glove. The simulation indicated that air flow and evaporation of sweat has a greater effect on cooling than heat transferred by conduction for the thin CNT layer considered. This simulation result suggests that ATs with forced air flow are a practical way to remove heat from FF apparel, which will lower the skin temperature and reduce heat stress for FFs. Reducing heat stress may increase the safety of a dangerous occupation. The trade-off is that ATs add weight and increase the cost of garments.

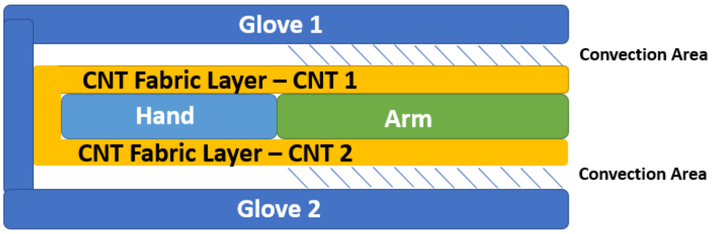


Figure 4. Simulation of an AT glove for FFs—Design of the glove. Glove 1 is the top outer layer of the glove, glove 2 is the bottom outer layer of the glove. CNT 1 is the top inner layer of the glove. CNT 2 is the bottom inner layer of the glove. The convection area is the area in which air flow from the air pump cools the glove. The thermal properties of the hand and arm are modeled in the simulation. A cold area to provide cooled air is not shown. The drawing is not to scale.

The simulation model can produce a range of results depending on the various input parameters. The temperature at the center of the hand can be estimated in this example under various environmental conditions, such as varied working temperatures. The air flow velocity and the temperature of the convection area (which defines the air flow temperature goes into the AT glove) are the two primary parameters that impact the temperature at the middle of the hand. The airflow velocity can be adjusted using a commercial fan integrated into the glove, and the temperature of the convection area (cooler area) can be controlled using an ice pack to create a low-temperature zone. Then, the low-temperature air flow can remove a significant quantity of heat that enters the glove from the high-temperature surroundings. The relationship between the temperature of the convection area and the temperature at the center of the hand is depicted in Figure 5. The ambient temperature is 60 °C, and the air flow velocity is 1 m/s in this scenario. The curve fitting equation $y = 0.63x + 15$ illustrates the accurate relationship between the convection area temperature and the temperature at the center of hand.

The temperature at the center of hand is 33 °C with 2 m/s air flow (29 °C air flow temperature), and the environment temperature is 60 °C. According to the simulation model, without the CNT layer and no air movement inside the glove, the temperature at the center of the hand was 58 °C, indicating that the air flow over the CNT layer inside the FF AT glove contributed a 43% reduction in temperature. Table 1 provides a more detailed comparison using various ambient temperature inputs. In this case, the CNT layer is used with forced convection heat transfer at 2 m/s air flow. The convection area temperature is 29 °C.

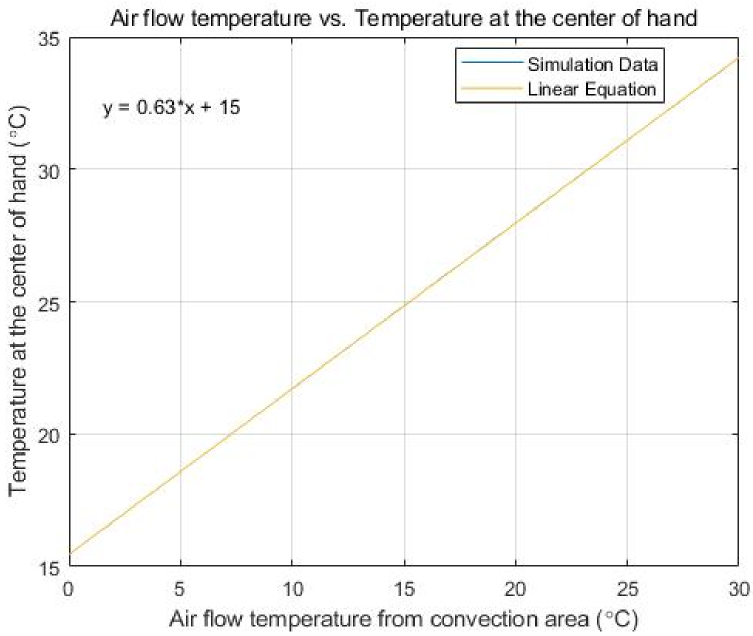


Figure 5. Air Flow Temperature vs. Temperature at the Center of the Hand.

Table 1. Comparison between temperature at the center of hand with and without the air flow and CNT layer.

Environment Temperature (°C)	Temperature at the Center of Hand with Air fCNT Layer (°C)	Temperature at the Center of Hand without Air Flow and CNT Layer (°C)	Reduction in Temperature (%)
40	32.0	39.7	19%
50	32.6	48.6	33%
60	33.2	57.6	43%
70	33.8	66.5	49%

As shown in Table 1, the percentage difference between the two scenarios with and without forced convection air flow and the CNT layer increases as the ambient temperature increases. Thus, the CNT layer design and the cool air flow are two critical features in AT gloves that contribute to the glove's ability to protect FF in a high-temperature work environment. The conventional commercial materials do not have a high thermal conductivity in the plane and a low thermal conductivity through the thickness. As a result, while providing cool air flow for other glove designs without CNT layers, the temperature in the hand's center will not see as dramatic of a reduction. The CNT layer and forced convective heat transfer coexist and complement one another.

A prototype of the CNT lined glove is shown in Figure 6. Experimental characterization of the glove and other apparel is ongoing. The glove is called active because the CNT fabric layer has special properties compared to conventional fabric. CNT fabric has low thermal conductivity through the thickness and good thermal conductivity in the plane of the fabric. Thus, the CNT layer will add thermal insulation to the glove, and also help spread heat in the glove. Air flow provides forced convection cooling which removes heat from the glove. Electrical conductivity has a similar trend to thermal conductivity. CNT fabric has small electrical conductivity through the thickness of the fabric, and good electrical conductivity in the plane of the fabric. The lower conductivity through the thickness is due to the many more nanotube to nanotube junctions, compared to the in plane direction.

Figure 6. General construction of a prototype Active Textile glove with CNT inner liner. The glove has an outer protective layer, CNT center layer, and soft inner layer against the skin. The tube at the cuff is for air flow into the glove.

5. Conclusions

Integration of CNT and textiles offers a range of novel applications that surpass the functionality conventional materials. CNTH fabrics offer thermal and electrical conductivity, a necessity of most wearable technology designs where sensing, outputs, and remote communication with devices are necessary. They have excellent versatility and tailorable properties that can be adapted for specific markets and product uses, particularly the technical and smart textile industries. Characterization and testing of the materials are being performed and material properties data will be presented in the future as the research develops. Both simulation and user testing will help designers better understand the potential of CNTH fabric for use by various target groups. Quantitative and qualitative data will help designers better understand the scope of effectiveness of CNTH materials, as well as consumer need, satisfaction and market readiness adoption through both user testing and focus groups. The research focuses on: (1) the synthesis of hybrid material and its applications; (2) techniques to increase the yield of the synthesis process including direct catalyst injection; and (3) the performance evaluation of different types of hybrid materials to customize fabrics for different applications.

In our study, we have tested optimal methods for joining CNTH sheet with fabrics for a variety of product application scenarios including firefighter personal protective equipment, workwear, and uniforms, and activewear clothing. We found that, for certain applications, the environmental conditions of the wearer could make one or more compositing method inappropriate for a particular application yet meet the needs of another. Our team takes a user-centered approach to the design of custom CNTH textiles wherein the end-use drives the start of the design and the engineering process and carries through to the construction of the final product. The applications can benefit from thermal or electrical conductivity of the fabric.

We predict that CNTH textiles will be easily customized for a range of applications on several different markets levels, from smart clothing with embedded electronics, communication capabilities, specialized military applications, personal protective equipment for service industry, performance garments for athletics, special medical applications, all the way to everyday casual sportswear. These materials will be used to improve the performance of conventional textiles to make users more comfortable and make their lives easier. The scale-up scenario has been a challenge for CNTs because of the prohibitive cost of manufacturing. In combination with low-cost composite materials like nonwoven textiles, and specific testing to determine the optimal amount of CNTH needed for customization of the performance level within the range of product applications, lower cost CNTH material development is promising. These developments can only be achieved at the intersection of apparel design and engineering.

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