



AFRL-RX-TY-TP-2010-0051

**AN APPROACH TO MASS CUSTOMIZATION  
OF MILITARY UNIFORMS USING  
SUPEROLEOPHOBIC NONWOVEN FABRICS  
POSTPRINT**

---

Dnyanada Satam, Hoon Joo Lee  
North Carolina State University  
Campus Box 7001  
Raleigh, NC 27695-3742

Eugene Wilusz  
Army Natick Soldier Research,  
Development and Engineering Center  
Natick, MA 01760

Contract No. FA8650-07-1-5916

November 2010

**DISTRIBUTION A:** Approved for public release; distribution unlimited.

**AIR FORCE RESEARCH LABORATORY  
MATERIALS AND MANUFACTURING DIRECTORATE**

<b>REPORT DOCUMENTATION PAGE</b>				<i>Form Approved</i> <i>OMB No. 0704-0188</i>	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
<b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b>					
<b>1. REPORT DATE (DD-MM-YYYY)</b> 30-NOV-2010		<b>2. REPORT TYPE</b> Journal Article POSTPRINT		<b>3. DATES COVERED (From - To)</b> 15-AUG-2009 -- 30-AUG-2010	
<b>4. TITLE AND SUBTITLE</b> An Approach to Mass Customization of Military Uniforms Using Superoleophobic Nonwoven Fabrics (POSTPRINT)				<b>5a. CONTRACT NUMBER</b> FA8650-07-1-5916	
				<b>5b. GRANT NUMBER</b> 	
				<b>5c. PROGRAM ELEMENT NUMBER</b> 0602102F	
<b>6. AUTHOR(S)</b> ^Satam, Dnyanada; ^Lee, Hoon Joo; ^^Wilusz, Eugene				<b>5d. PROJECT NUMBER</b> GOVT	
				<b>5e. TASK NUMBER</b> L0	
				<b>5f. WORK UNIT NUMBER</b> QL102006	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> ^North Carolina State University, Campus Box 7001, Raleigh, NC 27695-3742 ^^Army Natick Soldier Research, Development and Engineering Center, Natick, MA 01760				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b> 	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Air Force Research Laboratory Materials and Manufacturing Directorate Airbase Technologies Division 139 Barnes Drive, Suite 2 Tyndall Air Force Base, FL 32403-5323				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> AFRL/RXQL	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b> AFRL-RX-TY-TP-2010-0051	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> Distribution Statement A: Approved for public release; distribution unlimited.					
<b>13. SUPPLEMENTARY NOTES</b> Document contains color images.					
<b>14. ABSTRACT</b> <p>This paper examines the design of modern military uniforms with emphasis on protection against hazardous chemicals. Design of military uniforms is governed by protective functions, quality, and economic feasibility. Along with protection, key performance features include high strength, light weight, moisture management, and comfort. The surface of hydroentangled nonwovens and nylon-cotton blended woven fabrics were modified, and made superhydrophobic and superoleophobic to protect soldiers against the threat of hazardous chemical and biological agents. Scenarios for the use of nonwoven fabrics and computer-aided design in the mass production and customization of military uniforms are proposed.</p>					
<b>15. SUBJECT TERMS</b> mass customization, military, nonwovens, superhydrophobic, superoleophobic, uniforms					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b> UU	<b>18. NUMBER OF PAGES</b> 5	<b>19a. NAME OF RESPONSIBLE PERSON</b> Jeffery R. Owens
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			<b>19b. TELEPHONE NUMBER (Include area code)</b> 

Reset



# An Approach to Mass Customization of Military Uniforms Using Superoleophobic Nonwoven Fabrics

Dnyanada Satam and Hoon Joo Lee, North Carolina State University; and Eugene Wilusz, Natick Soldier Research, Development, and Engineering Center

## Abstract

This paper examines the design of modern military uniforms with emphasis on protection against hazardous chemicals. Design of military uniforms is governed by protective functions, quality, and economic feasibility. Along with protection, key performance features include high strength, light weight, moisture management, and comfort. The surface of hydroentangled nonwovens and nylon-cotton blended woven fabrics were modified, and made superhydrophobic and superoleophobic to protect soldiers against the threat of hazardous chemical and biological agents. Scenarios for the use of nonwoven fabrics and computer-aided design in the mass production and customization of military uniforms are proposed.

**Key Terms:** CAD, Mass Customization, Military, Nonwovens, Superhydrophobic, Superoleophobic, Uniforms

## Introduction

There is a growing emphasis on military clothing in soldiers' fighting kits since it enhances their performance and protects their lives during combat.<sup>1</sup> Functional textile materials must be provided for protection against numerous hazards such as extreme weather conditions, physical impact, and chemical biological (CB) threats. Awareness of the importance of protection has prompted military research and development efforts to introduce new technologies and fabric materials into military uniform production. Due to increased competitive pressures arising from technology advancement, new product development has become essential in many areas, including the defense sector. Defense relies heavily on emerging technology to develop textiles that have high performance value and varied applications in the military. The fiscal 2009 US Department of Defense (DoD) Budget provides US\$515 billion in discretionary authority.<sup>2</sup> In addition, the need for military clothing is increasing day-by-day with the increasing number of global military missions.

The US military is the second largest in the world, after the People's Liberation Army of China. As of April 2007, about 1.4 million people were on active duty, with a nearly 50/50 split between males and females.<sup>3</sup> To cater to these huge needs, mass production requiring a large labor force is necessary. However, there has been a constant decrease

in the number of workers employed in the US apparel industry over the past several decades due to globalization of the textile industry, leading to global outsourcing and offshore manufacturing.<sup>4</sup> Meanwhile, labor costs have steadily increased worldwide.<sup>5</sup> Due to continuous growth in labor costs, manufacturing units are expected to prefer more mechanized processes that require less labor. It is anticipated that labor costs can be reduced during sewing operations using automated assembly techniques, making domestic production of military clothing readily available. The dual objective of reducing the work force and achieving large-volume production can be accomplished by applying new fabric materials such as nonwovens and automated assembly techniques in military clothing production.

In this research, we focus on examining scenarios involving the use of nonwoven fabrics and computer-aided design (CAD) for the necessary domestic mass production of military uniforms. The pros of using nonwoven fabrics as a substitute for nylon-cotton blended (50/50 NYCO) woven fabric will be explained. By developing new CAD systems, it is expected that a versatile selection of fit will be provided to each soldier. A mass customization model is presented that has the potential to improve military uniform comfort and protection. In addition, a method for preparing superhydrophobic, superoleophobic textile surfaces, which can



contribute to CB protection for warfighters, will be proposed since one of the major threats faced are CB warfare agents.<sup>6</sup>

## Nonwovens in Military Clothing

According to the Association of the Nonwovens Fabrics Industry (INDA), a nonwoven fabric is a sheet, web, or bat of natural and/or manmade fibers or filaments, excluding paper, that have not been converted into yarns and are bonded to each other. Therefore, nonwoven technology allows the fibers to be constructed into fabric in an economical, rapid, and more versatile way.<sup>7</sup> Nonwovens can mimic the appearance, texture, and strength of woven fabrics and can be paper thin or as bulky as a thick padding insulator. Combined with other materials, they can provide a spectrum of products with diverse properties and varying life spans for the military. For applications in uniforms, a fabric should meet certain requirements such as superior strength, comfort, flame retardancy, bacterial barrier properties, and many more. Nonwovens, being highly engineered, can combine all these properties in one fabric. If nonwoven manufacturing techniques are selected correctly, the resultant fabric can easily match the required standards.

Current utility fabrics used for military uniform production are woven fabrics made of nylon and cotton. These fabrics are manufactured using traditional textile technologies. Woven fabric manufacturing comprises three main steps: spinning, weaving, and finishing, which, in turn, consist of as many as fourteen sub-steps (some of which cannot be performed in a single location). This makes the complete process time consuming as well as expensive. In comparison, nonwoven fabric processes are brief, having five steps: opening, blending, carding/web formation, bonding, and finishing. Thus, they tend to be less expensive. Woven fabric is composed of large yarns having twisted strands which fail to give a compact structure to the fabric. The loose structure leads to poor insulation, filtration, and barrier properties. On the other hand, nonwoven fabrics are produced by bonding finer individual fibers, thus providing a condensed structure, which can lead to better insulation, filtration, and barrier properties. Also, nonwoven fabric processes involve new technologies and innovations in which the US leads.<sup>8</sup> Producing military uniforms using nonwoven fabrics instead of woven fabrics will make domestic mass production of defense materials much easier.

Some recent developments in military clothing include progress in minimizing weight and maximizing durability and comfort. The US Army Natick Soldier Research, Development, and Engineering (RDE) Center is currently researching the use of enhanced nonwoven composite fabrics for military uniforms. This proposed fabric possesses high strength, softness, improved abrasion resistance, air permeability, and printability for camouflage patterns. The lighter weight and higher breathability can lead to potential reduction in heat stress and also improves fabric comfort properties. This nonwoven fabric has a composite multilayer structure that provides enhanced water absorbency inside for sweat management and exterior water repellency for rain protection. This nonwoven fabric can also be treated with fire retardant chemicals, imparting characteristics such as self-extinguishing, char formation, and low smoke generation to the fabric.

## Mass Customization Technology

A soldier is initially issued four pairs of uniforms, but after the use of this initial supply, it is the soldier's responsibility to buy new uniforms. These uniforms are generally bought by the soldier online. For military clothing, fit is very important for providing comfort and protection to the soldier. To provide a properly fitting uniform, the most efficient way could be to set up an internet-based intelligent computer-aided design (CAD) system with a friendly interface to support the soldier while ordering the desired uniforms. Thus, mass customization systems can be applied to the garment manufacture process for military uniforms. The garment manufacturing process can be divided into three stages: CAD, computer-aided process planning (CAPP), and computer-aided manufacturing (CAM).

### CAD

Mass customization transfers the customer's unique requirements into the merchandise with the speed of mass production. Essential technologies to help fulfill these needs are body scanning, garment modeling, digital pattern design, and garment simulation. These technological advancements improve manufacturing efficiency and production capacity, reducing labor costs and shortening production times (US Central Intelligence Agency, 2008).

### CAPP

CAPP is the bridge between CAD and CAM; it transforms design information into manufacturing

information and can be integrated with CAM. Over the past 30 years, many efforts have been made in the areas of CAPP and CAM. The development of the Unit Production System (UPS), tension-free spreading machines, automated cutting machines, and digital sewing machines have improved CAM efficiency greatly. Also, new technologies have been used in CAPP. For example, the current CAPP uses a generic algorithm to control workflow balance and dual robot work cells to control the UPS. Based on these efforts, mass production speed has been greatly improved.

## CAM

The process of mass customization based on 2D intelligent design starts from the customer's requirements. Fig. 1 represents a roadmap of an intelligent design and manufacturing system helping mass customization of military uniforms. First, the individual provides style requirements (various uniform styles are required depending on the soldier's post, mission, and gender) and body size to the intelligent design module. Second, the soldier sees the 2D style and evaluates the style. If the soldier is satisfied with the style, the style will be accepted and the process continues with the third step. If the soldier is not satisfied with the style, he or she can discard or adjust it. Third, the accepted style will be sent to the specialist pattern design module and the pattern will be generated automatically. Finally, the customized uniform is ready to be manufactured. After the planning CAM, the fabric needs to be cut and assembled. For many military uniforms, ultrasonic seaming is preferred to prevent needle holes which could lead to the intrusion of CB warfare agents.

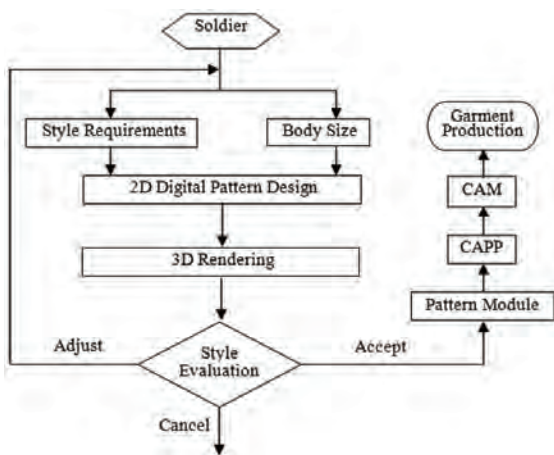


Fig. 1. Process of mass customization based on intelligent design and manufacturing.

## Ultrasonic Garment Bonding

Ultrasonic bonding uses high-frequency vibrations that create a rapid buildup of heat, and forms a finished seam or sealed edge without melting or affecting the base materials. Materials that are 100% synthetic or blends of up to 40% natural fibers are suited for ultrasonic bonding and are easily bonded.<sup>9</sup>

Ultrasonic bonding technology can be used as a tool of garment construction. If traditional sewing machines are used to produce garments with nonwoven fabrics having fine filament webs, the needles of the sewing machines may lead to entanglement of the fibers in the nonwoven fabric during its up-down sewing motion. More importantly, conventional sewing leaves holes where CB agents can penetrate. If an automatic cutting machine connected to CAD pattern software has an ultrasonic bonding unit beside the blade, the garment can be cut and assembled without sewing steps. This multifunctional equipment is expected to require fewer workers since it is completely automated. The advanced technology used would make the complete process of nonwoven garment manufacturing cost-effective.

At this point, the final garment is ready to package and ship. In summary, the soldier has input design criteria; a pattern has been created by CAD; and the soldier has approved the design, which then moves through CAM to the final product. In the CAM process, nonwoven fabric is automatically cut and ultrasonically seamed for a customized fit.

## CB Defense Management

Protection against chemical liquids, vapors, and bio-aerosols is the basic function of a CB defense system—a breach in this system may lead to serious injury or loss of life. One of the strategies for CB defense is to make the garment repel CB warfare agents having low surface energy. A surface that has a water contact angle greater than 150° is called a superhydrophobic surface.<sup>10</sup> In the same manner, a surface having an oil contact angle greater than 150° is called a superoleophobic surface. A method is proposed to prepare fabrics having a superhydrophobic superoleophobic surface, which can easily shed hazardous chemicals immediately.

## Experiment and Results

Nylon nonwoven and NYCO woven fabrics were chemically grafted with 1H,1H,2H,2H-perfluorodecyltrimethoxysilane (F-silane). The fabrics were dried in air for 24 h, followed by rinsing with distilled water. After treatment, both fabrics were subjected to 25 laundering cycles according to the AATCC Test Method 61 (Test No. 2A).<sup>11</sup> Contact angles for both water and oil (dodecane) were measured after each wash cycle using a lab-designed goniometer.

### Superhydrophobic Superoleophobic Nonwovens

Fig. 2 shows water and dodecane droplets on nonwoven fabric treated with F-silane. Both droplets sit almost spherically on the fabric surface—the fabric has low affinity for both water and dodecane. Table I gives the contact angles on the treated nonwoven fabric after up to 25 wash cycles.

Initially, both water and dodecane contact angles were constantly greater than 150°. However, water contact angles on the same fabric were between 100° and 150° depending on the location of droplets after up to ten washing cycles, while dodecane contact angles varied between 0° and 100° after 5 washing cycles. For 10 and above wash cycles, both water and dodecane were mostly absorbed into the fabric structures due to the lack of dimensional stability of nonwoven fabrics or weak chemical bonding between nylon and F-silane. Although the fabric had exhibited superhydrophobicity and superoleophobicity, washing durability needs to be improved.

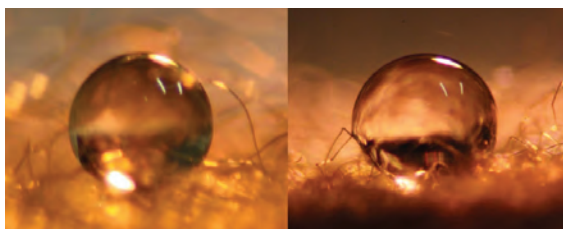


Fig. 2. Water (left) and dodecane (right): 2 µL droplets on F-silane grafted nylon nonwoven fabric.

Table I. Contact Angles on F-silane Grafted Nylon Nonwoven						
No. of Wash Cycles	0	5	10	15	20	25
Water Contact Angle (°)	168	150	Not stable			
Dodecane Contact Angle (°)	153	Not stable				

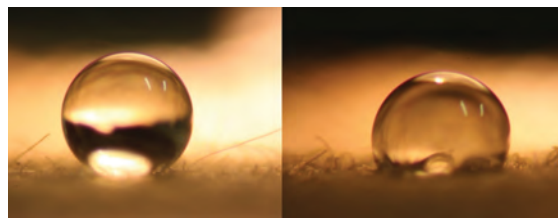


Fig. 3. Water (left) and dodecane (right): 2 µL droplets on F-silane grafted NYCO.

Table II. Contact Angles on F-silane Grafted NYCO						
No. of Wash Cycles	0	5	10	15	20	25
Water Contact Angle (°)	155	148	137	134	115	115
Dodecane contact Angle (°)	140	137	137	134	133	130

Table III. Contact Angles on the Current ACU Made of NYCO					
No. of Wash Cycles	0	5	10	15	20
Water Contact Angle (°)	151	147	138	136	124
Dodecane contact Angle (°)	84	Dodecane droplet absorbed completely by fabric			

### Superhydrophobic Superoleophobic NYCO

NYCO, made of nylon-cotton blend and used as a main fabric in military uniforms, was also treated with F-silane. Water and dodecane contact angles on the fabric surface were measured before washing and after up to 25 wash cycles. Fig. 3 shows water and dodecane droplets on the treated NYCO, and Table II gives the contact angles on the treated NYCO after up to 25 wash cycles.

NYCO fabric treated with F-silane had initial water and dodecane contact angles of 155° and 140°, respectively. After 25 wash cycles, both water and dodecane contact angles decreased slightly. Table II can be compared with Table III, which presents the washing durability of the current Army Combat Uniform (ACU) fabric having reasonable initial hydrophobicity but absorbing oil immediately.

### Preparation of Superhydrophobic Superoleophobic Uniform

A prototype sample of a military jacket was prepared using hydroentangled nylon nonwoven fabric, which was chemically grafted with F-silane, helping the fabric to attain superhydrophobicity and superoleophobicity. Garment patterns were generated using Gerber Acumark Software. After fabric treatment was completed, garment patterns were cut



using an automated sewing machine. Pattern pieces were then sewn using the Sonobond ultrasonic sewing machine. The prototype sample is shown in Fig. 4.

## Conclusion

As the saying goes, "Necessity is the mother of invention." Soldiers require new modifications in their uniforms to surmount extreme climatic conditions and to reduce the threat of various warfare agents during their mission. The requirement of the hour is having lightweight, more breathable uniform fabrics that also have superior tear and break properties. Composite nonwoven fabrics provide all these properties along with enhanced durability and wash resistance. In addition, many nonwovens can be ultrasonically bonded to create impervious seams that prevent penetration of CB warfare agents.

Improving the efficiency of CAD through a user friendly design system enables the manufacturers to design uniforms for each soldier in their own body shapes and sizes. We have described a potential CAD, CAPP, and CAM systems to facilitate the entire process of apparel mass customization. Incorporating intelligent design into online shopping could result in more accurate design and fit to military uniforms, which in turn would enhance uniform comfort.

In addition, a superhydrophobic superoleophobic textile surface has been developed to improve protection against CB warfare agents. Water and oil contact angles on the superhydrophobic superoleophobic prototype sample shows that this technology is an effective means of imparting both superhydrophobicity and superoleophobicity to nylon nonwoven surfaces, but requires better laundering durability.

## Acknowledgements

This material is based on research sponsored by the Air Force Research Laboratory (project number FA8650-07-1-5903) and Defense Threat Reduction Agency-Joint Science and Technology Office for Chemical and Biological Defense (grant number HDTRA1-08-1-0049). The US Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed



Fig. 4. Prototype sample of a superhydrophobic superoleophobic uniform.

or implied, of the US Government. The support of the US Army Natick Soldier RDE Center is also acknowledged. Lastly, we thank Nonwoven Institute for sharing hydroentangled nonwoven fabric.

## References

1. Muran, L., *Technical Textile Markets*, Issue 62, 3rd quarter, 2005, Textile Intelligence Ltd., Wilmslow, UK, pp8-26.
2. *News Release*, US Department of Defense, February 4, 2008, [www.defenselink.mil/comptroller/defbudget/fy2009/2009\\_Budget\\_Rollout\\_Release.pdf](http://www.defenselink.mil/comptroller/defbudget/fy2009/2009_Budget_Rollout_Release.pdf), accessed May 2008.
3. *US Military Deployment*, US Department of Defense, [siadapp.dmdc.osd.mil/personnel/MILITARY/history/hst0712.pdf](http://siadapp.dmdc.osd.mil/personnel/MILITARY/history/hst0712.pdf), accessed May 2008.
4. Plunkett Research Ltd., [www.plunkettresearch.com/Home/tabid/36/Default.aspx](http://www.plunkettresearch.com/Home/tabid/36/Default.aspx), accessed April 2008.
5. US Bureau of Labor Statistics, [ftp.bls.gov/pub/special.requests/ForeignLabor/industry/naics.txt](http://ftp.bls.gov/pub/special.requests/ForeignLabor/industry/naics.txt), accessed April 2008.
6. Sparks, E., *Military Textiles*, edited by E. Wilusz, CRC Press and Woodhead Publication, Cambridge, England, UK, 2008, pp3-16.
7. Block, E., *Future Trends in Raw Materials Supply*, Gothenburg Convention of EDANA, June 6, 1974.
8. Lee, H. J. and N. Cassill, *Journal of Textile and Apparel, Technology and Management*, Vol. 5, No. 3, Fall 2006, pp1-19.
9. *Sonobond Ultrasonics*, [www.sonobondultrasonics.com/ultra\\_tech.asp](http://www.sonobondultrasonics.com/ultra_tech.asp), accessed May 2008.
10. Wu, X. and G. Shi, *Journal of Physical Chemistry B*, Vol. 10 No. 23, May 2006, pp11247-11252.
11. *AATCC Technical Manual*, Vol. 82, 2007, pp86-90.

## Author

Hoon Joo Lee, North Carolina State University, 2401 Research Dr., Raleigh, NC 27606, USA; phone +1 919 515 1528; fax +1 919 515 3733; [hoonjoo\\_lee@ncsu.edu](mailto:hoonjoo_lee@ncsu.edu).