

Surface roughness and wettability of wool fabrics loaded with silver nanoparticles: Influence of synthesis and application methods

Hossein Barani, Majid Montazer, Alfredo Calvimontes and Victoria Dutschk
Textile Research Journal published online 8 January 2013
DOI: 10.1177/0040517512464290

The online version of this article can be found at:
<http://trj.sagepub.com/content/early/2013/01/07/0040517512464290>

Published by:



<http://www.sagepublications.com>

Additional services and information for *Textile Research Journal* can be found at:

Email Alerts: <http://trj.sagepub.com/cgi/alerts>

Subscriptions: <http://trj.sagepub.com/subscriptions>

Reprints: <http://www.sagepub.com/journalsReprints.nav>

Permissions: <http://www.sagepub.com/journalsPermissions.nav>

>> [OnlineFirst Version of Record](#) - Jan 8, 2013

[What is This?](#)

Surface roughness and wettability of wool fabrics loaded with silver nanoparticles: Influence of synthesis and application methods

Hossein Barani^{1,4}, Majid Montazer², Alfredo Calvimontes³ and Victoria Dutschk⁴

Abstract

Hydrophilization of wool fabrics was performed by silver nanoparticles with different surface charge using three different methods: exhausting, pad-dry-cure and in situ synthesis. Dynamic wetting measurements and surface topography analysis were used to evaluate surface changes on wool fabrics. The wool samples in situ loaded revealed the highest fabric roughness and porosity, while the use of the pad-dry-cure method leads to the lowest fabric porosity, and its roughness values approximately were the same as those for samples loaded with the exhaustion method. The results revealed that loading silver nanoparticles with high surface charges onto wool fabrics via the exhaustion method can significantly improve the hydrophilicity of wool fibre surface. The possible reasons for this improvement are discussed.

Keywords

wool fabric, silver nanoparticles, hydrophilicity, roughness

Wool fibre is a protein fibre composed of keratin and its outer surface is covered by a fatty acid layer. The presence of this layer creates a hydrophobic surface, preventing water drop absorption and sweat venting, which affects the wearing comfort of wool textiles.¹ It is well known that the chemical composition and surface topography² affect the fabric wettability. Surface roughness has different effects on the hydrophobic and hydrophilic surfaces. On hydrophilic surfaces, the wetting time decreases with increasing roughness, while on hydrophobic surfaces, it increases with increasing roughness.³ Several techniques were applied to create hydrophilic wool fibre surface, which can be classified into two major types: decomposing the fatty surface layer^{4–6} and coating the fatty surface layer of wool fibres with hydrophilic materials.^{7–10}

Applying nanoparticles onto fabric surfaces is a versatile method providing multifunctional textile materials. It was reported that applying nanoparticles can improve the substrate wettability.^{8,11,12} Silver nanoparticles commonly applied as antibacterial agents^{13,14} are often used as a modifying substance to improve the fabric wettability,¹² simultaneously providing a wool

fabric with two additional properties, hydrophobicity and antibacterial effect. Owing to the high surface energy of silver nanoparticles, the wettability of a loaded substrate can be increased. However, the presence of a stabilizing agent has an influence on this effect. In general, loading silver nanoparticles onto the fabric structure can be conducted by pad-dry-cure,¹² exhaustion methods,¹⁵ and in situ synthesis as well as loading simultaneously onto fabrics.^{16,17}

¹Department of Carpet, Faculty of Art, University of Birjand, Birjand, Iran

²Textile Engineering Department, Amirkabir University of Technology, Center of Excellence, Hafez Avenue, Tehran, Iran

³Leibniz Institute of Polymer Research Dresden, Germany

⁴Engineering of Fibrous Smart Materials, Faculty of Engineering Technology, University of Twente, Enschede, The Netherlands

Corresponding author:

Victoria Dutschk, Engineering of Fibrous Smart Materials, Faculty of Engineering Technology, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands.

Email: v.dutschk@utwente.de

In the present study, a wool fabric was loaded with colloidal silver nanoparticles at different concentrations of lecithin as a stabilizing agent. Lecithin is a phospholipid,¹⁸ which stabilizes silver nanoparticles in a dispersion. The stability of silver nanoparticles in an aqueous dispersion depends on the lecithin concentration.¹³ Lecithin molecules can easily be absorbed by wool fibre¹⁹ and, therefore, change the permeability of the wool fibre structure.²⁰ Different physico-chemical methods were used to quantify topographic modification effects on nano- and macro-scales as well as the wettability of the wool fabric. It was shown that the loading methods applied and the nanoparticles concentration used have different effects on the fatty layer surface.

Materials and methods

Reagent and wool fabric

All chemical agents used in this study were of analytical grade. Millipore water was used throughout the studies. Silver nitrate (AgNO₃ extra pure, >99.8%) and sodium borohydride (NaBH₄, 99.9%) were purchased from Merck (Germany). Lecithin was provided by Lipoid (Lipoid® S 75, Germany). The standard wool fabric was purchased from wfk Testgewebe (Germany). The structure information of the wool fabric used is summarized in Table 1. The 2D and 3D images of the wool fabric structure and its type of weave are shown in Figure 1.

Table 1. Characteristics of the wool fabric used

Area weight (g/m ²)	Warp density (Count/cm)	Weft density (Count/cm)	Yarn Type of weave	Fibre mean diameter* (µm)
125	21	18	plain 1/1	300/300 19 ± 3

*The mean wool fibre diameter was calculated using 2D microscopic images of 20 samples.

Silver nanoparticles loading methods

Silver nanoparticles were synthesized as described in details elsewhere.^{13,21} The colloidal solution of silver nanoparticles was prepared at various lecithin concentrations (Table 2). Their surface charges were determined with a Zetasizer Nano ZS (Malvern, UK) at 25°C. The synthesized silver nanoparticles were loaded onto wool fabric by three different methods: exhaustion, pad-dry-cure and in situ synthesis. By using exhaustion method, the scoured wool fabric samples were immersed in an aqueous solution containing silver nanoparticles (liquor ratio of 40:1) at 40°C with different lecithin-to-silver ratio as listed in Table 2. The temperature was gradually increased up to 90°C in 25 min. In pad-dry-cure method, the scoured wool fabrics were immersed into the colloidal solution of silver nanoparticles (400 ppm) with different lecithin concentrations for 15 min at room temperature. After that, the soaked wool fabrics were squeezed using a laboratory padder machine to adjust solution take up to 80% wet pickup. The padded samples were dried at 80°C for 20 min, followed by curing at 130°C for 5 min. By the in situ synthesis method, the silver nanoparticles were synthesized in the wool fibre structure. Wool acts as a template for silver nanoparticles. The scoured wool fabric samples were immersed in a silver nitrate solution (400 ppm, liquor ratio of 40:1) with various lecithin-to-silver ratios at room temperature for 1 h.

Table 2. Preparation of colloidal silver nanoparticles with their surface charge

Sample code	[Lecithin]/[Ag]	Ag (ppm)	NaBH ₄ (ppm)	Surface charge (mV)
K ₀	0	400	800	-26.3
K _{0.2}	0.2	400	800	-48.8
K ₁	1	400	800	-49.1
K ₂	2	400	800	-63.1

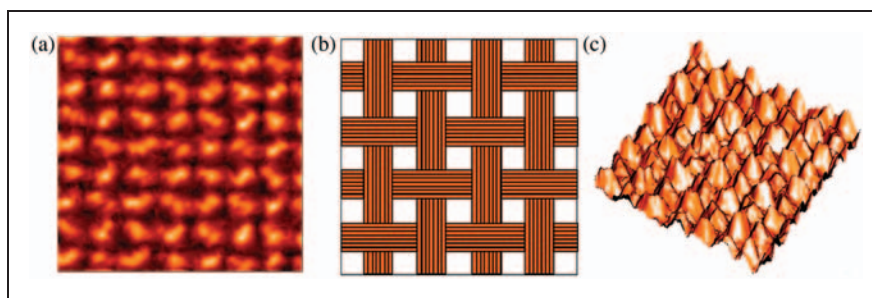


Figure 1. Two- and three-dimensional images of an untreated wool fabric: (a) untreated wool fabric (scan area of 4 mm × 4 mm); (b) type of weave; (c) 3D image of untreated wool fabric (scan area of 4 mm × 4 mm).

After that, the treated sample was immersed in the reducing agent bath (800 ppm, liquor ratio of 40:1) at room temperature for 20 min. Finally, the wool fabric loaded with silver nanoparticles was rinsed and dried in an oven at 80°C for 20 min. The samples loaded were coded according to the method applied as follows: exhaustion method EhK_a, in situ synthesis method ISK_a and pad-dry-cure method PDCK_a; the subscript shows the lecithin-to-silver ratio.

Topography analysis

The surface topography of samples was examined at the nano- and macro-scales. A non-contact stereophotogrammeter TraceIt (Innowep, Germany) was used as an optical imaging instrument to analyze the macro-topography of wool fabric samples. FRT Mark III software (Version 3.8.10) was used to calculate the roughness parameters from images of 4 mm × 4 mm size. Surface roughness parameters such as S_a , S_q , and S_t as well as a hybrid parameters (S_{rl}) and functional parameters (S_{V0}) were obtained from the topographical measurements according to ISO/DIS 25178-2.

The parameter S_a is the arithmetic mean surface roughness²² being the arithmetic average of all distances between Z -value and mean height inside a range of captured area. The parameter S_a is usually used for describing the surface roughness. The parameter S_q is the root mean square surface roughness between the Z -value and the mean surface height. The parameter S_t is the maximum height, between the highest and lowest points in the evaluation area. The parameter S_{rl} is a hybrid parameter which was introduced by Wenzel.²³ The Wenzel roughness factor is defined as the ratio between measured (real) area and projected area. The parameter S_{V0} is a volumetric characteristic to present the free volume available at the textile surfaces through evaluating porosity or filling quantities as a function of depth.²² According to Stout et al.,²⁴ S_{V0} is the valley fluid retention index, a topographical parameter that characterizes the porosity of rough surfaces such as textiles. This is the ratio of the void volume of the unit sampling area at the valley zone over the S_q deviation.

A high-resolution scandisk confocal microscope usurf explorer (NanoFocus, Germany) was used to analyze the nano-topography of the wool fibres surface. The 60 × objective lens was used for measuring field size of 260 μm × 260 μm with a 100 nm vertical resolution. Nano Explorer premium software (Version 4.1) was used to calculate the roughness parameters from images by profiling in lengths of approximately 100 μm. Arithmetic mean roughness parameters (R_a) of wool fibres were calculated from 10 different positions of each sample.

Dynamic contact angle measurement

A contact angle value is an indicator for the wetting behaviour of a liquid droplet on a solid surface. A FibroDAT 1122 device (Fibro system, Sweden) was used for measuring contact angles of water as a function of time on different treated wool fabrics. A drop of 17 μl volume was applied on the surface of wool fabric sample (1 cm × 1 cm) by a minimal pulse stroke which leads to lowest oscillation, measuring details of which were described elsewhere.²⁵ A water droplet on the wool fabric surface was recorded and captured for 8 seconds by 4000 frames with a high-speed video camera. The dynamic contact angle measurements were repeated five times for each sample in a laboratory with controlled temperature and relative humidity of 23 ± 1°C and 50 ± 4%, respectively.

Results and discussion

Influence of the silver nanoparticles loading method on the macro-topography of wool fabrics

Macro-topographical characteristics of wool fabrics treated with colloidal silver nanoparticles by three various methods are presented in Table 3. Loading silver nanoparticles onto the wool fabric increased the surface roughness of all treated wool fabrics. The samples loaded with the in situ method revealed the highest surface roughness parameters S_a , S_q , S_t , S_{rl} (as averages) and S_{V0} . All treatments show a significant roughness increase after treatment.

The wool fabric sample treated with silver colloidal solution without stabilizing agent (EhK₀) using the exhaustion method shows the largest S_t value (maximum height between the highest and lowest points of the surface) compared with that treated with lecithin solutions. This colloidal solution has the lowest stability,^{13,18} easily agglomerated on the wool fabric and cannot diffuse into the wool fibre structure. Then it can be assumed that the silver nanoparticles were only deposited on the yarns surface and did not diffuse into the wool fibre surface. However, EhK₀ shows the lowest developed surface ratio S_{rl} by the exhaustion method, confirming silver nanoparticles agglomeration on the wool fibre surfaces. The samples loaded with the pad-dry-cure and in situ methods without lecithin present the lowest value of S_t and S_{rl} because the uptake of unstable silver nanoparticles was low due to the short immersion time and lead to the lowest roughness parameters. In addition, the presence of lecithin by using in situ method can enhance the uptake of silver ions,²⁶ so the sample without lecithin presents the lowest value of S_t and S_{rl} .

Table 3. Surface roughness and porosity characteristics of wool fabrics loaded with silver nanoparticles

Sample	S_a (μm)	S_q (μm)	S_t (μm)	S_{rl}	S_{V0} ($\mu\text{m}^3/\mu\text{m}^2$)
Untreated	17.7	21.3	122.6	1.1	0.135
EhK ₀	23.2	28.4	163.5	1.072	0.591
EhK _{0.2}	20.4	24.8	152.3	1.125	0.414
EhK ₁	23.3	28.2	156.8	1.154	0.506
EhK ₂	23.5	28.3	154.0	1.126	0.371
ISK ₀	32.9	40.3	246.6	1.142	1.075
ISK _{0.2}	35.2	42.9	272.7	1.152	0.793
ISK ₁	32.7	40.0	264.3	1.142	0.923
ISK ₂	34.2	41.7	268.0	1.148	0.943
PDCK ₀	22.0	26.6	147.2	1.106	0.279
PDCK _{0.2}	23.1	27.9	153.0	1.132	0.272
PDCK ₁	23.3	28.1	152.9	1.128	0.411
PDCK ₂	24.1	29.0	168.8	1.189	0.366

An increase of lecithin concentration in the formulation of silver nanoparticles aqueous dispersion resulted in rougher surface (S_a , S_q , S_t and S_{rl}) of PDCK samples. For EhK and ISK no precise trend for surface roughness was found. The porosity of the S_{V0} of the wool sample, which was loaded by exhaustion and in situ methods, tends to be reduced by increasing lecithin concentration. As S_{V0} characterizes the fabric void spaces, i.e. inter-yarn spaces, with the result that the lecithin molecules and silver nanoparticles were also deposited onto the porous structure of wool fabrics. In addition, the samples prepared with in situ synthesis and pad-dry-cure methods, have the highest and the lowest porosity, respectively (Figure 2). As by in situ synthesis the wool fibre is swollen by absorbing silver ions and, finally, converted into the silver nanoparticles. In woven structures, fibre swelling results in an increase in weave angle and thickness of yarn cross-section due to the wet relaxation.²⁷ Therefore, swelling of fibres leads to larger S_t and, as a consequence, larger S_{V0} values (larger and deeper inter-yarn spaces). However, the fabric was basically squeezed using the pad-dry-cure method and has the lowest porosity value and lower thickness (Figure 3). The height histogram presented in Figure 3 helps to compare the thickness between the fabrics treated by the three different methods.

Macro-topography of the wool fabric is altered dependent on the loading methods applied. A schematic presentation of changes in the wool fabric cross-section after loading silver nanoparticles is schematically shown in Figure 4. According to the value of S_t for each sample loaded, it can be confirmed that the sample loaded in the pad-dry-cure method is compressed, while the sample prepared in situ synthesis causes vertical swelling.

Influence of the silver nanoparticles loading method on the nano-topography of wool fibres

Wool fibre is a natural fibre which intrinsically has a rough surface. A 3D reconstructed image of wool fibre presented in Figure 5 shows that it has an average roughness value of 138 nm. This is in agreement with other data reported,²⁸ which were collected using 3D scanning electron microscopy. However, this value depends on the wool fibre type as well as applied characterization methods.²⁹

Profiled arithmetical mean roughness (R_a) of all samples is presented in Figure 6. Loading silver nanoparticles at various lecithin concentrations by exhaustion and pad-dry-cure methods lead to increasing the average nano-roughness of wool fibres. The highest concentration of lecithin in the colloidal solution can cause a higher affinity to wool fibre due to higher surface charges.³⁰ Loading at the highest lecithin concentration by exhaustion and pad-dry-cure methods causes the higher fibre roughness, which confirms the higher uptake of silver nanoparticles by the methods mentioned at the nanometer scale. However, in case of the in situ method, the wool fibre roughness decreased with lecithin presence. The differences observed between roughness parameters at the nano- and macro-topographical scales are discussed in Section 4.

Wetting dynamics results

The wettability results are presented in Figure 7. The contact angle value is reported at 0.2 s after applying a water droplet on the fabric surface in order to reduce the effect of drop oscillation on the contact

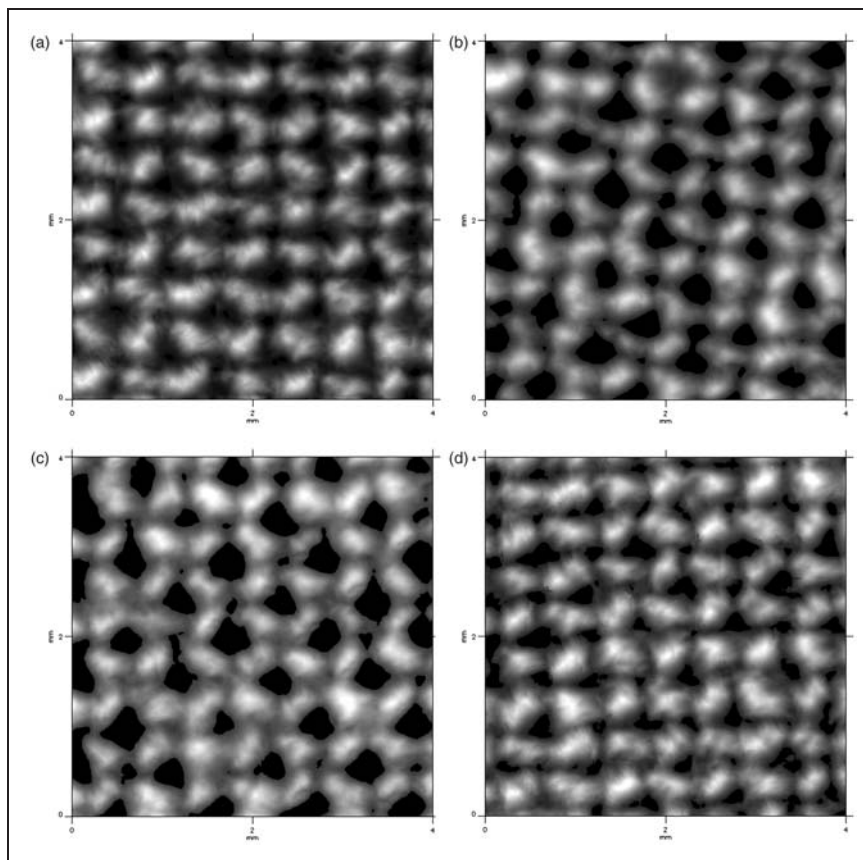


Figure 2. Images of wool fabric loaded with silver nanoparticles without lecithin using different methods: (a) untreated; (b) EhK₀; (c) ISK₀; and (d) PDCK₀.

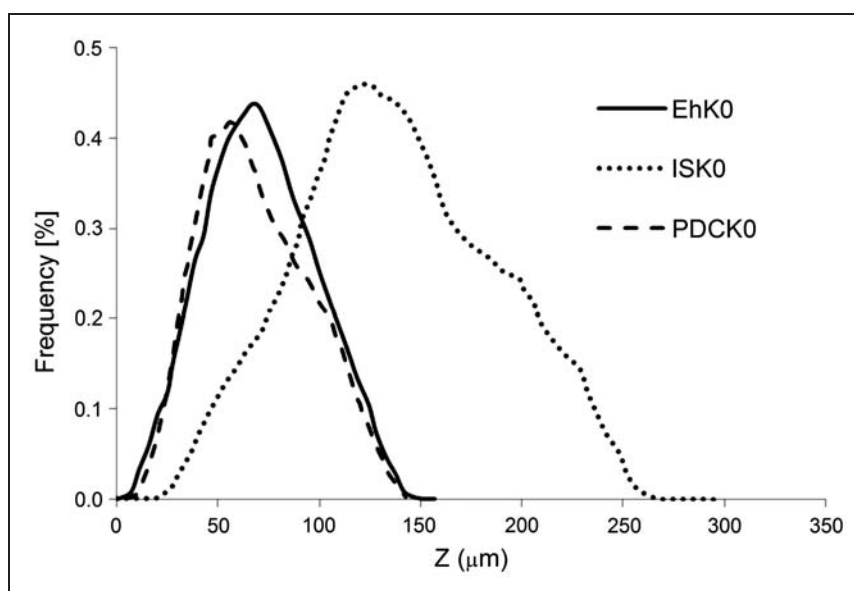


Figure 3. Heights histogram of wool samples treated with silver nanoparticles using different loading methods.

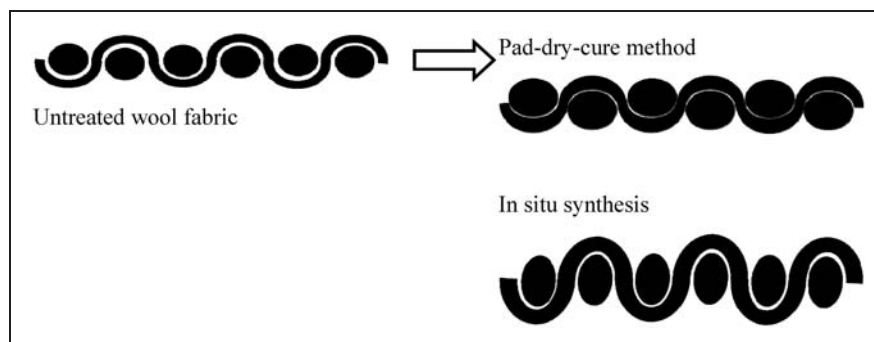


Figure 4. Schematic representation of a cross-section of the wool fabric loaded.

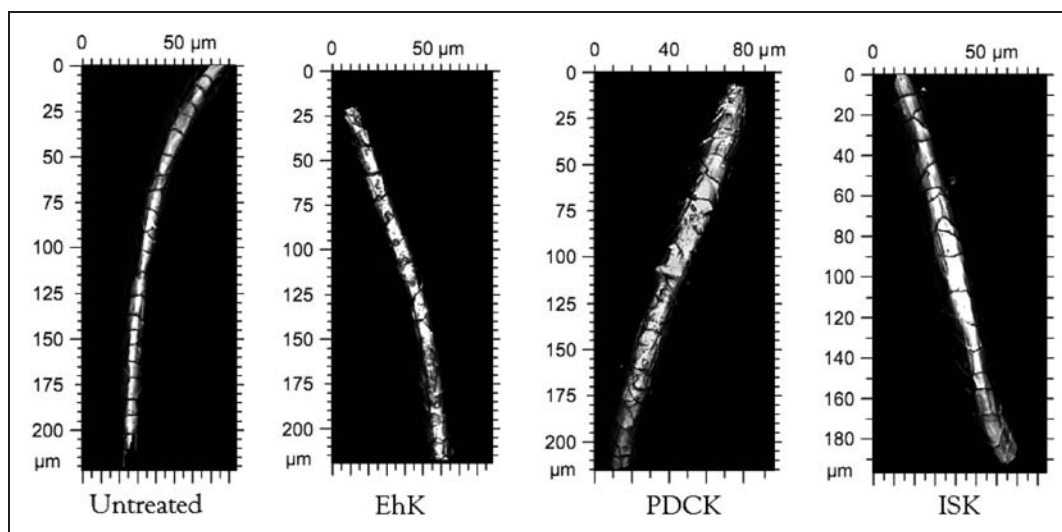


Figure 5. Optical image of the untreated wool fibre and treated with different methods.

angle measured. The spreading rates of water droplets on wool fabrics were calculated from the slope of the linear part of the drop base curve versus time. Contact angles for EhK₁ and EhK₂ were measured as 24° and 12°, respectively. The higher porosity of EhK₁ compared with that of EhK₂ leads to a higher spreading rate. No spreading was observed on untreated samples, K₀ and K_{0,2}.

Loading silver nanoparticles by exhaustion method with a higher lecithin concentration (samples EhK₁ and EhK₂) results in a hydrophilic surface in terms of the water contact angle and spreading rate.

The use of the pad-dry-cure method leads to a slight surface hydrophilization. The in situ method used shows a different trend. In this case, silver nanoparticles were synthesized inside wool fibres and had little effect on the fatty layer of the wool fibre surface. Loading silver nanoparticles onto wool fibres, measured as an increase of S_a and S_g , cannot change the native hydrophobicity of wool surface. However, an increase of S_r ,

i.e. yarn amplitude, leads to a decrease of the amount of wool contact points with a water droplet resulting in a much hydrophobic fabric.³ The relationship between the water contact angles measured and fibre roughness is shown in Figure 8. Creating roughness on the hydrophobic substrate of micrometre dimensions can enhance hydrophobicity.³⁰ An increase in fibre roughness by the in situ method leads to an increase of the water contact angle, because the fatty layer was not altered and only its roughness was increased; at the same time, an increase of yarns amplitude S_r (Table 3) seems to control the hydrophobic character of the fabric. On the other hand, in the use of the pad-dry-cure method, an increase of fibre roughness slightly reduces their hydrophobicity. However, when using the in situ method, the yarn amplitude seems to control the hydrophobic character.

The fabric loaded by the exhaustion method shows a completely different trend. The treatment increases surface smoothness and opens the spaces between yarns

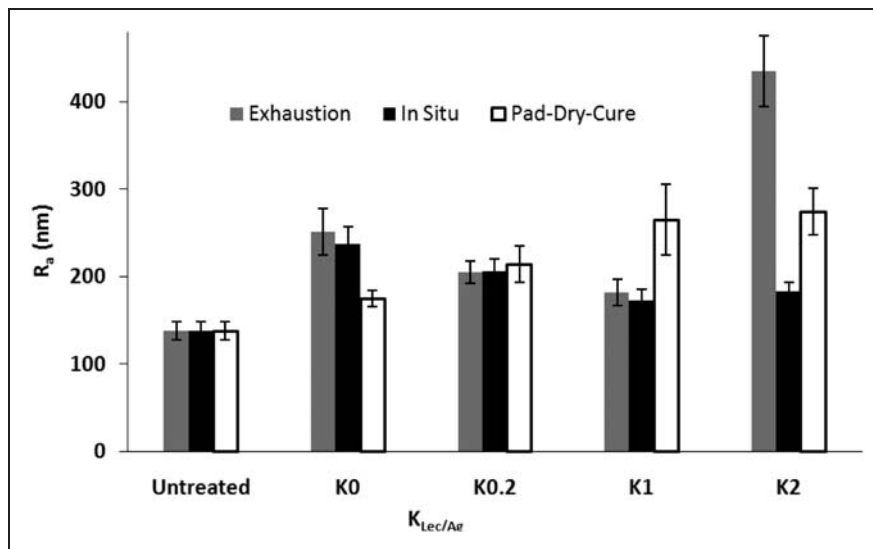


Figure 6. Roughness characteristics of the wool fibres loaded with silver nanoparticles using different methods. The R_a values presented are average values of 10 measurements.

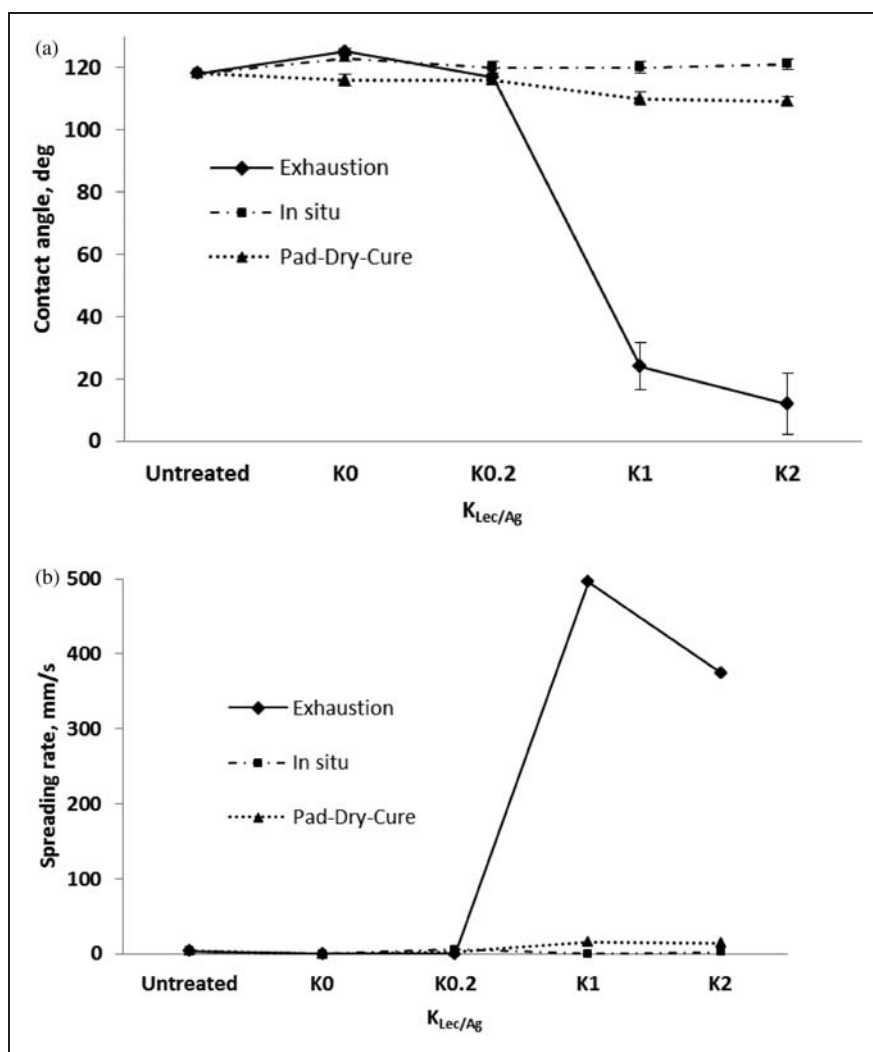


Figure 7. Effects of various modification methods and lecithin concentrations on (a) contact angle and (b) spreading rate.

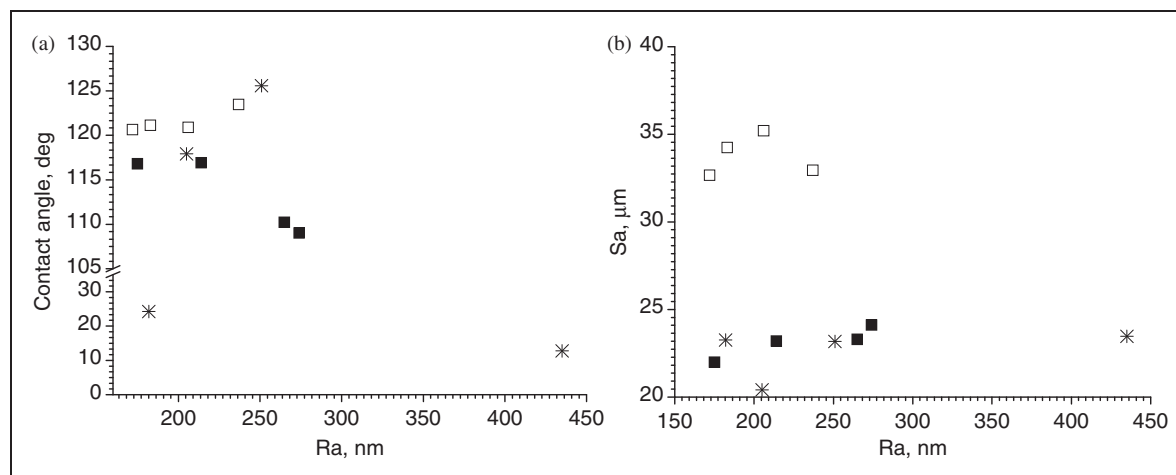


Figure 8. Correlation between water contact angle and wool fibre roughness R_a (a) and arithmetic mean surface roughness S_a and wool fibre roughness R_a (b) for different application method: (*) exhaustion method; (■) pad-dry-cure method; and (□) in situ synthesis method.

(Figure 2) maintaining the yarn amplitudes almost unchanged. This effect leads to water spreading and penetrating into the fabric structure (Figure 7).

Conclusions

Loading stabilized silver nanoparticles on wool surface using exhaustion method creates a surface which is more hydrophilic than the untreated one due to opening inter-yarn spaces despite to an increase of the fibres roughness. By concentrations equal or smaller than 1 [Lecithin]/[Ag], lecithin prevents agglomeration and penetration of nanoparticles into nanopores of the fibres. At larger lecithin concentrations, nanoparticles agglomerate and the fibre nano-roughness increases.

The wool samples loaded by the in situ method revealed the highest value for roughness and porosity and the smoothest fibre surfaces. Topographical changes on both length scales, nano and macro, compensate for each other, however, with a predominance of fabric roughness in controlling wetting. For this reason, a slight increase of hydrophobicity is observed.

The use of different methods to load silver nanoparticles revealed different effects on the contact angle. The sample loaded with silver nanoparticles using the pad-dry-cure method shows a smaller water contact angle on the wool fabric by covering the fatty surface layer with silver nanoparticles; the presence of lecithin enhances this effect. There is a stronger electrostatic interaction between stabilized silver nanoparticles with lecithin and wool fabric, due to their higher zeta potential. For the loaded sample, a reverse trend was observed by using in situ synthesis method. The water contact angle slightly increased due to silver nanoparticles loaded. Loading silver nanoparticles into the wool

fibre structure cannot alter the fatty surface layer of wool fibres and only increases their roughness. This higher roughness leads to a more hydrophobic surface. Loading stabilized silver nanoparticles using the exhaustion method can alter the surface of wool fibres and create a more hydrophilic surface due to three combined effects: (i) smoothening of fibres by filling the gaps with silver nanoparticles; (ii) opening inter-yarn spaces; and (iii) decreasing or maintaining the yarn amplitudes. Lecithin prevent nanoparticles agglomeration and their penetration into the fibres nano-pores.

Funding

This research was supported by the University of Twente (Netherlands) and Leibniz Institute of Polymer Research Dresden (Germany).

References

- Li Y. The science of clothing comfort. *Textile Prog* 2001; 31: 1–135.
- Hasan MMB, Calvimontes A, Synytska A and Dutschk V. Effects of topographic structure on wettability of differently woven fabrics. *Textile Res J* 2008; 78: 996–1003.
- Calvimontes A, Dutschk V and Stamm M. Advances in topographic characterization of textile materials. *Textile Res J* 2010; 80: 1004–1015.
- Molina R, Jovančić P, Jocić D, Bertran E and Erra P. Surface characterization of keratin fibres treated by water vapour plasma. *Surf Interface Anal* 2003; 35: 128–135.
- Morent R, De Geyter N, Verschuren J, De Clerck K, Kiekens P and Leys C. Non-thermal plasma treatment of textiles. *Surf Coatings Technol* 2008; 202: 3427–3449.
- Montazer M, Dadashian F, Hemmatinejad N and Farhoudi K. Treatment of wool with laccase and dyeing with madder. *Appl Biochem Biotechnol* 2009; 158: 685–693.

7. Malkov GS and Fisher ER. Pulsed plasma enhanced chemical vapor deposition of poly(allyl alcohol) onto natural fibers. *Plasma Process Polym* 2010; 7: 695–707.
8. Chen D, Tan L, Liu H, Hu J, Li Y and Tang F. Fabricating superhydrophilic wool fabrics. *Langmuir* 2009; 26: 4675–4679.
9. Ristić N, Jovančić P, Canal C and Jocić D. Influence of corona discharge and chitosan surface treatment on dyeing properties of wool. *J Appl Polym Sci* 2010; 117: 2487–2496.
10. Meade SJ, Caldwell JP, Hancock AJ, Coyle K, Dyer JM and Bryson WG. Covalent modification of the wool fiber surface: the attachment and durability of model surface treatments. *Textile Res J* 2008; 78: 1087–1097.
11. Montazer M, Pakdel E and Moghadam MB. The role of nano colloid of TiO₂ and butane tetra carboxylic acid on the alkali solubility and hydrophilicity of proteinous fibers. *Colloids Surf A Physicochem Eng Aspects* 2011; 375: 1–11.
12. Dastjerdi R, Montazer M and Shahsavan S. A novel technique for producing durable multifunctional textiles using nanocomposite coating. *Colloids Surf B Biointerfaces* 2010; 81: 32–41.
13. Barani H, Montazer M, Toliyat T and Samadi N. Synthesis of Ag-liposome nano composites. *J Liposome Res* 2010; 20: 323–329.
14. Tang B, Wang J, Xu S, et al. Application of anisotropic silver nanoparticles: Multifunctionalization of wool fabric. *J Colloid Interface Sci* 2011; 356: 513–518.
15. King DG and Pierlot AP. Absorption of nanoparticles by wool. *Coloration Technol* 2009; 125: 111–116.
16. El-Shishtawy RM, Asiri AM, Abdelwahed NAM and Al-Otaibi MM. In situ production of silver nanoparticle on cotton fabric and its antimicrobial evaluation. *Cellulose* 2011; 18: 75–82.
17. Dong Q, Su H and Zhang D. In situ depositing silver nanoclusters on silk fibroin fibers supports by a novel biotemplate redox technique at room temperature. *J Phys Chem B* 2005; 109: 17429–17434.
18. Barani H and Montazer M. A review on applications of liposomes in textile processing. *J Liposome Res* 2008; 18: 249–262.
19. Barani H and Maleki H. Plasma and ultrasonic process in dyeing of wool fibers with madder in presence of lecithin. *J Dispersion Sci Technol* 2011; 32(8): 1191–1199.
20. Baptista ALF, Coutinho PJG, Oliveira MECDR and Gomes JINR. Lipid interaction with textile fibres in dyeing conditions. *Prog Colloid Polym Sci* 2004; 123: 88–93.
21. Barani H, Montazer M, Samadi N and Toliyat T. Nano silver entrapped in phospholipids membrane: Synthesis, characteristics and antibacterial kinetics. *Mol Membrane Biol* 2011; 28: 206–215.
22. Calvimontes A, Grundke K and Müller A. Volumetrical characterization of sheet molding compounds. *Materials* 2010; 3: 5083–5096.
23. Wenzel RN. Surface roughness and contact angle. *J Phys Colloid Chem* 1949; 53: 1466–1467.
24. Stout KJ, Sullivan PJ, Dong WP, et al. The development of methods for the characterization of roughness on three dimensions. Publication number EUR 15178 EN, Commission of the European Communities, Luxembourg, 1994.
25. Dutschk V, Sabbatovskiy KG, Stolz M, Grundke K and Rudoy VM. Unusual wetting dynamics of aqueous surfactant solutions on polymer surfaces. *J Colloid Interface Sci* 2003; 267: 456–462.
26. Barani H, Montazer M, Toliyat T and Samadi N. In situ synthesis of nano silver/lecithin on wool: Enhancing nanoparticles diffusion. *Colloids Surf B Biointerfaces* 2012; 92: 9–15.
27. Carr CM. *Chemistry of the Textiles Industry*. New York: Springer-Verlag.
28. Bahi A, Jones JT, Carr CM, Ulijn RV and Shao J. Surface characterization of chemically modified wool. *Textile Res J* 2007; 77: 937–945.
29. Wortmann F-J and Phan K-H. Cuticle scale heights of wool and specialty fibers and their changes due to textile processing. *Textile Res J* 1999; 69: 139–144.
30. Jachowicz J, Garcia M and Wis-Surel G. Relationship between triboelectric charging and surface modification of human hair: polymeric versus monomeric long alkyl chitin quaternary ammonium salts. *Textile Res J* 1987; 57: 543–548.