Tribological behaviour of laser-textured UHMWPE under simulated dry and wet joint conditions using a biomimetic sunflower oil-hyaluronic acid lubricant

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Abstract. UHMWPE is a widely used biomaterial for articulating components in total joint replacements (TJR), but its lifetime performance was reduced by wear and friction. To enhance the performance, surface modification was introduced. This present study investigates the effect of circular texturing combined with biomimetic lubrication on the tribological properties of UHMWPE. A laser marking machine was used to do the surface texturing on the specimen. Pin-on-disc tribometer was used to conduct tribological experimental tests under both dry and wet conditions. A refined sunflower oil-hyaluronic acid blend is the lubricant. The experimental tests were conducted with different velocities of 0.05 m/s, 0.15 m/s, and 0.25 m/s, that are match the human motions and the applied force of 60 N. The results demonstrate that lubrication significantly reduced friction in wet conditions compared to dry conditions. Textured samples exhibit a declining trend in the friction when compared to untextured samples. The wear rates exhibited a comparable trend on both the textured and lubricated specimens by showing remarkably improved wear resistance. The hybrid application of surface texturing and lubrication resulted in a significant enhancement in the tribological performance of UHMWPE, suggesting promising implications for increasing the longevity of orthopaedic implants.

1 Introduction

Many researchers identified the primary failure of implants caused due to the reactive response of biological tissues with UHMWPE wear debris, which affects the long-term performance. The typical lifespan of UHMWPE implants ranges between 5 to 10 years, a duration that is particularly problematic for younger patients who often require longer-lasting solutions. Additionally, the financial burden associated with revision hip surgeries significantly exceeds that of the initial implantation. Given these constraints, there is an increasing need to enhance the durability of UHMWPE-based artificial joints. Despite its wear characteristics, UHMWPE exhibits superior abrasion resistance among thermoplastic

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materials. It also possesses notable impact and fatigue resistance, a low friction coefficient, self-lubricating properties, and a strong ability to dissipate mechanical energy. During the service life of these materials, oxidative degradation affects their mechanical properties and the lifespan of implants. To overcome these issues, various advancements have been developed, including vitamin E blending, cross-linking, and reinforcement with nanoparticles. These developments will enhance its resistance to oxidation and the tribological performance[1]. In high-stress biomedical applications, incorporating silicon into UHMWPE will improve wear resistance and overall durability[2]. A recent cutting-edge technology of surface texturing was used to optimise the tribological characteristics of UHMWPE by generating circular texturing on the specimen surfaces. Laser Surface Texture (LST) created circular texturing, which will act as a lubricant reservoir, inducing the reduction of adhesive wear and increasing load-carrying capacity. This technique emulates the natural lubrication mechanisms of cartilage, resulting in significantly reduced wear rates in synthetic joint applications [3]. Under wet sliding lubrication conditions, the wear performance of UHMWPE is heavily influenced by experiencing low wear and friction, whereas under dry sliding, UHMWPE experiences high wear and friction, which limits its effectiveness in load-bearing joints. In contrast, the application of biofluids or synthetic lubricants significantly mitigates wear by establishing protective tribofilms on surfaces. Studies demonstrate that parameters such as surface roughness and sliding velocity play pivotal roles in this process. Under lubricating conditions, increasing sliding velocity exhibits better wear resistance due to its improved hydrodynamic effects, facilitating better load support and reducing direct contact between surfaces [4]. Recent studies have turned to lubricants derived from plant oils to replicate the synovial fluid in artificial joints. A Refined sunflower oil and hyaluronic acid combination has shown improved tribological properties by reducing friction and wear. The intrinsic low friction coefficient of sunflower oil is augmented by the viscosity-enhancing and load-distributing qualities of hyaluronic acid, closely mimicking the characteristics of natural synovial fluid. Experimental trials using four-ball and pin-on-disc tribometers indicate its potential as a sustainable and biocompatible lubricant in orthopaedic applications [5]. Inclusion of nanoparticle additives of SiO_2 and TiO_2 in the sunflower oil has shown enhanced wear resistance further [6]. A Pin-on-disc tribometer test is the most suitable method for assessing the tribological properties of UHMWPE under simulated joint conditions. An applied load of 100 N replicates the usual joint stresses experienced in real-time, providing information on wear mechanisms [7]. A velocity range of 0.5 m/s to 2.5 m/s is a common sliding velocity range used to simulate human walking, standing, and running conditions. Literature shows that higher sliding velocities under lubrication conditions can reduce wear due to hydrodynamic film formation, whereas dry conditions increase wear damage [8]. The present study investigates overcoming the challenges of oxidative degradation and wear rate under high loading conditions. Due to processing complexities and cost concerns regarding the implementation of vitamin E blending and nanoparticle reinforcement are making way to do the alternative arrangements of surface modification are being made to offer significant enhancement in the performance of these biomaterials. LST shows considerable potential in improving lubrication and reducing wear. Likewise, bio-lubricants such as sunflower oil and hyaluronic acid blends demonstrate strong potential as eco-friendly alternatives to traditional lubricants. However, their long-term stability, susceptibility to oxidation, and consistency under dynamic physiological conditions require further study [9,10]. The pin-on-disc tests provide only valuable information based on the laboratory setting, they do not fully replicate the complex biological synovial joints, thereby limiting direct clinical application. Advancements in materials, surface modification and lubrication methodologies show great potential; however, integrating these innovations into clinically effective implant systems remains a significant challenge.

2 Experimental trials

2.1 Materials

In this study pin specimens were fabricated in a cylindrical configuration as per the ASTM G99 standards. Figure 1 shows the machined specimen size from the raw materials were sourced as rods. The counter body disc in the pin-on-disc experimental study, where the pin specimens sliding over the surface resulted in friction. In our applications involving plastic-on-metal interactions, a metal disc made from 316L stainless steel (SS) has been selected due to its favourable properties. This alloy has a density of 8000 kg/m³ and offers a commendable balance of strength and corrosion resistance. 316L is the low-carbon variant of stainless steel, which enhances its biocompatibility and makes it suitable for biomedical applications.

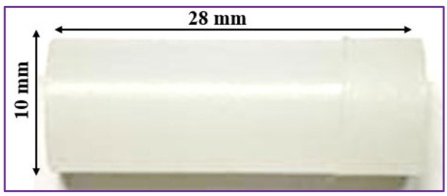

Fig. 1. UHMWPE - pin specimen.

2.2 Laser surface texturing

Using the MLS F20 Fibre marking machine, the surface texturing was performed on UHMWPE pin specimens as shown in Figure 2. The operator uses the EZCAD software tool to draw the circular texturing pattern before the laser processing. The laser texturing was executed under the following machine parameters of 2 kHz of laser pulse rate, 10 W of output power, 1064 nm of Wavelength, 200 mm/s of scanning speed and with a single loop configuration. Proper positioning of the specimen is crucial in this process by maintaining the focal tip at approximately 320 mm from the target surface. Finally, the laser beam is applied to the specimen to achieve the circular texturing pattern effectively.

Fig. 2. Laser surface texturing process.

2.2.1 Calculation of texture parameters

$$\text{Pin surface area} = \frac{\pi \times D^2}{4} = \frac{\pi \times 10^2}{4} = 78.539\ \text{mm}^2 \qquad (1)$$

$$\text{Texture area} = \frac{\pi \times d^2}{4} = \frac{\pi \times 0.4^2}{4} = 0.1256\ \text{mm}^2 \qquad (2)$$

$$\text{Texture density } (\mathrm{D}_t) = \pi \times \left(\frac{d}{2 \times S}\right)^2 \times 100\% \qquad (3)$$

$$\mathrm{D}_t = \pi \times \left(\frac{0.4}{2 \times 0.9}\right)^2 \times 100 = 0.15514 = 15.514\ \%$$

The equation calculates the number of circular textures:

$$\text{Number of textures} = \frac{\text{Pin surface area} \times D_t}{\text{Texture area}} \qquad (4)$$

$$= \frac{\left(\frac{\pi \times 10^2}{4}\right) \times 0.15514}{\left(\frac{\pi \times 0.4^2}{4}\right)} = 97$$

Nomenclature:

D is the diameter of the pin specimen, 10 mm.

d is the circular texture diameter, 0.4 mm.

D_t is the texture density area.

Figure 3. (a) shows the circular texturing pattern designed using EZCAD software and applied onto the UHMWPE specimen using an LST machine. Figure 3. (b) shows the microscopic image of the textured UHMWPE surface and its uniform distribution of circular textures. These circular textures serve as lubricant reservoirs and debris traps to improve the tribological performance. Figure 4 compares the surface roughness profiles of UHMWPE specimens before and after LST. The textured surface exhibited a roughness value higher than the untextured surface as listed in Table 1.

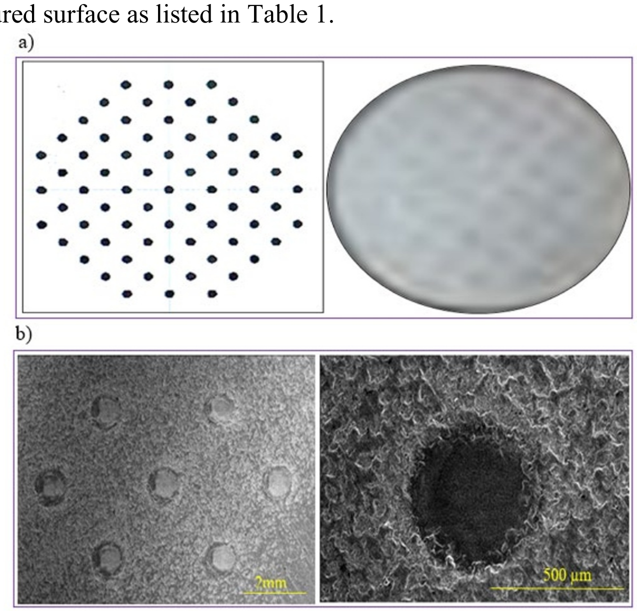

Fig. 3. (a) Circular texturing pattern on the specimen, and (b) SEM morphology of circular texturing pattern.

Table 1. Roughness values before and after texturing.

Specimen Type	R_a	R_q	R_z
UHMWPE Untextured	0.30	0.39	0.43
UHMWPE Textured	0.54	0.71	0.67

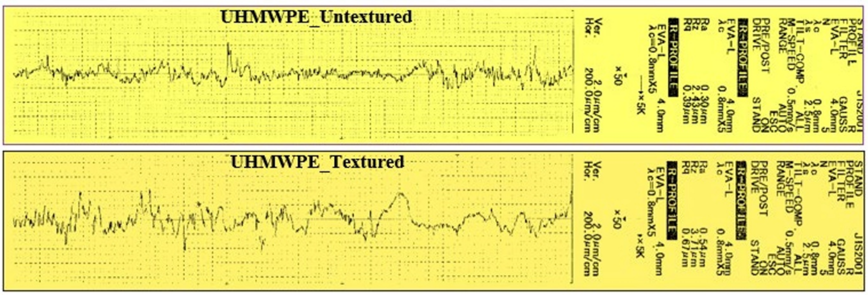

Fig. 4. Surface roughness in the UHMWPE specimen before and after texturing.

2.3 Lubrication

Synovial fluid is also called as joint fluid. These are complex, viscous non-Newtonian fluids that are present within the synovial cavities of diarthrodial joints, as shown in Figure 5. Its primary role is to facilitate smooth joint movements by reducing friction between the articular cartilage surfaces. This fluid is produced and secreted by the synovial membrane that lines the joint capsule. It is an ultrafiltrate of plasma that contains various proteins derived from blood plasma and others synthesised locally by joint tissue. It also contains interstitial fluid generated from plasma filtration processes. The primary function of the fluid creates a hydrodynamic layer about 50 µm on the surface by penetrating surface irregularities and micro-cavities. This characteristic will serve as a lubricating reservoir within the cartilage surface. During joint movement, this reserved fluid provides a continuous lubrication on the surface known as weeping lubrication. It is essential for maintaining the biomechanical integrity and physiological functionality of synovial joints, ensuring optimal movement and even load distribution.[11]

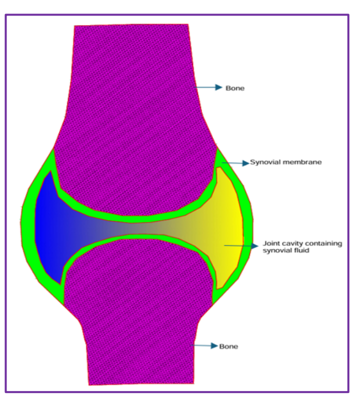

Fig. 5. Total joint replacement and its synovial fluid.

Recent research has indicated that applications of sunflower oil serum are a replacement for synovial fluid. In this experimental study 1.5 litres of refined sunflower oil mixed with 5 ml of hyaluronic acid was proposed to use sunflower oil serum in clinical settings. The mixing of hyaluronic acid in synovial fluid has several advantages: water retention capability, enhanced lubrication performance, Cation control, Influence on bacterial virulence, and Wound healing properties. Overall, the integration of sunflower oil serum with hyaluronic acid presents a novel approach to augmenting synovial fluid replacement therapies.

2.4 Tribometer test

The pin-on-disc test is the most frequently used method to find the tribological properties in joint simulation, as illustrated in Figure 6. This experimental setup has a pin with a cylindrical surface orientation perpendicular to a circular disc that rotates. As the disc revolves around its centre, the pin traces a circular sliding path on the disc surface as the track diameter. The orientation of the disc can vary by setting it either horizontally or vertically. Force sensors are used to measure the frictional force continuously during sliding, and the linear variable differential transducer (LVDT) measures the wear rates in real-time. But the wear rate can be measured by assessing mass loss before and after testing. When mass loss is used, it is converted to volume loss in cubic millimetres using the specimen density. The same experimental setup was capable of measuring the tribological properties in wet conditions. It has a lubricant pumping unit with a 3 L tank capacity. The lubricant is run over the disc and pin interaction zone continuously to reduce the tribological properties of the specimen under study. The specimens were tested under dry and lubrication with blend sunflower oil conditions at room temperature under the variable sliding velocities 0.05 m/s, 0.15 m/s and 0.25 m/s, with a constant load of 60 N[12,13]. The experimental setup of the pin on disc under dry wear and wet wear conditions is shown in Figure 7. The UHMWPE pin specimens subjected to both dry wear and wet wear conditions are presented in Figure 8.

Fig. 6. Tribometer experimental setup.

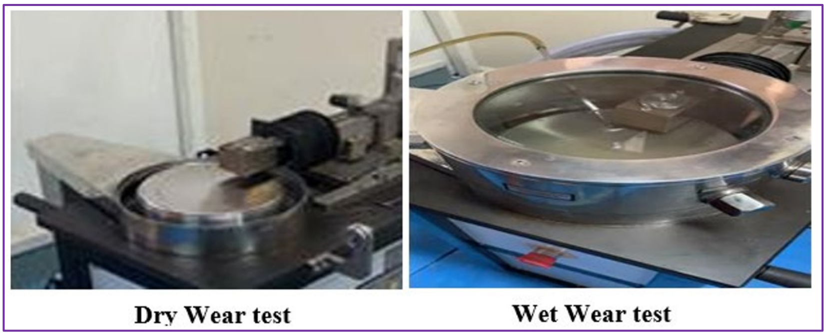

Fig. 7. Experimental set-up for dry wear and wet wear.

Fig. 8. UHMWPE pin specimen under dry and wet wear.

3 Results and discussions

A comparative tribological performance of both untextured and textured UHMWPE specimens was performed under dry and wet conditions at ambient temperature. The results indicate that the surface temperature slightly increases with increases in sliding time, and the wear rates continuously increase with higher sliding velocities. LST modified specimens indicate a lower wear rate compared to their untextured counterparts. The analysis involved determining the maximum friction, mean friction, and wear rate at sliding velocities of 0.05 m/s, 0.15 m/s, and 0.25 m/s for both untextured and textured UHMWPE specimens. Data presented in Table 2 summarizes findings from experimental tests conducted via a sliding wear tribometer.

Table 2. Mass loss, volume loss, wear rate and friction coefficient of different specimens.

Specimen Type	Mass before test (g)	Mass after test (g)	Mass loss (g)	Volume loss (mm^3)	Specific wear rate x 10^{-5} (mm^3/N-m)	Friction coefficient
UHMWPE_UT_D_0.05	2.06	2.027	0.033	34.02062	2.86	0.185272
UHMWPE_UT_D_0.15	2.007	1.984	0.023	23.71134	2.63	0.221528
UHMWPE_UT_D_0.25	2.065	2.0483	0.0167	17.21649	2.47	0.269474
UHMWPE_UT_W_0.05	1.959	1.944	0.015	15.46392	1.29	0.051876
UHMWPE_UT_W_0.15	2.092	2.082	0.01	10.30928	1.15	0.077535
UHMWPE_UT_W_0.25	2.066	2.0585	0.0075	7.731959	1.04	0.091367
UHMWPE_T_D_0.05	1.889	1.871	0.018	18.5567	1.5	0.149416
UHMWPE_T_D_0.15	2.037	2.0245	0.0125	12.8866	1.43	0.175558
UHMWPE_T_D_0.25	2.052	2.043	0.009	9.278351	1.32	0.191524
UHMWPE_T_W_0.05	2.064	2.0544	0.0096	9.896907	0.826	0.072779
UHMWPE_T_W_0.15	2.075	2.06821	0.00679	7	0.785	0.074708
UHMWPE_T_W_0.25	2.054	2.04947	0.00453	4.670103	0.669	0.079001

At the lowest velocity of 0.05 m/s, UHMWPE_UT_D specimens exhibit the highest friction values from 0.18 to 0.20, as shown in Figure 9. This is mainly because of strong interactions and adhesive wear phenomena. UHMWPE_T_D has a lower reduction in friction values from 0.14 to 0.16 due to the introduction of micro-textures in dry conditions. This micro-texturing acts as a trap for wear debris and reduces the effective contact area by resulting in decreased adhesive interactions[14]. UHMWPE_UT_D has shown very low friction values from 0.04 to 0.05 has a severe influence of boundary lubrication at lower velocities. UHMWPE_T_W has shown some fluctuation in friction values, indicating the textures may retain a lubricant film and then destabilize at the early stages of operation.

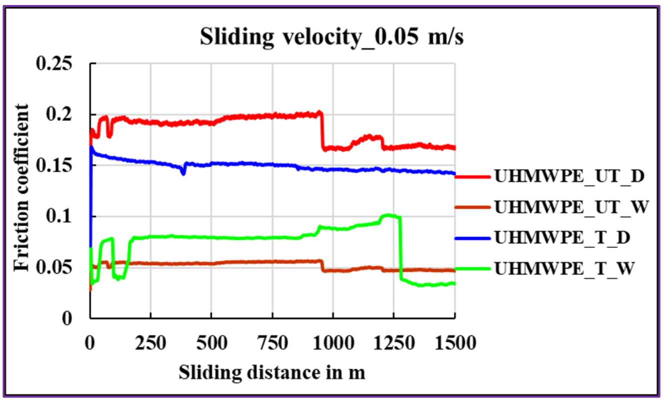

Fig. 9. Friction at 0.05 m/s of sliding velocity.

Figure 10 shows friction characteristics at an intermediate velocity of 0.15 m/s, and the values remain consistent across conditions. Both UHMWPE_UT_W and UHMPWE_T_W specimens exhibit low and stable friction values, indicating a transition toward a mixed lubrication regime where hydrodynamic effects play a significant role in maintaining film stability[15]. The influence of LST has less impact in this condition, but the lubricating condition has a high influence on the tribological performance. In contrast, both UHMWPE_UT_D and UHMWPE_T_D exhibit higher friction values ranging from 0.17 to 0.22.

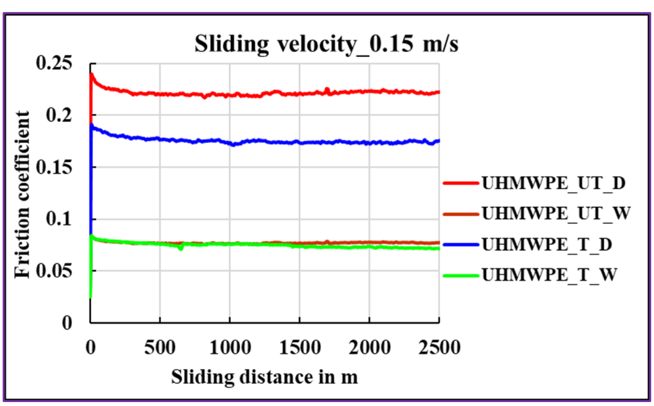

Fig. 10. Friction at 0.15 m/s of sliding velocity.

Figure 11 illustrates the friction characteristic at a maximum velocity of 0.25 m/s between dry and wet conditions. Both UHMWPE_UT_D and UHMWPE_T_D specimens exhibit very high and unstable friction values ranging from 0.20 to 0.25. These unstable values are caused due to thermal softening, the accumulation of wear debris, and the degradation of transfer films at the sliding interface. But UHMWPE_UT_W and UHMWPE_T_W exhibit low and stable friction values. Out of this, UHMWPE_T_W has a very low friction value of 0.08, which is the most favourable performance. This most suitable performance is due to the hybrid effect of lubrication and surface texturing. The micro-textures serve as micro-reservoirs for lubricant, effectively sustaining a consistent lubricating film even under conditions of high sliding velocity.

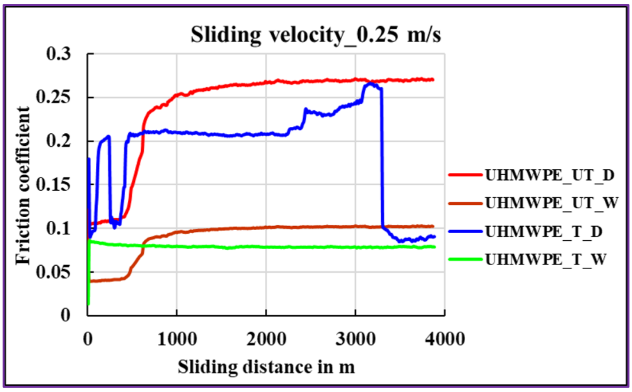

Fig. 11. Friction at 0.25 m/s of sliding velocity.

The results clearly indicated that lubrication serves as an important factor for the reduction in friction values across all sliding velocities. LST provides an added advantage under dry conditions and optimizes lubrication performance at high velocity, as illustrated in Figure 12. These observations align with the recorded tribological performance, suggesting that friction regimes transition from boundary lubrication at lower speeds to mixed and hydrodynamic lubrication at higher velocities.

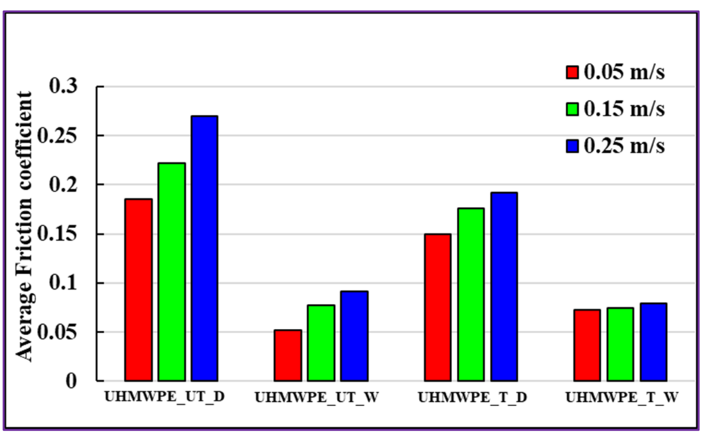

Fig. 12. Average friction coefficient versus sliding velocities.

Figure 13 illustrates the wear of UHMWPE hybrid modified specimens for their impact of texturing, lubrication, and sliding velocity. The highest wear rates were noted in UHMWPE_UT_D, due to its direct asperity interactions will influence both adhesive and abrasive wear mechanisms. The introduction of lubrication in UHMWPE_UT_W has huge impact on the wear rate, highlighting the critical function of synovial fluid supports in reduction of wear in biomedical applications. LST has improved wear resistance by generating micro-dimples that serve as reservoirs for lubricants, traps for debris, and stressrelief structures. LST surface modification in both the dry and wet conditions has optimum performance, resulting in the lowest specific wear rates. The sliding velocity is another key factor influencing wear behaviour, with increased velocities leading to a reduction in wear rate across all conditions. This behaviour is related to the development of stable transfer films and a shift towards hydrodynamic lubrication at higher velocities for the specimens under wet conditions. These findings suggest that UHMWPE components implanted for active patients could greatly benefit from surface modifications combined with robust lubrication strategies.

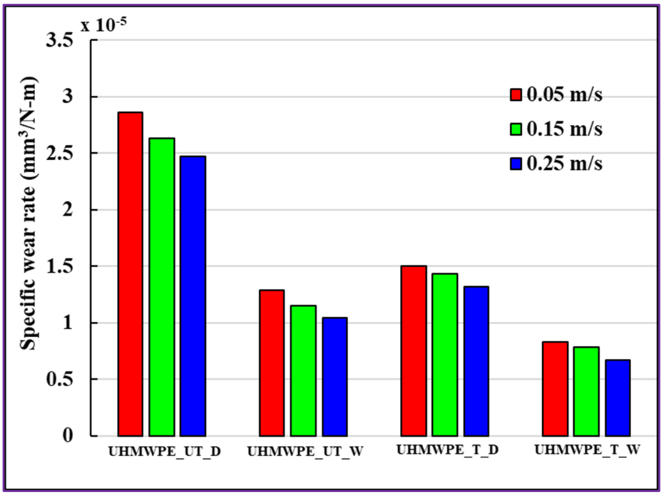

Fig. 13. Specific wear rate versus sliding velocities.

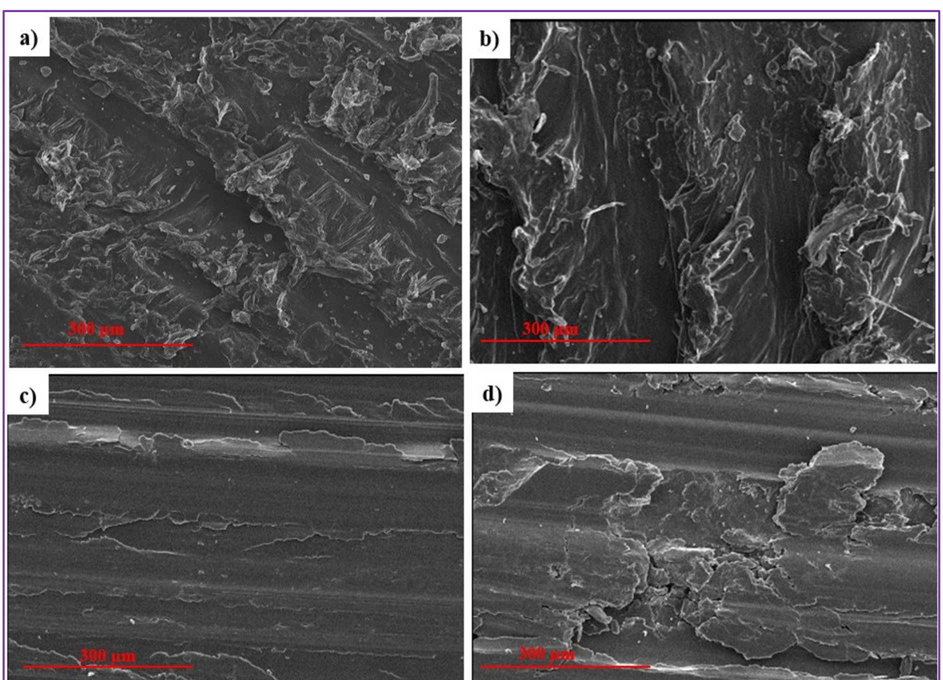

Fig. 14. SEM micrographs after wear test: (a) UHMWPE_T_D, (b) UHMWPE_UT_D, (c) UHMWPE_T_W, and (d) UHMWPE_UT_W.

Figure 14 presents SEM micrographs of UHMWPE surfaces after tribological testing under varying conditions. Figure 14. (a) show the UHMWPE_T_D specimen, where significant wear tracks and debris are visible, suggesting abrasive and adhesive wear mechanisms. Figure 14. (b) Illustrates UHMWPE_UT_D specimen, reveals more severe surface damage with pronounced material delamination and ploughing, indicating poor wear resistance due to direct asperity-asperity contact. Figure 14. (c) illustrates the UHMWPE_T_W specimen, the surface appears relatively smooth with fewer cracks and minimal debris, highlighting the effectiveness of the lubricant in maintaining a stable tribofilms and reducing friction. Figure 14. (d) shows the UHMWPE_UT_W specimen, which has an improved scenario when compared to dry conditions.

4 Conclusion

The tribological behaviour of UHMWPE surfaces was investigated with a focus on the influence of LST modification methods using a pin-on-disc tribometer setup. Experiments were carried out under two distinct conditions of dry and wet using a sunflower blend. The study concludes the following key findings:

(i) Circular dimples were successfully introduced onto the UHMWPE surface through the use of an Nd: YAG laser texturing system. The implementation of LST led to a substantial improvement in tribological performance by showing reductions in wear rate and friction across both dry and lubricated conditions. Overall reduction in wear rate values ranged from 30% to 50%.

(ii) Under dry sliding conditions, an increase in sliding velocity has slightly rise in the wear rate, suggesting that higher velocity negatively impact the wear resistance of UHMWPE substrates in the absence of lubrication.

(iii) Under wet conditions, the UHMWPE samples resulted in improvement in wear resistance. The application of sunflower oil serum significantly lowered wear rate and friction. Nearly 90% wear rate was observed with effectiveness of lubrication in preserving material integrity under identical testing parameters.

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