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Tribology of alumina materials for the circular economy of manufacturing textile industries

Abrar Hussain*, Vitali Podgursky, Dmitri Goljandin, Maksim Antonov and Mart Viljus

Department of Mechanical and Industrial Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia

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Abstract. Circular economy is still a theoretical field. In this research, alumina ceramic material was used to measure the coefficient of friction (COF) of cotton fabric with the objective of supporting the circular economy of textile industries. A scanning electron microscope (SEM), optical profilometer, mechanical profilometer and tribometer were used for evaluations of the cotton fabric surface and the coefficient of friction (COF). The cotton fabric surface was detected rough and damaged while the ceramic balls displayed smoothness along with high microhardness. The dynamic COF values were 0.12 to 0.15 in warp and 0.11 to 0.17 in weft directions. Based on the COF values, deformation, wear and morphologies evaluations, alumina ceramic materials could be used operationally for surface alterations of textile machinery parts. The results could also enhance the quality and performance of textile products.

Key words: fabric tribology, circular economy, ceramic materials, wear, fabric friction, textile fabrics, textile machinery.

1. INTRODUCTION

Circular economy is an industrial system where products are manufactured with negligible waste. It has appeared as an innovative solution for the manufacturing and recycling of textile materials [1,2]. Ceramic materials have been widely used for their industrial and tribological properties [3–5]. Generally, thin-film oxides (Al_2O_3/Cr_2O_3/ZrO_2, etc.), carbon-based coatings (SiC/WC/VC, etc.) and ceramic coatings are utilized as surface modification for textile manufacturing industries [6–8]. The surface modification of these materials enhances wear, fatigue, corrosion, abrasion and erosion resistance of manufacturing machinery components [9–11]. These materials also increase the quality and performance of textile products [12].

Typically, two methods are used for tribology and wear evaluations. In the first method, an object with the mass “m” slides over cotton fabric as a counter body. The mathematical equation is expressed as follows:

$$\mu_{\text{dynamic}} = \frac{F}{mg}, \tag{1}$$

where “F” is the friction force, “μ_{dynamic}” denotes the friction constant, “g” represents the gravitational acceleration constant, and “m” is the mass of the sliding body.

The formulation of the second method for inclined surfaces is given as

$$\mu_{\text{static}} = \tan\theta. \tag{2}$$

Here, μ_{static} is the static friction constant and “θ” refers to the inclined angle [13–15].

This research focuses on the evaluations of tribological properties of alumina ceramic materials and cotton fabrics for industrial applications. The developed method was employed for wear and deformation determination in regard to cotton polymer. Moreover, a scanning electron microscope (SEM), surface profilometer and Vickers hardness tester were used for surface and hardness determination.

* Corresponding author, abhuss@taltech.ee

2. EXPERIMENTAL

Initially, the subjective assessment [16] of dark green cotton fabric was performed. Ten mild steel blocks with the dimensions of 25 mm × 10 mm × 50 mm were used for sample preparation. The cotton fabric was cut into strips which were pasted on steel blocks using epoxy resin. The various parameters are shown in Table 1.

The tribological observations were performed by CETR/Bruker UMT-2 tribometer. The tribometer has two parts: the upper part was used for sliding and the lower part for holding the sample. The normal force, speed, time, and sliding distance of 0.5 to 9 N, 1 to 10 mm/s, 4 to 40 s, and 0 to 80 m, respectively, were used to evaluate tribological properties. The experimental setup is illustrated in Fig. 1a–d.

Redhill C10 grade alumina oxide ceramic balls were utilized as a counter body. The balls of 10 mm diameter had 99.5% alumina and 1450 HV hardness on Vickers scale. The additional balls had rupture strength of 0.26 kN/mm^2, compressive strength of 2.4 kN/mm^2, tensile strength of 0.025 kN/mm^2 and fracture toughness of 13.5 kN/mm^2. The modulus of elasticity and the modulus of temperature resistance were 350 kN/mm^2 and 1900 °C, respectively. A scanning electron microscope (SEM), optical and mechanical profilometers were also used for surface evaluation.

3. RESULTS AND DISCUSSION

Initially, the surface of the alumina balls was observed by the SEM. Impurities, scratches and micro pits were detected on the ball surface as seen in Fig. 2. Moreover, surface roughness was also measured using optical and mechanical profilometers. The results are given in Table 2. The alumina balls were coated with gold for SEM and

Table 1. Subjective assessment of post-consumer cotton textile

Physical property	Unit	Value	Physical property	Unit	Value
Woven weft	–	Plain	Thread diameter in weft direction	mm	0.345
Woven warp	–	Plain	Thread diameter in warp direction	mm	0.345
Weight	g/m^2	237	Twist value	T/m	800
Warp linear density	cm^{-1}	29	Thickness	mm	0.45
Weft linear density	cm^{-1}	29	–	–	–

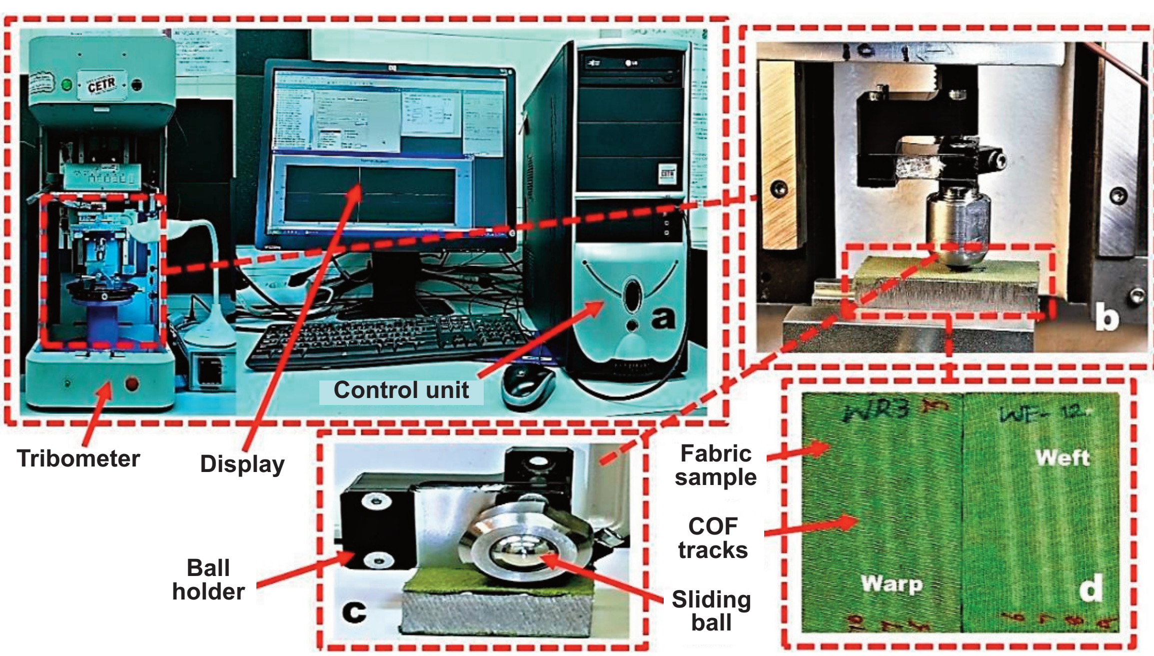


Fig. 1. Experimental setup: (a) tribometer equipment, (b) experiment demonstration, (c) ball slider and (d) fabric sample after tribology testing.

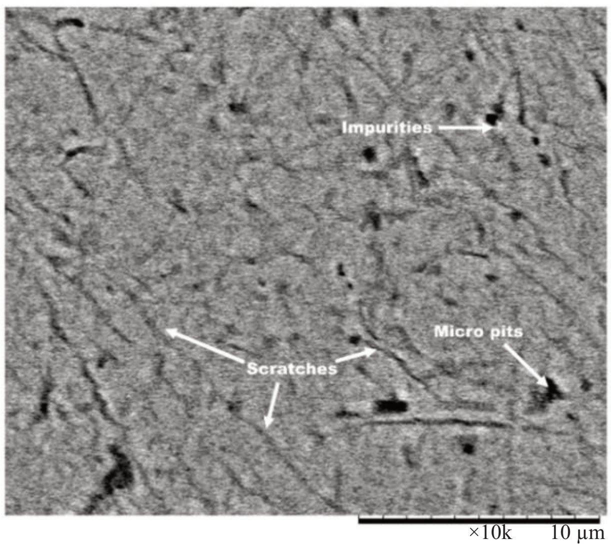


Fig. 2. Alumina ball SEM image.

Table 2. C10 alumina ceramic balls' surface roughness

Device	Surface roughness parameters (µm)		
	Ra	Rz	Rp
Optical	0.24	0.34	0.32
Mechanical	0.24	0.37	0.39

profilometer observations. The surface of cotton fabric was also studied and the SEM surface characterization was performed in weft and warp directions. The yarns were woven from left to right in the weft direction. At higher magnification the yarns and fibres were detected rough and distorted, see Fig. 3a, b.

The yarns in the warp direction were woven from bottom to top. Again, at higher magnification the yarns and fibres were seen rough and distorted, as illustrated in Fig. 4a, b. Hearle et al. have demonstrated a detailed and standard collection of more than 1500 SEM images. This collection also provides the characterization of newly formed textile fabrics [17].

Figs 5a–c and 6a depict graphs demonstrating the coefficient of friction (COF) values. At the start, force, speed, and time were altered to study the COF in weft and warp directions. Additionally, Fig. 5b, c shows the COF variations with speed and force. The evaluations reveal that in the case of alumina ceramic balls, at the constant speed of 1 mm/s and for the value of force increasing from 0.5 to 9 N, the COF value increases from 0.05 to 0.12 in the weft and warp directions, see Fig. 5b. Furthermore, in the case of alumina ceramic balls, at a constant force of 8 N and for the value of speed increasing from 1 mm/s to 10 mm/s, the fabric COF value increases from 0.12 to 0.17 in warp and weft directions, see Fig. 5c.

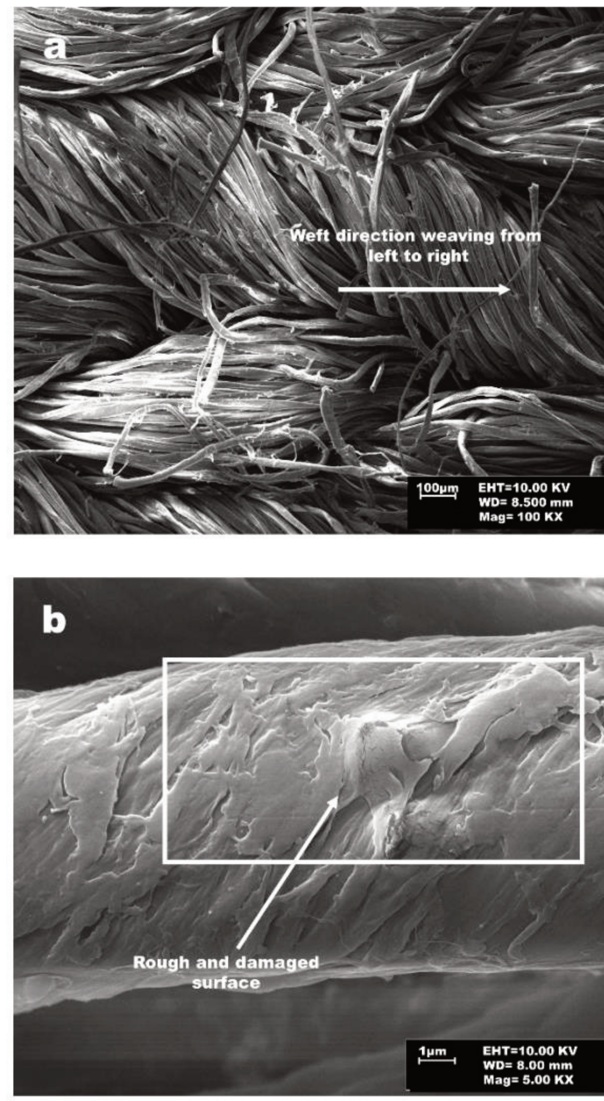


Fig. 3. (a) SEM image of weft direction woven from left to right, (b) surface damage at higher magnification.

Disparate observations and evaluations can be described using COF results. The COF of cotton fabric was detected the same for force variations while the speed variations affect the COF values. The difference in thread density, higher twist value, fabric weight (grams per square metre), and plain woven fabric pattern could cause such type of response [18]. This response was not observed in the case of other polymer investigations. Fabric thread and yarn orientations, the nature of fabric materials, the composition and nature of the counter body can also contribute to the change in COF values [18]. That type of

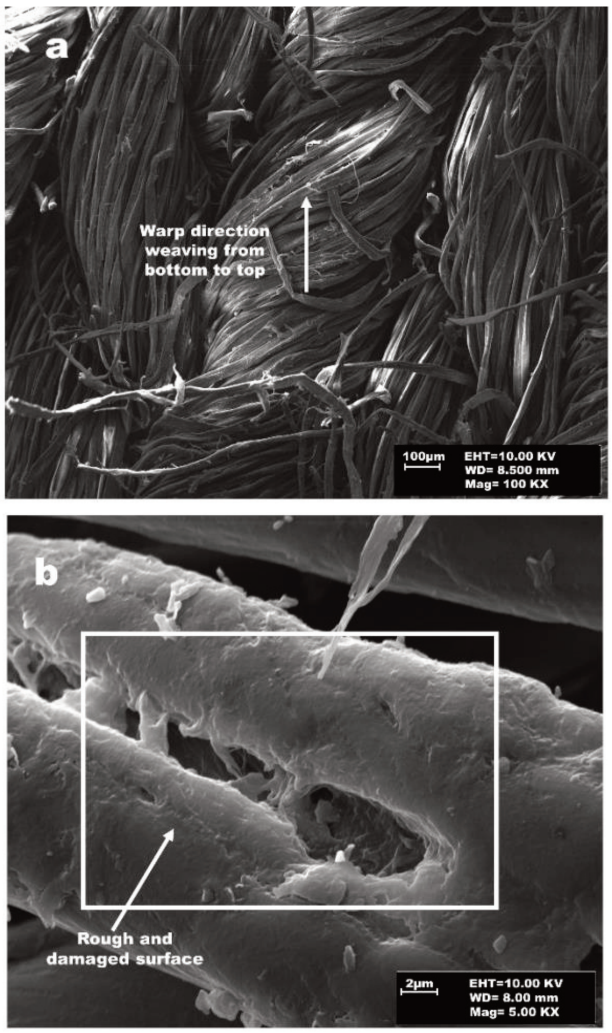


Fig. 4. (a) SEM image of warp direction woven from bottom to top, (b) surface damage at higher magnification.

behaviour of polymers and counter bodies is demonstrated in Figs 2, 3a, b and 4a, b. The threads woven from left to right served as a reference track for the sliding of the alumina ceramic balls, see Fig. 1d.

To assess the applications for manufacturing industries, the sliding distance was increased for fabric wear, deformation, and COF evaluation. The sliding motion was also changed to reciprocation motion to study the wear and damage of cotton fabric in more detail. At a load of 3 N and speed of 1 mm/s, for 80 m of sliding distance, the alumina ceramic ball slightly deformed cotton fabric. This deformation produced negligible wear on the fabric surface in warp and weft directions. Throughout 80 m of the evaluation distance, the COF value remained constant in both directions. The corresponding effects are depicted in Fig. 6a, b, respectively. This manifestation is very important for the applications of manufacturing industries.

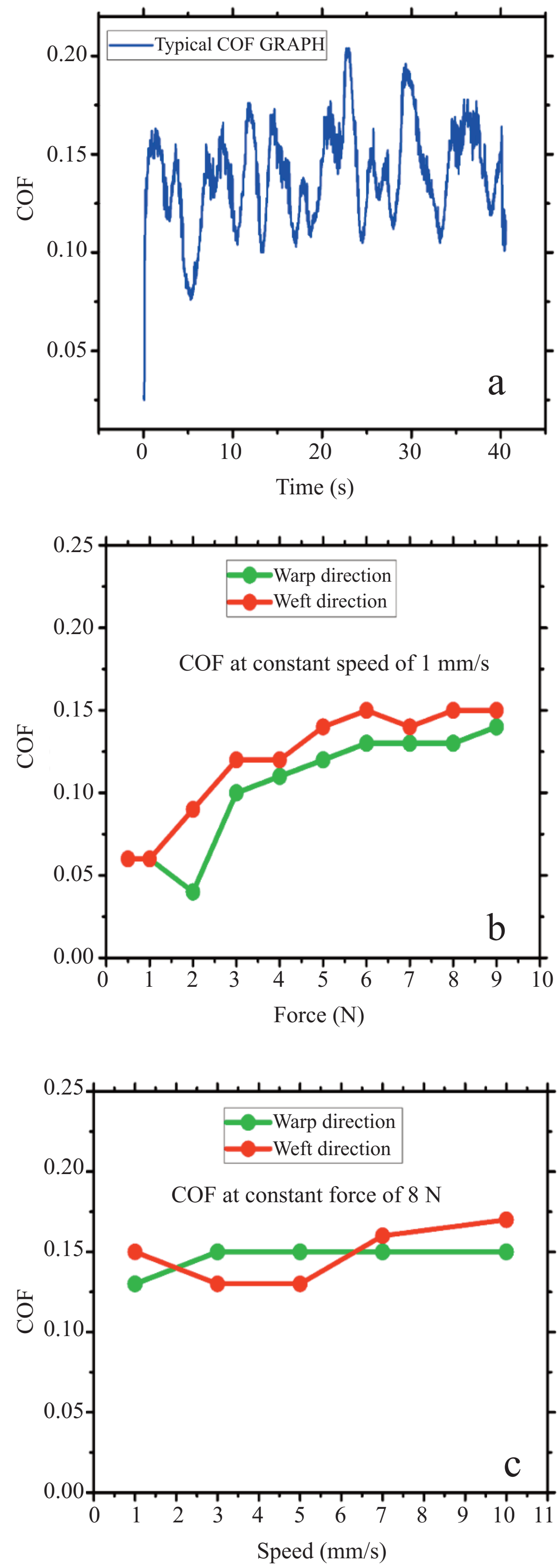
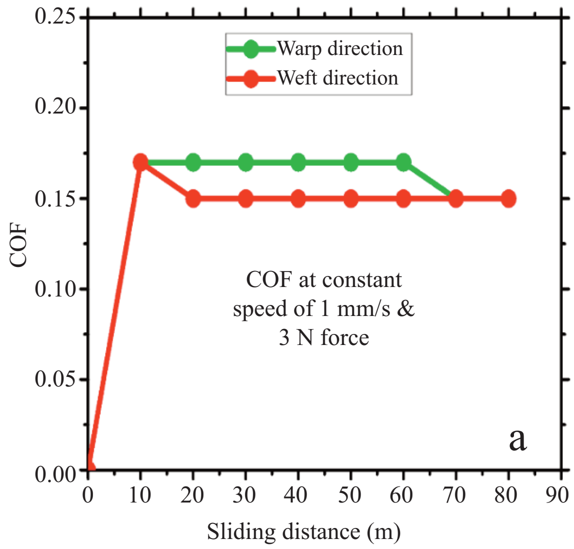


Fig. 5. (a) COF versus time, (b) COF versus force variations and (c) COF versus speed comparison.



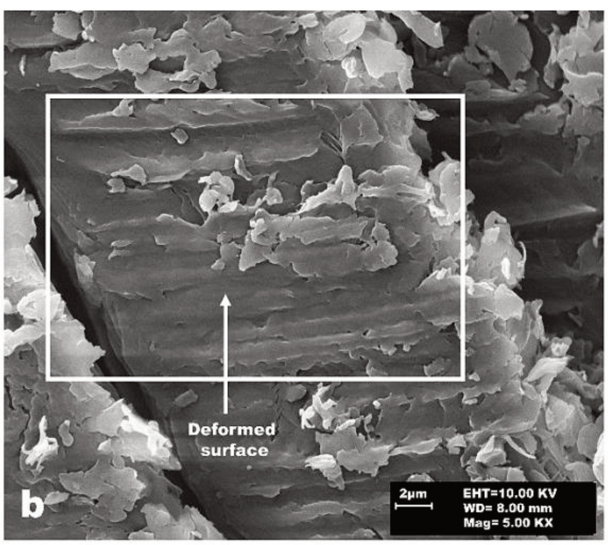


Fig. 6. (a) COF versus sliding distance observations and (b) SEM image of deformed fibres.

In the previous research we demonstrated that usually higher COF values would have important applications in textile recycling industries [19]. Kothari et al. have studied the cutting and shredding phenomenon of textile materials and shown that COF values could be expressed in terms of the cutting resistance index (CRI) and the grip between textile fabric and its counter body. The higher are the COF values, the lower will be the CRI [20]. Higher COF values also increase the grip between cotton fabric and its counter body. Formally, higher COF values deform and cause the removal of local materials from the fabric surface. The materials and coatings which provide a higher COF could be used for surface modifications of the components of recycling industries [17–19].

Alumina ceramic material has not fractured or removed local materials from the cotton surface. The creation of minimum deformation and wear on cotton fibres is an indication of better grip between the cotton fabric surface and its counter body. The optimized quality and performance of textile fabrics are basic requirements for newly manufactured textile products. Therefore, alumina ceramic material can be used for surface modification of textile manufacturing machinery components to enhance textile quality. Moreover, the higher are the values of thread setting density, linear density, grams per square metre (GSM) and tensile properties, the better will be the performance and quality of textile products. The results and discussions have proved that minimum relative COF values are required for the manufacturing of textile products [19–22] as they provide the maximum possible quality and performance for textile products, avoiding also surface damage and distortion.

4. CONCLUSIONS

Tribometer tests were performed to determine relative COF values between the cotton fabric surface and alumina ceramic balls. The alumina ball surface roughness parameters R_{max}, R_z, R_p were 0.24 µm, 0.34 µm, 0.37 µm, respectively. The alumina surface hardness was 1450 HV on Vickers scale. This is related to lower surface roughness, reasonable hardness, and is an indication of good performance. The average COF in weft and warp directions was 0.15 for force, speed, sliding, distance, and time variations. SEM images at lower and higher magnification show that the warp and weft weaving of cotton fabrics is rough and damaged. Lower COF values provide better grip, lower cutting resistance and hence better performance and quality to manufactured textile products. These characteristics make alumina ceramic materials a remarkable candidate for modifying the surface of textile machinery components for the manufacturing of textile products.

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Alumiiniumoksiidi materjalide triboloogia töötleva tekstiilitööstuse ringmajanduse jaoks

Abrar Hussain, Vitali Podgursky, Dmitri Goljandin, Maksim Antonov ja Mart Viljus

Ringmajandus on endiselt teoreetiline valdkond. Selles töös kasutati alumiiniumoksiidi keraamilist materjali puuvillase kanga hõõrdeteguri (*coefficient of friction*, COF) mõõtmiseks. COF-i mõõdetakse tekstiilitööstuse ringmajanduse toetamiseks. Puuvillase kanga pinna ja hõõrdeteguri (COF) hindamiseks kasutati skaneerivat elektronmikroskoopi (*scanning electron microscope*, SEM), optilist profilomeetrit, mehaanilist profilomeetrit ja tribomeetrit. Puuvillase kanga pind oli kare ja kahjustatud. Keraamilised kuulid olid siledad ja suure kõvadusega. Dünaamilised COF-väärtused olid lõimes 0,12 kuni 0,15 ja koesuunas 0,11 kuni 0,17. COF-väärtuste, deformatsioonide, kulumise ja morfoloogiate hindamise põhjal võiks alumiiniumoksiidi keraamilisi materjale kasutada tekstiilimasinate osade pinna muutmiseks. Tulemused võivad parandada ka tekstiilitoodete kvaliteeti ja vastupidavust.