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Application of Silver Nanoparticles to Industrial Sewing Threads: Effects on Physico-functional Properties & Seam Efficiency

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Abstract: In this study, the role and impact of silver nanoparticles on industrial sewing threads have been investigated. Study of nanocoating on industrial sewing threads may be useful especially in the areas where skin comes in contact with the garments where anti-bacterial properties may be very useful. Silver particles are considered to have excellent anti bacterial properties. To understand the impact on sewability, investigation was focused to changes at the structural level, changes in physical and surface properties, tensile properties and anti-microbial properties of the nanotreated sewing threads. The structure and morphology of the silver nanoparticles on the sewing threads was observed by scanning electron microscopy (SEM) and quantitatively confirmed by fourier transform infrared spectroscopy (FT-IR). A number of experimental methods and mathematical formulae were used to test individual threads. Custom designed fixtures were used for the study. All the results have been statistically analyzed and found to be significant. The effect of silver nanoparticles on physical properties, functional properties and seam efficiency was illustrated. The difference of the impact of silver nanoparticles on cotton and polyester sewing threads has been compared. It was found that silver nanotreatment leads to a significant reduction of tensile strength. The warp-way seam strength increased where as weft-way seam strength decreased due to damage of yarn. Deformation properties of the threads are not influenced significantly by nanotreatment. The nanotreatment of threads improves its frictional properties significantly. The threads also acquire effective anti-microbial properties with silver nanotreatment. Study of the impact of nanotreatment on the properties of cotton and polyester samples showed a bigger impact on cotton samples than polyester samples. The effect was durable even after several laundering treatments.

Keywords: Sewing threads, Silver nanoparticles, SEM, FTIR, Antimicrobial property, Seam efficiency

Introduction

Sewing thread is an important component of stitching. Through technological development, the sewing threads have undergone various advancements and refinements. Workwear garments must be constructed from durable fabrics with suitable seams and strong sewing thread to withstand heavy usage and laundering. More importantly, an antimicrobial property is highly recommended in such threads in seams, which come in direct skin contact of the wearer. Seam is defined as a joint between two pieces of fabric or it is the application of a series of stitches or stitch type to one or several thickness of material. It was assumed that ultimate seam failure results from thread rupture rather than fabric breakage or excessive opening of seams. The ratio of seam strength: fabric strength expressed as a percentage is known as the seam efficiency, and it has been found that in practice it seldom exceeds 85-90 % [1,2].

Silver nanoparticles are of great interest because of the unique properties (e.g., size and shape dependent optical, electrical, and magnetic properties), which can be incorporated into antimicrobial applications, biosensor materials, composite fibers, cryogenic superconducting materials, cosmetic products, and electronic components. The silver nanoparticles play a crucial role in inhibiting bacterial growth in aqueous and solid media. The effect of nano treatment on other physical and chemical properties of textiles is hardly found in the literatures [3]. Therefore, a need is felt to conduct studies on applications of such nanoparticles to commonly used industrial sewing threads from cotton and polyester.

Industrial sewing techniques impose extreme demands on the threads involved in the process. The sewability of the threads have a profound effect on seam quality and also influences the cost of production. The thread must be capable of withstanding various kinetic and lateral movements during the sewing process and hence tensile strength or breaking strength becomes an essential property of a thread used in sewing. While sewing at high speeds, the needle thread is subjected to repeated tensile stresses and comes under the influence of heat, bending, pressures, torsion and wearing. The stresses generated have a negative impact on the processing and functional characteristics of the thread. There is significant reduction in the thread strength after sewing due to the dynamic and thermal loading of the thread and is influenced by the thread frictional properties, thread tensioning during sewing, needle size, stitch length and number of fabric layers in the seam. The thread need to possess adequate strength and elongation in order to perform satisfactorily during sewing and in seam [4-7].

The main objective of this study is the application of silver

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*Corresponding author: rajesh.mishra@tul.cz nanoparticles to cotton and polyester industrial sewing threads, characterization of its effect on various physical, functional properties as well as seam efficiency. In this work, attempts are made to study the effect of silver nanotreatment on linear density, flexural rigidity and frictional properties of sewing threads. The seam efficiency of the nanotreated industrial sewing threads was studied. Also, a study of the impact of silver nanoparticles on cotton and polyester sewing threads was conducted. All results were statistically analyzed and found to be significant. An application area may be to use nano treated threads on garments that come in direct contact with human skin, to incorporate better anti bacterial properties. Also, the study can feed into providing data for developing nanotreated threads that are capable of withstanding several dynamic loads and lateral deformations during the sewing process.

Experimental

Materials

Industrial sewing threads with different finenesses were selected for the study. Commercially available cotton and polyester sewing threads were used as given in the Table 1.

Table 1. List of sewing thread samples and their linear densities

Sample no.	Linear density (Tex)	Composition
Sample 1	125	Cotton
Sample 2	100	Cotton
Sample 3	50	Cotton
Sample 4	40	Cotton
Sample 5	30	Cotton
Sample 6	25	Cotton
Sample 7	20	Polyester
Sample 8	10	Polyester
Sample 9	8	Polyester

Methods

Various methods were used for fiber analysis, thread fineness, characterization with physical and functional tests. For fiber analysis, microscopic examination of both longitudinal and cross sectional samples was conducted. Solubility test was also conducted to analyze the fiber. The samples were immersed in boiling distilled water for a period of five minutes to remove pre-existing finishes on the thread. This process was repeated twice to ensure existing finishing was completely removed.

Synthesis and Application of Silver Nanoparticles

For the synthesis of silver nanoparticles, silver nitrate solution (from 1,0 mM to 6,0 mM) and 8 % (w/w) sodium dodecyl sulphate (SDS) were used as a metal salt precursor and a stabilizing agent, respectively. Sodium borohydrate with a concentrate ranging from 2.0 mM to 12 mM was used as reducing agent. Citrate of sodium was also used as stabilizing agent at room temperature. The transparent colorless solution was converted to the characteristic pale yellow and pale red color, when citrate of sodium was used as stabilizing agent. The occurrence of color indicated the formation of silver nanoparticles. The silver nanoparticles were purified by centrifugation. To remove the excess silver ions, the silver colloids were washed at least three times with deionized water under nitrogen stream. Dried nanosize silver powder was obtained by freeze-drying. The silver nanoparticle powder in the freeze-drying cuvette was re-suspended in deionized water; the suspension was homogenized with ultrasonic cleaning container. Using UV-visible spectroscopy and TEM, it was found that the particles range in size from 8 to 50 nm with mean diameter 24 nm. The soaking and drying method was used to apply the nanoparticles to the sewing threads [8,9]. The samples were immersed for 5 hours in the solution containing silver nanoparticles. Then, the threads were dried in oven at 40 °C.

Characterization of Nanotreated Samples

The fourier transform infrared spectroscopy (FTIR) and scanning electron microscope (SEM) were used for characterization of nanotreated samples. The treated sewing threads were tested for mechanical properties. The samples were conditioned at 65±2 % relative humidity and 27±2 °C, before testing them. The thread samples treated with the silver nanoparticles were mounted on a specimen stub with a double-sided adhesive tape and coated with gold in a sputter coater and examined with a scanning electron microscope of Hitachi VP-SEM S-3400N model. The scanning electron microscope (SEM) tests were done at a magnification of 5.00-10.00 μm. The make/model of fourier transform infrared spectroscopy used was Perkin Elmer RXI FTIR. The ground samples were studied as potassium bromide (KBr) pellets as it does not influence the IR spectrum in the wave number range 4000 till 400 cm^{-1}. A few milligrams of sample was mixed with about 200 mg of KBr powder. The mixture was then pressed into a tablet, which was used in the analysis. The fingerprints were obtained at the spectral range of 4000-400 cm^{-1} and have a resolution of 0.9 to 1 cm.

Functional Properties of Nanotreated Samples

Müller-Hinton agar was used for anti-bacterial functional test, Müller-Hinton agar is an microbiological growth medium that is commonly used for antibiotic susceptibility testing. It is also used to isolate and maintain Neisseria and Moraxella species. It typically contains (w/v) 30.0 % beef infusion, 1.75 % casein hydrolysate, 0.15 % starch, 1.7 % agar and pH adjusted to neutral at 25 °C. Müeller-Hinton broth (HIMEDIA) was prepared from a commercially available dehydrated base according to the manufacturer's instructions. Medium is prepared and autoclaved at 121 °C for 15 mins. Immediately after autoclaving, it is allowed to cool. In the sterile 5 m*l* of Müeller-Hinton broth test tubes containing uncoated thread and silver nanotreated thread individually, 50 μl of E.coil culture (10-6 cells) was inoculated. It is mixed well and incubated in shaker at room temperature for 16-24 hours. After 24 hours, the growth of culture was determined by turbidity and also read at 600 nm.

Antimicrobial Property and Fastness After Laundering

By virtue of its small size and high surface energy, nanoparticles are bound to the yarn surface by Van der Waals forces. It is correlated to the adhesion of nanoparticles to the fibers [10]. The antibacterial properties of both untreated and treated cotton sewing threads before and after washing were quantitatively evaluated against the *Escherichia coli* (*E.coli*). The reduction in number of bacteria was calculated using the following equation [11]:

$$R(\%) = \frac{B-A}{B} \times 100 \tag{1}$$

where A is the number of bacteria colonies from the treated specimen after inoculation over a 24 hours contact period and B is the number of bacteria colonies from untreated control specimen after inoculation at 0 contact time. Antimicrobial property after 5, 10, 15 & 20 washing cycles was evaluated as per ASTM D2096-11 [12].

Mechanical Properties of Nanotreated Samples

The tensile properties were tested on Instron 3360 series dual column tabletop Universal testing system. The gauge length used was 250 mm at the speed of 250 mm/min. The test was conducted as per ISO 2061 standard. Yarn to metal friction was measured by Capstan method. Ring-loop test was conducted to study the flexural rigidity and effect on bending properties of the threads, the formation of loop and the size of the loop are dependent on the rigidity of the thread. The loop of the threads was maintained at 1.6 cm circumference (L). It was loaded with a rider weight. The difference of the initial and final diameter of the loop gave the values of deflection (d). The following formula was used to calculate the bending rigidity [13]:

$$G = KWL^2 \mathrm{Cos}\theta / \mathrm{Tan}\theta \ \mathrm{mN.mm^2} \tag{2}$$

Where K: 0.0047; W: Weight of the rider; L (Circumference): $2\pi r$; θ: 493 *(d/L)

The capstan method was used to calculate the frictional property of the thread. In this method, a tube with smooth surface and a circumference of 1.6 cm is taken. The thread is pulled over it, one end being connected to a constant weight (T_2) and the other to a container to which weight is added until the thread slips. Once the thread slips ever-so-slightly from its position, addition of weight is stopped and the weight of the container is noted as T_1 [14,15]. The arrangement is shown in Figure 1.

The co-efficient of friction is calculated using the formula:

$$\mu = 0.733 * \log (T_2/T_1) \tag{3}$$

Where T_1 is weight of the container after loading, T_2 is Constant weight

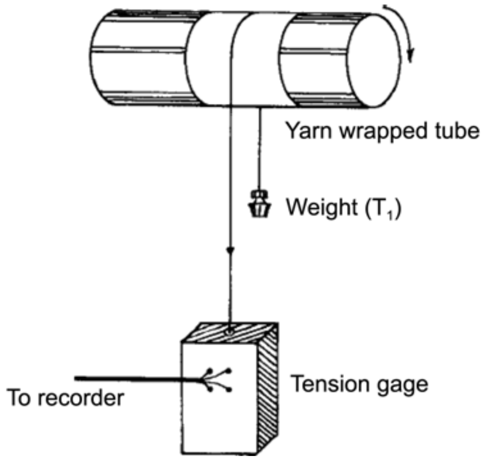

Figure 1. Measurement of friction co-efficient using capstan method [15].

Seam Efficiency of Nanotreated Samples

The seam efficiency of fabrics was measured using Instron 3360 Series Dual Column Tabletop Universal Testing Systems. The test was conducted as per ISO13935-2:1999 (Grab Test). Four fabric samples were selected to suit the thread fineness. Appropriate needles were also selected to prepare the samples. Samples of size 20×10 cm with 10 mm allowance were measured and stitched. Five samples each in warp and weft directions were prepared. Sewing was done on the industrial sewing machine, Brother Straight Stitch UBT (S7200B-403) Auto Lift, under sewing conditions that is commercially adapted by apparel manufacturers. All samples were sewn by single needle lockstitch (ISO 301) in both warp and weft directions. The seam efficiency was tested as per ISO13935-2:1999 (Grab Test).

Results and Discussion

Various evaluation techniques were used for measurement of physical and functional properties of sewing threads both before and after nanotreatment. The average of fifteen measurements for each sample was taken for all the properties. The data were statistically analyzed using data analysis software ORIGIN LAB (origin pro 8). One sample t-test was used to statistically analyze the results. The overall accuracy of the measurements of the sewing thread properties of before and after nanotreatment was found to be better than 2 %, repeatability - 0.5 % and reproducibility - 0.8 %.

Deposition of Silver Nanoparticles on Samples

The structure and morphology of the silver nanoparticles on the threads were clearly visible in scanning electron microscope (SEM) images. The deposition of silver nanoparticles on the sewing threads is shown in the Figures 2, 3.

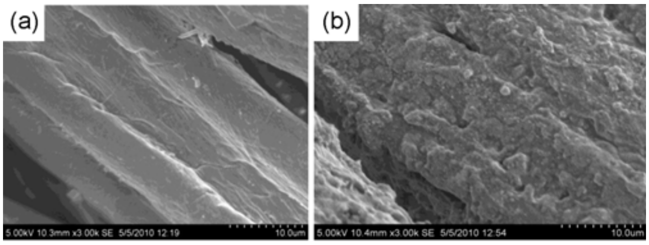

Figure 2. SEM image of nanotreated cotton sewing thread (a) before nanotreatment and (b) after nanotreatment (Sample 3).

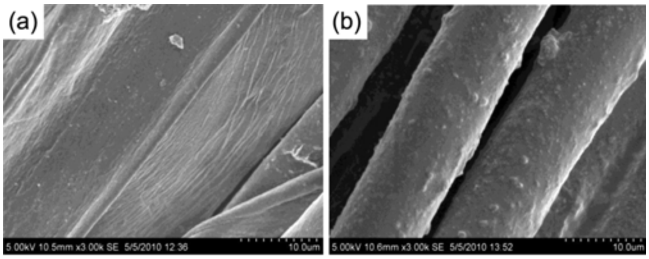

Figure 3. SEM image of nanotreated polyester sewing thread (a) before nanotreatment and (b) after nanotreatment.

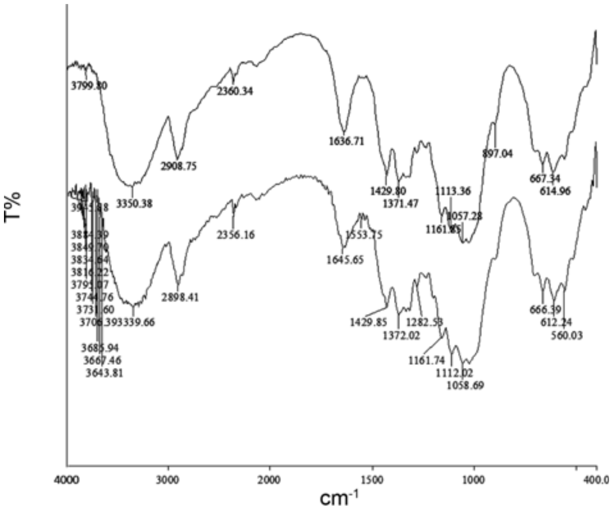

Figure 4. FTIR comparison of coarse cotton sewing thread before and after nanotreatment.

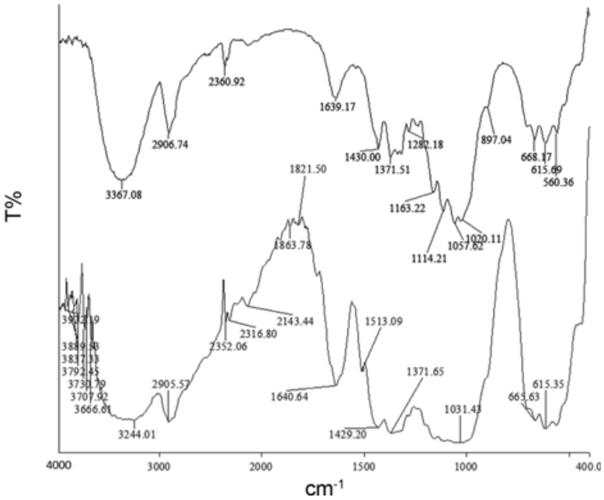

Figure 5. FTIR comparison of finer cotton sewing thread before and after nanotreatment.

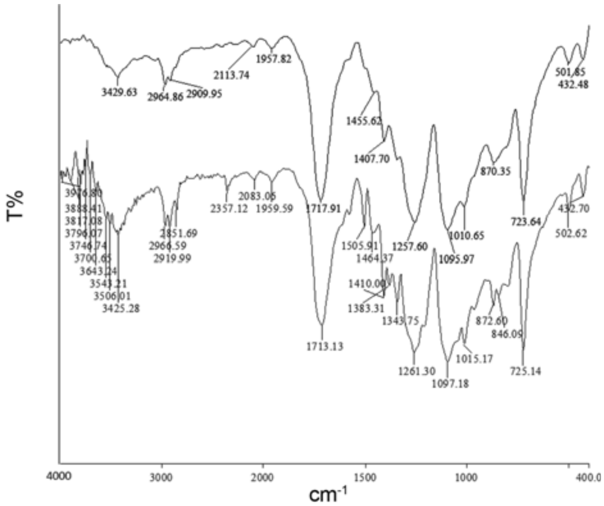

Figure 6. FTIR comparison of coarse polyester sewing thread before and after nanotreatment.

The application of silver nanoparticles on cotton and polyester industrial sewing threads was quantitatively confirmed by fourier transform infrared spectroscopy (FTIR) graphs. The Figures 4-7 shows the comparison of sewing threads before treatment (shown in black) and after treatment (shown in grey) with silver nanoparticles.

IR spectrum of the silver nanotreated cotton and polyester thread show peaks in the range of 3300-3448 cm^{-1} which corresponds to moisture, doublet at 2918 cm^{-1} corresponds to the aldehyde -CH stretch, -CH$_3$ group, 1800-1742 cm^{-1} corresponds to aldehyde moiety, 1630-1647 cm^{-1} corresponds to =C=O group present, sharp absorptions at ~1600, 1550, 1512, 1461, 1429 cm^{-1} corresponds to benzene rings. Absorption in 1400 cm^{-1} corresponds to -CH in plane vibrations of aldehyde. 1029, 1230 cm^{-1} were due to the phenolic ether linkage. The deposition of the nanoparticles on the threads was thus confirmed through scanning electron microscope (SEM) and fourier transform infrared spectroscopy (FTIR).

Effect of Nanotreatment on Tensile Strength and Seam Efficiency of Sewing Thread

Experiments to study the tensile strength of samples before and after nanotreatment were conducted. If an external force is applied to a material, it is balanced by internal stresses

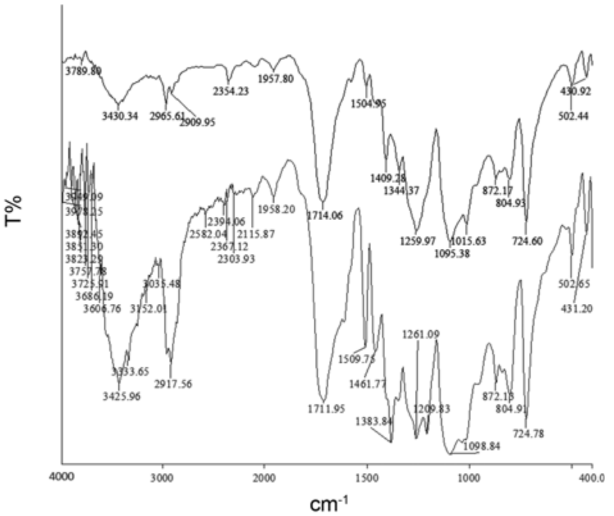

Figure 7. FTIR comparison of finer polyester sewing thread before and after nanotreatment.

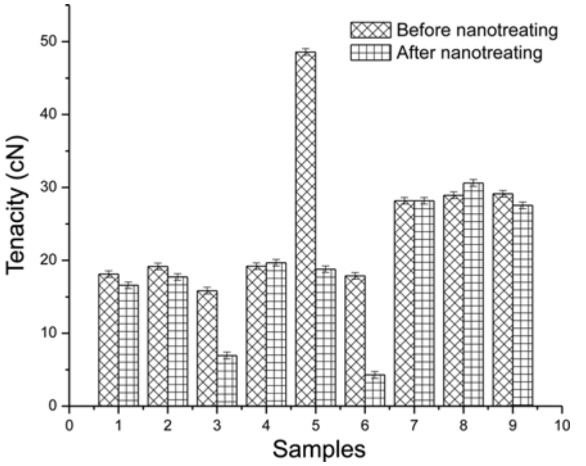

Figure 8. Comparison of tenacity before and after nanotreatment of samples.

developed in the molecular structure of the material. In high speed sewing machines the external force applied on the needle thread is as high as 200 gf. In order to withstand this force during sewing, a thread must possess adequate strength and elasticity. Since different materials have different molecular structures, their behavior in response to this force will be different. The tensile strength and elongation of sewing thread must be adequate for good sewing performance and seam strength. The elongation of a thread determines the effectiveness of the tensile force acting on the thread. Highly extensible thread is generally required only for extensible knitwear garments. From the Figure 8, it is evident that there was a decrease of tensile strength in most of the samples (1, 2, 3, 5, 6 & 9). The decrease of strength may be attributed to the increased absorption of silver nanoparticles by finer thread samples (shown in Figure 2, 5) and related lower level of inter-fiber friction. The increased absorption of silver nanoparticles on finer cotton sewing thread was confirmed by the FTIR and SEM images. Figure 5 shows the FTIR spectra of nanotreated finer cotton sewing thread containing silver nanoparicles. The characteristic peaks of cotton due to cellulose macromolecules which appear at 3300, 3448 cm^{-1} (O-H stretching), 2918 cm^{-1} (C-H stretching), sharp absorptions at 1600, 1550, 1512, 1461, 1429 cm^{-1}, 1400 cm^{-1} (C-H wagging), and 1029, 1230 cm^{-1} (C-O stretching) have become broad, shifted and with strong intensity for silver nanotreated cotton sewing thread. This result indicates binding of silver nanoperticles with -O- in cellulose macromolecule. On the other hand, the spectra of silver nanocoated cotton sewing thread doesn't reveal new peaks different from the case of blank sample, which means that no chemical reaction on cellulose takes place during the treatment of silver nanoparticles. The morphological changes of cotton thread caused by deposition of silver nanoparticles were followed by SEM. SEM images before and after silver nanotreatment of cotton sewing thread are shown in Figure 2(a), (b). Significant differences are clear between these before and after silver nanotreated cotton sewing thread; before nanotreatment, the thread has a smooth surface and is uniform, whereas after nanotreatment there is a significant roughness on the surface of the thread samples. It was determined by weighing that finer threads had a higher add-on of nano particles as compared to coarser threads. The initial modulus is one of the important properties in case of sewing thread. However initial modulus in tenacity elongation curve is not only measure of sewing seam quality. On testing the initial modulus, higher absorption rate of nanoparticles has resulted in higher modulus value due to reduced elongation of threads after nanotreatment.

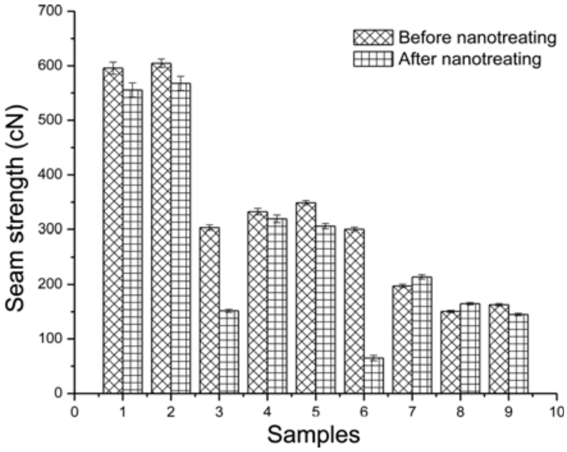

Figure 9. Seam strength before and after nanotreatment of samples.

The variations in seam strength before and after nanotreatment are shown in Figure 9. After nanotreatment, it was found that seam strength has increased in most cases where as for sample 8 & 9 it has decreased. This is attributed to

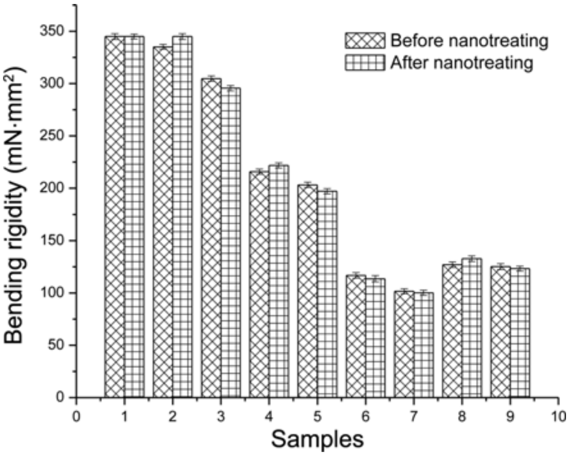

Figure 10. Bending rigidity before and after nanotreatment of samples.

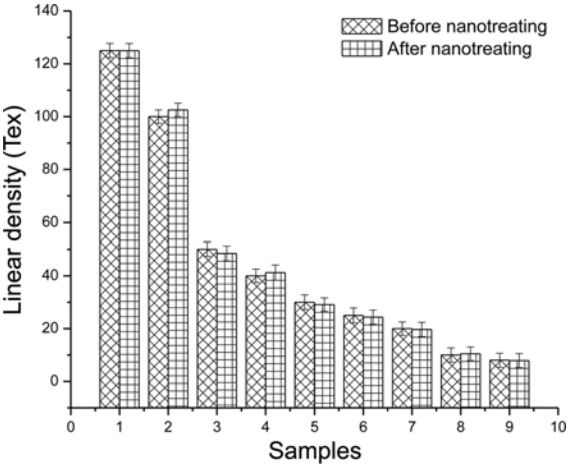

Figure 11. Linear density before and after nanotreating of samples.

higher level of frictional restraint between fabric and the nanotreated sewing thread at the stitching points. The correlations between the tensile strength and seam strength of the sewing thread have been influenced by the strength of the fabric (which is not the prime focus in this study). A moderate to high level of toughness helps in improving amount of damage during sewing, which corresponds to seam quality. For higher seam strength adequate yarn strength, tenacity - elongation characteristics and recovery behavior are important for performance of a sewing thread.

Effect of Nanotreatment on Bending Rigidity and Linear Density

The bending rigidity of a yarn is defined as the couple required to bend the yarn to unit curvature [16-18]. The most severe bending takes place when (i) the needle thread is bent at the needle hole and (ii) at the thread eyelets [19,20]. All the thread must be flexible to ensure it passes through the sewing machine and imparted into the seam as smoothly as possible. From the Figure 10, it can be observed that bending rigidity of the threads have not been significantly influenced by silver nanotreatment. The same is also reflected in the linear density change, which is statistically insignificant as shown in Figure 11. This attiributes to the flexibility of a fiber which is the basic raw material in yarn manufacturing depends on its shape, its modulus and its density.

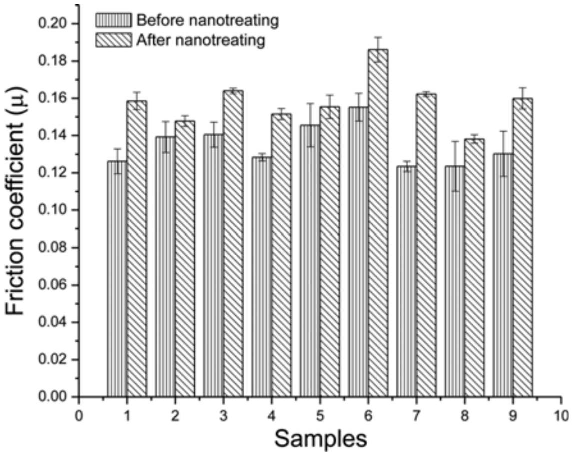

Figure 12. Frictional coefficient of samples.

Effect of Nanotreatment on Frictional Coefficient

The frictional forces developed in the sewing thread are mostly due to the friction with the fabrics and machine parts. The friction occurs mostly in two places, (i) the thread and the needle. (ii) the thread and the fabric being sewn [21-24]. To express the magnitude of the friction under particular conditions it is useful to quote values of frictional coefficient, μ. The coefficient of friction varies with experimental condition, especially on the exact state of the surface. In high speed sewing machine the needle threads rubs against the needle or thread eyelet placed at several points in the machine. However, the coefficient of friction between a needle thread and a stainless steel or other guide should be less than 0.2. Thus all the synthetic and natural fiber needle threads require a lubricant finish to reduce this friction to an acceptably low level. It can be observed that the frictional coefficient of the threads has increased significantly after silver nanotreatment as shown in Figure 12. This may be attributed to the diffusion of the silver nanoparticles in the sewing threads, which creates surface roughness, resulting in higher level of friction. From the results, it is important to note that friction must not be too high, which causes the thread breakage, and not too low, which causes loss of thread control. Although coarse and medium fineness yarns showed a more hairy appearance, resulting in poor seam appearance after friction.

Functional Test - Anti-Bacterial Properties

To study the changes in anti-bacterial properties of the nanotreated samples, müeller-hinton agar was used. After 24 hours, the growth of culture was determined by turbidity and also read at 600 nm. Growth was inhibited in tubes containing silver nanotreated thread. Complete growth in control tubes containing uncoated thread was studied.

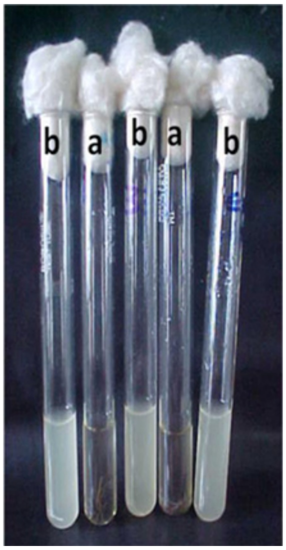

Figure 13. Threads in Müeller-Hinton broth (a) after nanotreatment and (b) before nanotreatment.

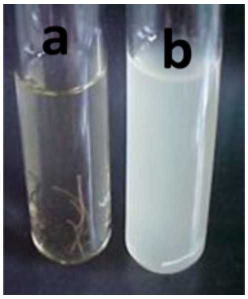

Figure 14. Difference in turbidity (b) before and (a) after nanotreatment of sewing threads.

The Figures 13, 14 show a significant increase of anti-microbial properties due to application of silver nanoparticles. This may be due to the extremely large relative surface area of the silver nanoparticles, which enhances the contact with the bacteria and fungi. There is an increase in the effectiveness of anti-microbial properties of the treated threads. This affects the cellular metabolism and reduces cellular growth. As a result, it reduces the growth of microbes and in turn may results in reduction of itchiness, sores, infection etc.

Wash Fastness of Silver Nanotreated Sewing Threads

The wash fastness of silver nanotreated sewing threads were found to be significant and there were no significant losses of antibacterial property up to 20 washing cycles as per ASTM D2096 - 11. The results are shown in Table 2.

Characterization of Cotton and Polyester Sewing Threads

As part of this investigation, the change in physical properties of cotton and polyester threads were investigated before and after nanotreatment. The differences in changes in physical properties are discussed.

Tensile Strength

On analyzing the cotton and polyester samples together, it was found that the tensile strength of the cotton threads have

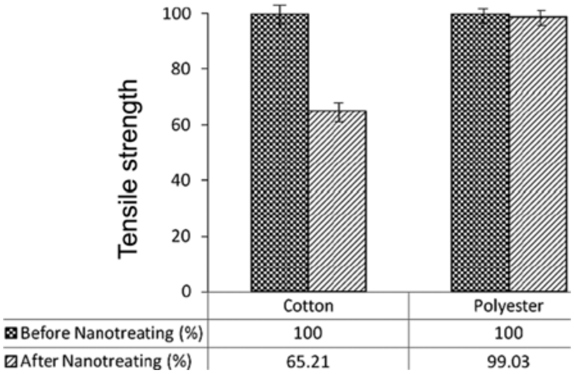

Figure 15. Change of tensile strength (Cotton & Polyester).

Table 2. Bacteria reduction on sewing threads treated with silver nanoparticles (*E. coli*) before and after washing

Sample	Before washing (%)	After 5 washing cycles (%)	After 10 washing cycles (%)	After 15 washing cycles (%)	After 20 washing cycles (%)
1	100	99.98	99.98	99.98	99.97
2	100	99.98	99.98	99.97	99.97
3	100	99.99	99.99	99.98	99.98
4	100	99.99	99.98	99.98	99.98
5	100	100	99.99	99.98	99.98
6	100	100	99.99	99.98	99.98
7	100	99.99	99.98	99.97	99.97
8	100	99.99	99.99	99.98	99.98
9	100	99.99	99.99	99.98	99.98

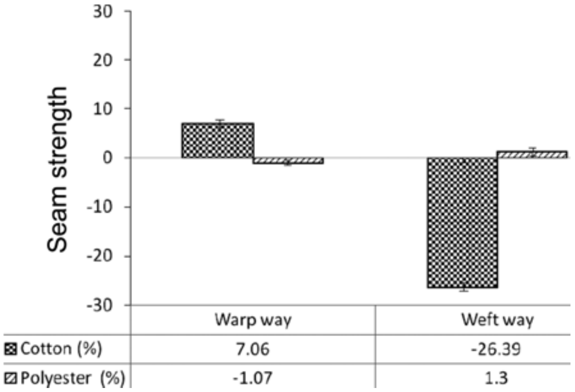

Figure 16. Change of warp-way/weft-way seam strength (Cotton & Polyester).

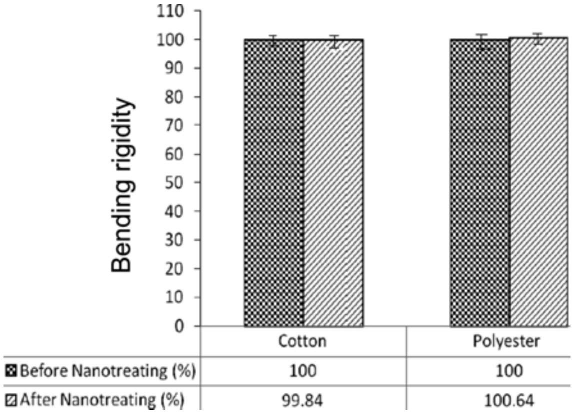

Figure 17. Change of bending rigidity (Cotton & Polyester).

reduced more significantly than that of the polyester threads as can be seen in Figure 15. The gain or loss of strength is not very significant in polyester samples. It is attributed to the more reactive cellulose configuration in cotton and a relatively resistant ester group in PET.

Seam Strength

Figure 16 shows an increase of warp-way seam strength and reduction of weft-way seam strength, after silver nanotreatment. Weft way seam strength of all cotton threads have decreased. The change in tensile strength of the threads after silver nanotreating may have influenced the seam strength. As discussed earlier, the relatively reactive cellulose content in cotton is responsible for higher loss of strength.

Bending Rigidity

The changes in bending rigidity of both cotton and polyester threads are statistically less than 5 % for all samples shown in Figure 17. It can be concluded from the results that there is no significant change in bending rigidity.

Friction Coefficient

From the Figure 18, all samples have statistically shown a significant increase in frictional co-efficient. The changes range from 5-25 % for cotton threads and 10-32 % for polyester threads. This change may be attributed to the higher surface area of the silver nanoparticles applied on the surface of the threads. It can be concluded that application of silver nanoparticles increases the frictional properties of the threads.

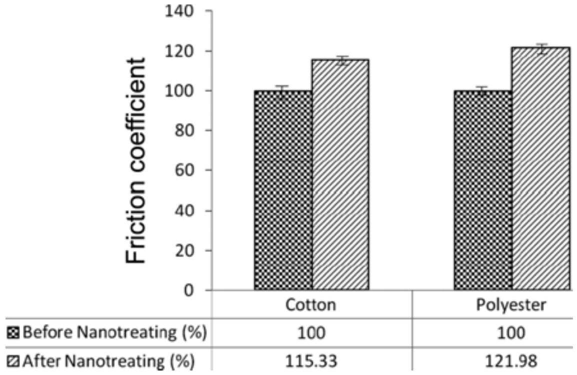

Figure 18. Change of frictional coefficient (Cotton & Polyester).

Conclusion

The investigations lead to the conclusion that finer threads are more efficient in absorption of silver nanoparticles. The cotton sewing threads have higher absorption of silver nanoparticles as compared to polyester threads. It was found that silver nanotreatment also leads to a significant reduction of tensile strength. This may impact the ability of the threads to withstand the stresses that adversely influence both its sewing and seam performance. The warp-way seam strength increased where as weft-way seam strength decreased due to damage of yarn. Deformation properties of the threads are not influenced significantly by nanotreatment. The nanotreatment of threads increases its frictional properties significantly. Increase in friction between needle and thread may lead to break or burn of the thread. Friction between the thread and fabric may damage the fabric due to high heat generated. The threads also acquired effective anti-microbial properties with silver nanotreatment. The effect is significantly retained up to 20 washing cycles. Study of the impact of nanotreatment on the properties of cotton and polyester samples showed a bigger impact on cotton samples than polyester samples. This research finding would further expand the knowledgebase to create garments with enhanced anti-microbial properties, especially those which come into contact with the human skin. This is expected to seed further studies on use of nanoparticles in industrial sewing threads and their transmission of antimicrobial properties to the fabrics sewn using nanotreated threads.

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