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An experimental investigation on tribological performance of UHMWPE composite under textured dry sliding conditions

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KEYWORDS

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Dry sliding
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Wear
Friction
Indentation hardness

ABSTRACT

Polymer and polymer composites have been increasingly used in various industrial applications such as, aerospace, automotive and chemical industries. This is because these materials provide high strength to weight ratio. In this work attention is given to investigate the effect of surface texturing on tribological performance of UHMWPE and its composite considering various dry sliding conditions under varying loads of 181.42 N, 171.61 N, 156.9 N and different sliding velocities of 0.12 m/s, 0.105 m/s and 0.09 m/s. In this work plain AISI SS 304 stainless steel disc and disc having triangular surface texturing pattern were used for experimentation. Effects of surface texturing densities 0%, 10%, 20% and orientation of texture pattern were identified experimentally by using a pin-on-disc type wear tester (TRLE-PHM400). It was observed that specific wear rate is least for UHMWPE +2% for 10% dimple density with surface texture orientation of equilateral triangles base towards the center of disc. Worn surface of UHMWPE composites with carbon black shows groove patters perpendicular to sliding direction. As carbon black percentage increases in the UHMWPE composites, grooves are flattened indicating less specific wear rate; this is due to formation of transfer layer at the dimpled counter face.

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1.0 INTRODUCTION

Ultra-high molecular weight polyethylene (UHMWPE) is the important polymer in tribology. It has excellent chemical resistance, high damping properties, high impact resistance and its self-lubricating performance made it widely used in engineering applications of bearing materials subjected to sliding wear and corrosive environment (Weston et al., 2011). UHMWPE is known to be an attractive engineering polymer for applications where wear and friction are the main concerns. Such bearing materials are essential for the manufacturing of friction assemblies, which operate in the inaccessible sections of vehicle, textile, food processing machinery and chemical industries. Different types of bearing composites have been developed for operation without an additional lubricant (Gutiérrez, 2011). UHMWPE is an advanced engineering plastic that exhibits ultra- low water absorption, excellent chemical stability, and high impact strength and advantages that make it potentially suitable for application in water lubrication (Wang, 2009 & Xiong, 2001).

Vadivel et al. (2018) newly developed hybrid composite with UHMWPE as base polymer and grapheme oxide, nano diamonds and short carbon fibers as filler were manufactured. Effects of fillers on mechanical and thermal properties of composites were investigated. Tribological performance of these composites in water lubrication was studied. Results showed low coefficient of friction and high wear resistance compared to unfilled UHMWPE composites. Wang et al. (2017) studied effect of glass fiber and carbon fiber filler material on the friction and wear characteristics of UHMWPE based composites. Composites were evaluated against GCr 15 steel for dry and water lubricated conditions. Glass fiber and carbon fiber significantly reduces the friction coefficient under water lubricated and dry conditions.

The tribological and mechanical properties of UHMWPE reinforced with poly tetra fluoro ethylene (PTFE) under dry and water lubrication conditions showed that the wear rate of composites was greatly reduced, while mechanical characteristics did not change significantly after the addition of PTFE (Panin et al.,2015). Tong et al. (2003) studied the effects of regular and surface-modified wollastonite fibres on the tribological behaviour of UHMWPE at varying wollastonite contents. Results showed that the friction coefficient of UHMWPE composites increased with an increase in fibre content, and the wear resistance was highest when the fiber content was about 10 weight percentage. Blanchet et al. (2010) filled PTFE with alpha-phase alumina nanoparticles and found that an increase in filler content was able to reduce the wear rate against a rougher counter face. Researchers suggested that counter face morphology has a great influence on the friction and wear characteristics of composites (Zsidai et al., 2002; El-Domiaty et al. 2002 & Wang et al., 2009). Counter face morphology plays sacrificial role in the occurrence of different wear mechanisms, which is intrinsically connected to friction coefficient values (Barrett et al., 1992 & Stupak et al., 1990). Toughness of epoxies can be enhanced by the incorporation of second phase filler like UHMWPE. A property of UHMWPE that distinguishes it from other polymers is its highly entangled molecular chains which make it wear resistant. UHMWPE is known as a long chain wear resistant polymer with a moderate coefficient of friction against steel counter face (Golchin et al., 2015). Quaglini et al. (2009) investigated effects of the roughness of the metal counter face (mirror finished or polished) on the coefficient of dry friction for some of the most common engineering plastics currently used in bearing technology. Results showed that an optimal roughness for minimum friction is likely to exist for any polymer, and it depends on the bulk properties of the polymer itself. ‘‘Soft” plastics characterized by a low modulus of elasticity exhibit better sliding behaviour on very smooth and mirror finished surfaces whereas for high-modulus plastics lower friction is measured in combination with rougher and polished counter faces. The influence of the contact pressure and sliding velocity were also investigated and found to be dependent on the layout of the tribological system.

Vilhena et al. (2009) identified that specific textures on a tribological surface can contribute to friction reduction in sliding contacts. Micro-dimple array has been generally considered as valuable textures for sliding surfaces. It can improve lubrication and reduce wear by acting as reservoirs of lubricants and grinding debris. Laser shock processing (LSP) is an innovative process which not only improves fatigue, corrosion and wearing resistance but also shape of metallic parts accurately. Zhang et al. (2012) identified surface texturing as one of the effective surface engineering technologies to significantly improve tribological performance of mechanical parts. Kovalchenko et al. (2009) studied laser surface texturing (LST) as an emerging effective method for improving the tribological performance of friction units lubricated with oil.

It is advantageous to replace metal parts in various industries such as manufacturing of cars, airplanes, etc. by polymer-based materials. Advantages include lower density, less need for maintenance and lower cost. The main reason for the trend of replacing metal parts by polymers is energy-saving. Density of polymers is generally lower than the density of metals, therefore with a certain amount of fuel the car with the polymer parts can travel greater distance compared with a standard car with metal parts; the same applies to airplanes (Brostow et al., 2010). Chang et al. (2013) studied UHMWPE reinforced with micro-zinc oxide (ZnO) and nano-ZnO under different filler loads. The wear and friction behaviors were monitored using a pin-on-disc (POD) test rig and observed that UHMWPE reinforced with micro- and nano-ZnO would improve the wear behavior. The average coefficient of friction (COF) for both micro- and nano-ZnO/UHMWPE composites was comparable to pure UHMWPE. Xiong et al. (2001) studied friction and wear behavior of UHMWPE sliding against Al_2O_3 ceramic under dry sliding and lubrication by fresh plasma, distilled water and physiological saline were investigated with a self-made pin-on-disk apparatus and observed that the wear rate of UHMWPE under dry sliding is the highest and under plasma lubrication is the lowest.

Xiong, D. (2005) presented that increase in carbon fiber percentage in UHMWPE reduces specific wear rate however hardness of composite goes on increasing. In this work an application of sugar mill bearing material was considered. Considering the hardness required for sugar mill bearing material in the range of 60-80 HRC, UHMWPE composites with carbon particles in the proportions of 1% and 2% by weight were tested using a pin-on-disc tribometer (TRLE-PHM400). AISI SS 304 stainless steel disc was used with and without triangular surface texturing pattern. Zhang, H. et al. (2016) presented numerical model for mixed lubrication of different surface texture patterns like circular, square and equilateral triangle. Numerical model for the lubrication was validated by pin on disc experimentation. Results showed least coefficient of friction for equilateral triangle surface texture pattern. However, from literature it is seen that effect of dimple densities on specific wear rate was not identified for UHMWPE composites. Therefore, counter face disc with surface textured densities 0%, 10 % and 20% was used for experimentation. Orientation of equilateral triangle surface texture with apex of triangle towards center and base of triangle towards center of disc was used. Tests were carried out at ambient conditions under dry sliding conditions with loads of 181.42 N, 171.61 N, 156.9 N and sliding velocities of 0.12 m/s, 0.105 m/s and 0.09 m/s.

2.0 MATERIALS AND METHODS

2.1 Preparation of UHMWPE Composite Pins

UHMWPE composite pins were manufactured from UHMWPE in powder form and carbon black powder by the process of injection moulding. UHMWPE powder is shown in Figure 1(a) and carbon black powder is as shown in Figure 1(b).

(a) (b)

Figure 1: (a) UHMWPE powder and (b) carbon black powder.

The mould is designed to get pins of diameter 10 mm and length 30 mm. The mould is shown in Figure 2. Carbon black powder was mixed with UHMWPE powder by weight percentages of 0%, 1% and 2%.The mould was attached to injection moulding machine as shown in Figure 3 and the mixture of UHMWPE and carbon back of different proportions is fed into the mixer which prepares a homogeneous mixture by rotating in clockwise and anti-clockwise direction.

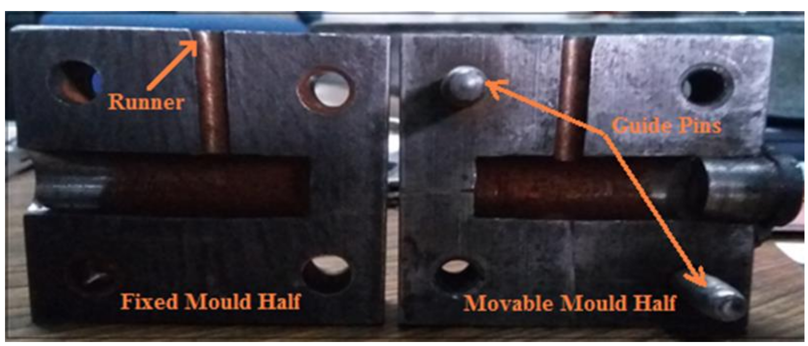


Figure 2: Mould for manufacturing UHMWPE composite pins.

Finally, the mixture is fed into the injection moulding machine and different pins of UHMWPE composites are obtained by finishing process to get desired dimensions as shown in Figure 4. Mechanical and physical properties of pure UHMWPE and UHMWPE composite with 1 % and 2 % carbon black (CB) powder are as shown in Table 1.

Figure 3: Injection moulding machine.

(a) (b)

Figure 4: (a) UHMWPE composites pins (b) schematic diagram of pin with dimension.

Table 1: Mechanical and physical properties of pure UHMWPE and UHMWPE composites with 1 % and 2 % carbon black (CB) powder.

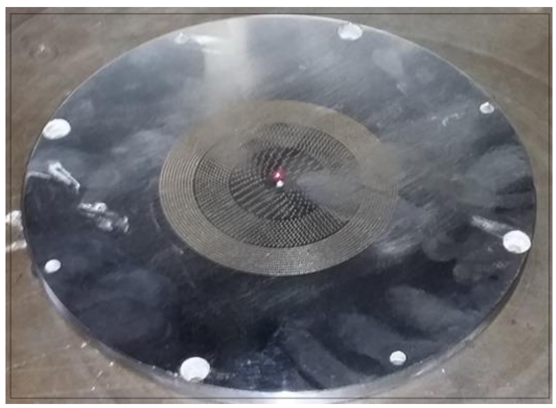
Sr. No.	**Property**	**Units**	**UHMWPE**	**UHMWPE + 1% CB**	**UHMWPE + 2% CB**
1	Density	Kg/m^3	930	1180	1210
2	Tensile strength	N/mm^2	83.30	85.35	87.31
3	Elongation	%	9.88	10.36	11.87
4	compressive strength	N/mm^2	1297.7	1479.81	1576.87
5	Flexural strength	N/mm^2	8838.10	91387.92	8962.09
6	Flexural modulus	N/mm^2	260.39	272.97	283.75
7	Hardness	HRC	46-53	57-60	60-63

2.2 Preparation of Disc

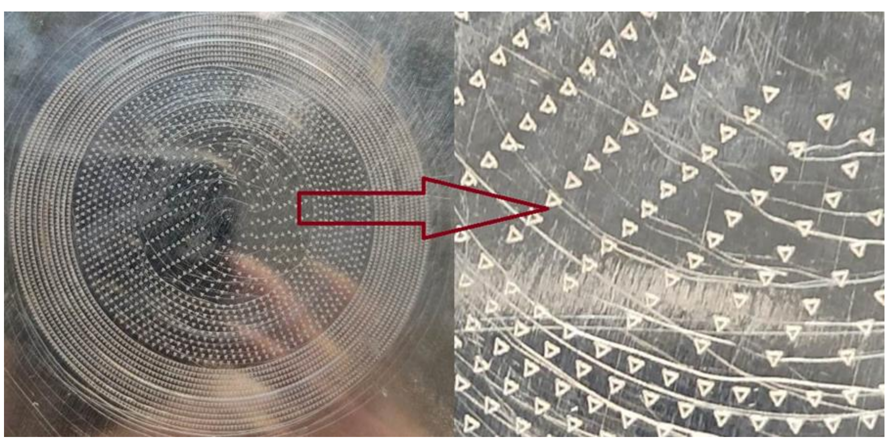
The material of disc is AISI SS 304 stainless steel. The equilateral triangular texture pattern with varying densities of 0%. 10% and 20% was manufactured as shown in Figure 5. The chemical composition of disc is as shown in Table 2.

Table 2: Chemical Composition of AISI SS 304 stainless steel disc.

Content	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**
Percentage	0.069	0.294	0.901	0.030	0.007	18.36	8.3



(a)



(b)

Figure 5: (a) AISI SS 304 stainless steel disc (b) Textured view of AISI SS 304 stainless steel disc.

Equilateral triangle surface textures are arranged on disc with base of triangle towards center and apex of triangle towards center as shown in Figure 6(a) and 6(b) respectively.

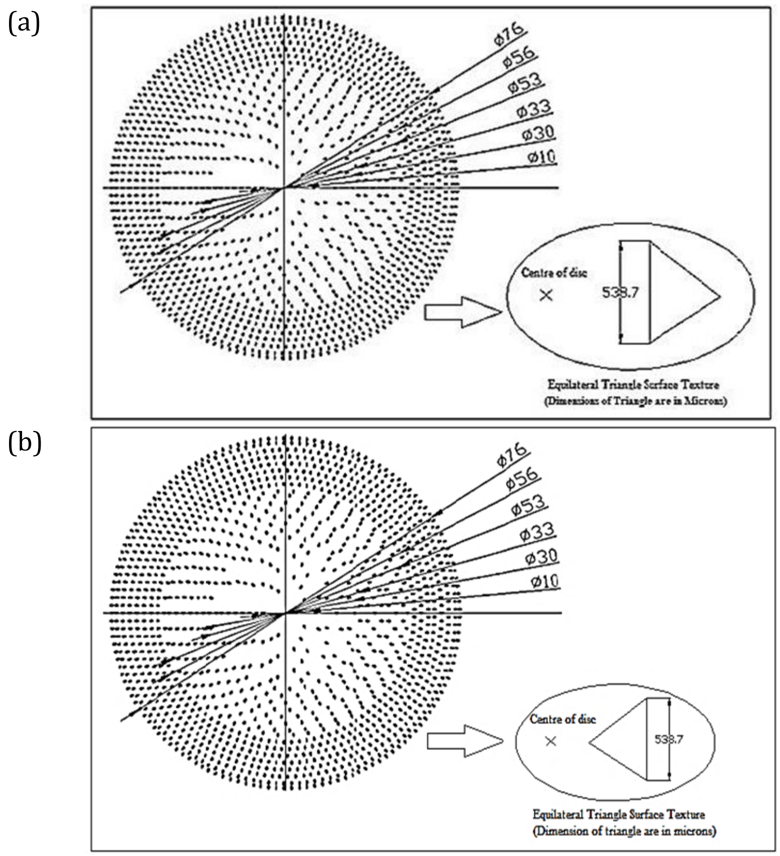


Figure 6: Orientation of equilateral triangle surface texture on the disc with (a) base of triangle and (b) apex of triangle towards center of the disc.

3.0 EXPERIMENTAL DETAILS

3.1 Experimental Setup

The tribometer TRLE-PHM400 Pin on disc wear test rig as shown in Figure 7 is an advanced set up regarding the simplicity and convenience of operation, ease of specimen clamping and accuracy of measurements, both of wear and frictional force along with lubrication and environmental facility.

The machine is designed to apply loads up to 197N and is intended both for dry and lubricated test conditions. It facilitates study of friction and wear characteristics in sliding contacts under desired test conditions within machine specifications. Sliding occurs between the stationary pin and a rotating disc. Normal load, rotational speed and wear track diameter can be varied to suit the test conditions. Tangential frictional force and wear are monitored with electronic sensors and recorded on computer. These parameters are available as a function of load and speed. The machine consists of spindle assembly, loading lever assembly, sliding plate assembly and environmental chamber, all mounted on base plate over structure made up of welded steel tubes which absorbs entire force and load acting during testing. To minimize the vibration during testing, it is fitted with four numbers of adjustable anti- vibration pads at base. Some items like AC motor, variable frequency drive and all electrical items are fitted inside the structure and sides of it are covered with panels.

The wear disc is mounted on the spindle top and is driven by an AC motor through a timer belt, which provides high torque drive with low vibration. The loading lever with specimen holder fixed at one end and at other end, it carries a wire rope for suspending dead weights to apply normal load on specimen. The frictional force produced between specimen pin and disc is directly measured by the load cell at another end. The specimen pin is placed inside a hardened split jaw and clamped to specimen holder. To clamp different sizes of specimens, individual jaws are provided for different sizes of pin specimens. The oil for test is supplied by a lubrication unit fixed at base of machine.

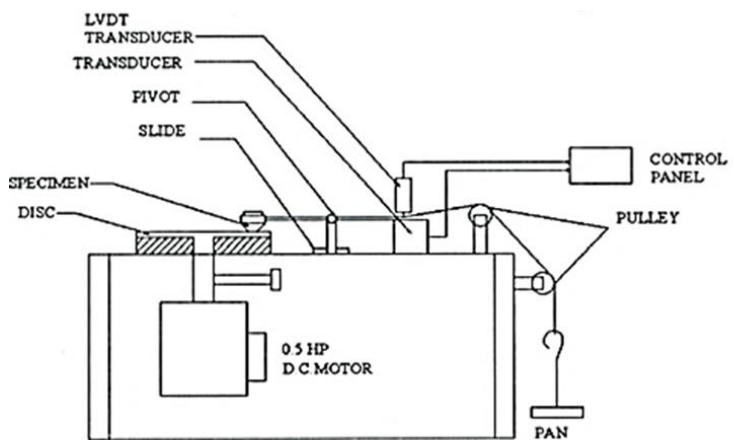


Figure 7: Pin on disc wear test rig.

The wear between specimen pin and disc is measured by LVDT (linear variable differential transducer) and is sensed by a sensor mounted on lever. Wear rate is measured using LVDT. Wear of specimen is measured directly as the sensor is mounted at exactly same distance from pivot to specimen with equal leverage 1:1. The plunger of sensor rests on hardened pin specimen projection from lever and as wear occurs, plunger moves in and loading lever is lifted upwards. This movement is displayed on wear monitor as wear. Wear is measured in microns. The least count of LVDT is 0.1 micron.

The friction between specimen pin and rotating disc is measured by a strain gauge type load cell mounted on a bracket. The spindle speed is measured by proximity sensor through a rpm sensor disc. The machine operation is controlled by a electronic controller which is connected to machine through a set of cables, control cable and signal input cable. The signals pass from machine to controller and then controller processed signals to connect to computer. The signals from wear and frictional force sensor are sent to instrumentation card, the output from which is sent to data acquisition card and the output from it is sent to display on controller and to computer.

3.2 Design of Experiments

Number of experiments are decided according to Taguchi design. Factors for design of experiments are load, sliding velocity; dimple density and material at 3 levels of each, Orientation of triangular surface texture pattern are also accounted in the design of experiments. Factors and their levels for design of experiments are as shown in Table 3.

For selection of parameters of load and sliding speed, an application of heavily loaded sugar mill journal bearing as shown in Figure 8 was considered.

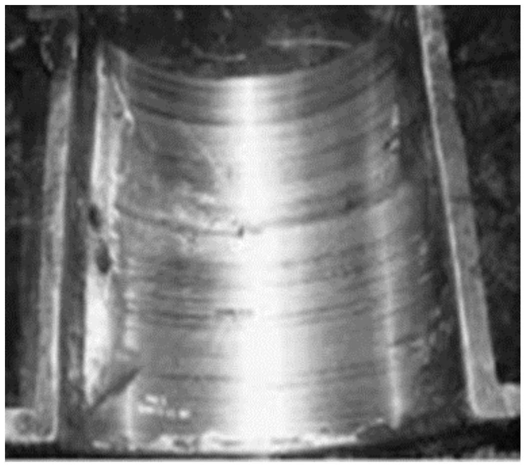


Figure 8: Sugar mill journal bearing.

Sugar mill bearings are subjected to oil pressure in the range of 6-8 Mpa and load of 2.1 MN. Journal speed of sugar mill is about 3.5-6 rpm. Considering load on bearing and speed of journal, sliding speed and load required for pin on disc experimentation are scaled as shown in Table 3. Load range for pin on disc was scaled considering contact pressure on the sugar mill journal bearing. The hydraulic load on sugar cane crushing mill is in the range of 5 to 7 N/mm^2. Considering the piston area of hydraulic loading mechanism and projected area of sugar mill bearing dimensions (length of bearing= 495 mm and diameter roller in bearing =380 mm), contact pressure range on sugar mill bearing was evaluated. Same contact pressure range was used to evaluate load parameter for pin on disc experimentation.

Table 3: Factors and their levels.

Control Factors	**Units**	**Type**	**Levels**	**Level**		
				I	**II**	**III**
Dimple density	%	Numeric	3	0	10	20
Material	Type	Text	3	UHMWPE	UHMWPE + 1 % CB	UHMWPE + 2 % CB
Load	N	Numeric	3	156.91	171.62	181.42
Sliding Velocity	m/s	Numeric	3	0.09	0.105	0.12
Orientation	-	Text	2	Apex towards center	Base towards center	-

According to Table 3 for design of experiments using Taguchi approach 18 optimum number of experiments are obtained for various combinations of different levels of the five factors as shown in Table 4. Wear is the response of experiments.

Table 4: Combination of parameters at different levels.

Run	Load N	Sliding Velocity m/s	Dimple Density	Material	Orientation
1	181.42	0.12	0	UHMWPE	Apex
2	181.42	0.105	10	UHMWPE + 1% CB	Apex
3	181.42	0.09	20	UHMWPE + 2% CB	Apex
4	171.62	0.12	10	UHMWPE + 2% CB	Apex
5	171.62	0.105	20	UHMWPE	Apex
6	171.62	0.09	0	UHMWPE + 1% CB	Apex
7	156.91	0.12	20	UHMWPE + 1% CB	Apex
8	156.91	0.105	0	UHMWPE + 2% CB	Apex
9	156.91	0.09	10	UHMWPE	Apex
10	181.42	0.12	0	UHMWPE	Base
11	181.42	0.105	10	UHMWPE + 1% CB	Base
12	181.42	0.09	20	UHMWPE + 2% CB	Base
13	171.62	0.12	10	UHMWPE + 2% CB	Base
14	171.62	0.105	20	UHMWPE	Base
15	171.62	0.09	0	UHMWPE + 1% CB	Base
16	156.91	0.12	20	UHMWPE + 1% CB	Base
17	156.91	0.105	0	UHMWPE + 2% CB	Base
18	156.91	0.09	10	UHMWPE	Base

As experiments were conducted for different load and sliding speed for different compositions of UHMWPE and CB, it was difficult to compare tribological performance on the basis of mere wear of pins. Therefore, comparison of wear of pins was done on the basis of specific wear rate of pins. Specific wear rate of pins is evaluated using Eq. (1)

$$k=\frac{W}{FVT} \tag{1}$$

Where k is specific wear rate in mm^3/N-m, W is wear volume in mm^3, F is normal load in N, V is sliding velocity in m/s and T is test duration in seconds.

4.0 RESULTS AND DISCUSSION

4.1 Effect of CB Content on Hardness and Specific Wear Rate of UHMWPE Composites

As shown in Table 1, hardness of UHMWPE increased with addition of CB 1% and 2 %. Figure 9 (a), (b) and (c) shows the specific wear rate of UHMWPE, UHMWPE + 1 % CB and UHMWPE + 2 % CB for 0%, 10% and 20% dimple densities respectively. Surface texture orientation of equilateral triangle on the disc is apex of triangle towards the center of disc.

Figure 10 (a), (b) and (c) shows the specific wear rate of UHMWPE, UHMWPE + 1 % CB and UHMWPE + 2 % CB for 0%, 10% and 20% dimple densities respectively. Surface texture orientation of equilateral triangle on the disc is base of triangle towards the center of disc.

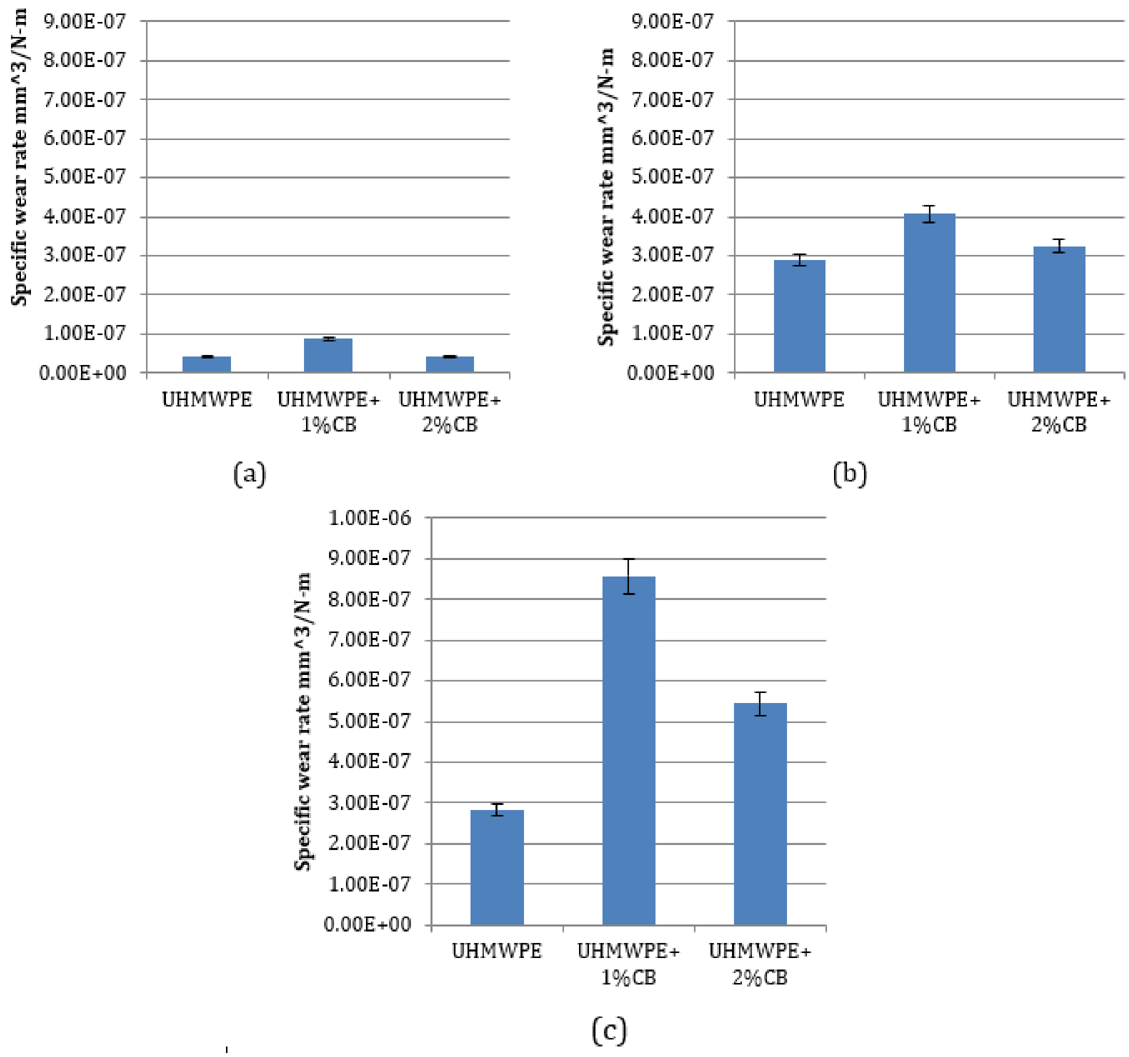


Figure 9: Specific wear rates with the orientation of surface texture equilateral triangle apex towards the center of disc for (a) 0% dimple density (b) 10% dimple density (c) 20% dimple density.

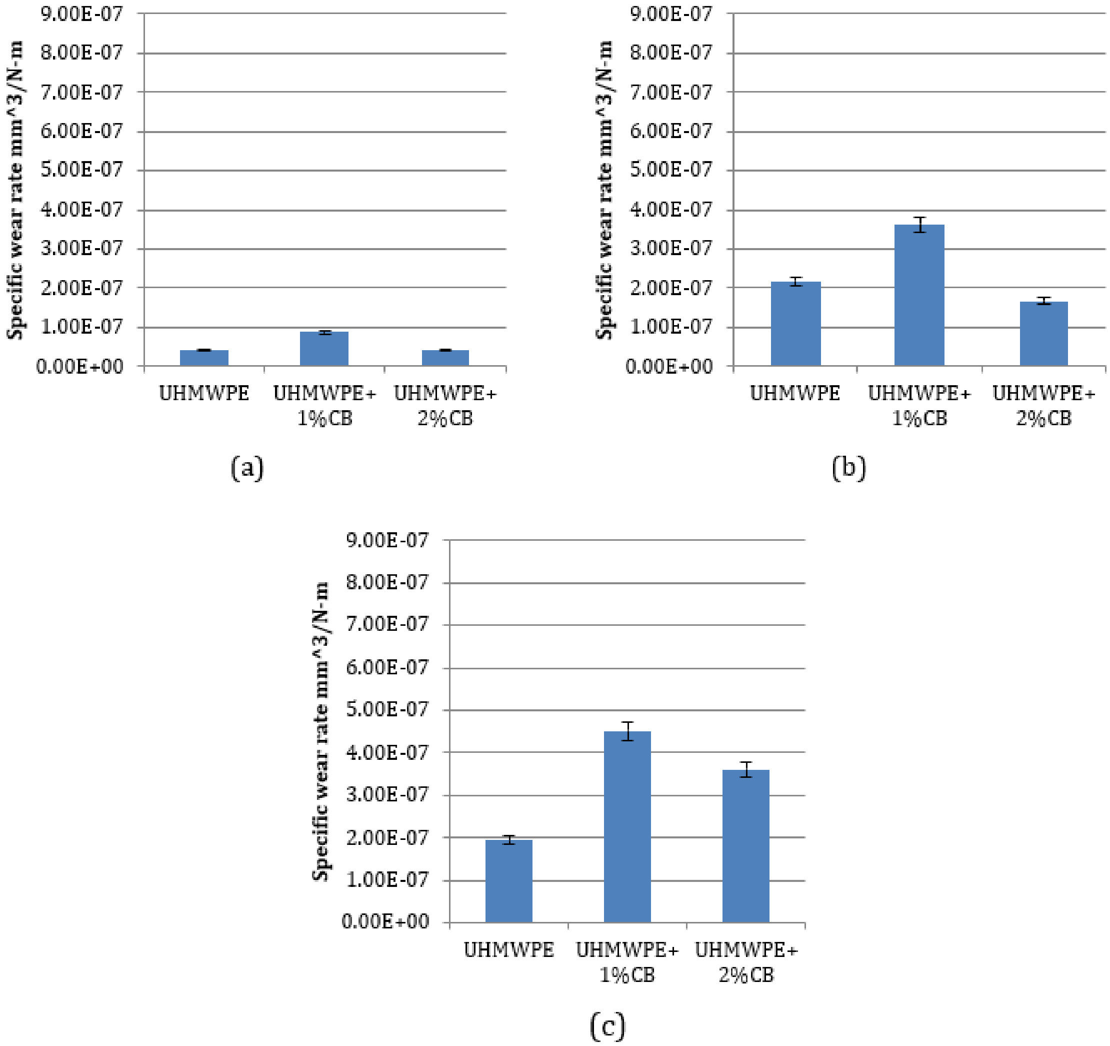


Figure 10: Specific wear rates with the orientation of surface texture equilateral triangle base towards the center of disc for (a) 0% dimple density (b) 10% dimple density (c) 20% dimple density.

From Figures 9 and 10, specific wear rate decreases with the increase in carbon black. For 2% carbon black in all cases, specific wear rate is least as compared to UHMWPE and UHMWPE +1%. As the load and sliding speed increases specific wear rate also increases. This is due to surface softening from frictional heating.

4.2 Effect of Surface Texture Orientation and Dimple Density on Specific Wear Rate of UHMWPE Composites

Figures 9 and 10 shows effect of orientation of surface texture and dimple densities on specific wear rates for UHMWPE composites. As dimple density increases specific wear rate increases. This is due to abrasion wear of UHMWPE composites. Due to increase in dimple density rapid wear is observed for 20 % dimple density counter face for both surface texture orientations. It was observed that for 10 % density specific wear rate was less as compared to 20% dimple density. As dimple density increases contact area between pin and disc decreases which results in increase in contact pressure, this causes increase in specific wear rate. Thus, increase in dimple density has adverse effect on specific wear rate. However, for surface texture orientation of equilateral triangles base towards the center of disc as shown in Figures 10 (a), (b) and (c) specific wear rate is less as compared to orientation of surface texture of equilateral triangle apex towards the center of disc. From Figures 9 and 10 it is observed that specific wear rate is least for UHMWPE +2% for 10% dimple density with surface texture orientation of equilateral triangles base towards the center of disc. Deposits of UHMWPE powder in the grooves of dimples forms the transfer film and reduces specific wear rate.

4.3 SEM Studies on Worn Surfaces and Transfer Film of UHMWPE Composites

The comparison on the worn surfaces of UHMWPE composites are shown in Figure 11, 12 and 13 for different load and sliding conditions. For all worn surfaces it is observed from SEM that wear grooves are formed perpendicular to sliding direction. However, with increased CB in the composite and increased dimple densities grooves are flattened indicating lower specific wear rate. This is due to deposition of carbon black and UHMWPE in pockets of dimples and forming the transfer film. Adhesion, abrasion, plastic deformation due to increase in temperature and fatigue are common wear mechanism for UHMWPE polymer composites under dry sliding condition. It is important to note that surface mechanical properties are significant factors to identify wear mechanism of polymers. From figure 11 it is clearly observed that a good transfer film of UHMWPE and CB with uniform thickness is formed over entire counter face. Transfer film smooth in morphology is observed when UHMWPE is modified with filler carbon black. Figure 12 shows that the smoother and more uniform transfer film leads to less frictional contact and hence results in lower specific wear rate. Figure 13 shows deeper wear grooves and non-uniform transfer film. From SEM analysis it is observed that a good quality transfer film reduces the wear of UHMWPE composites against dimpled counter face.

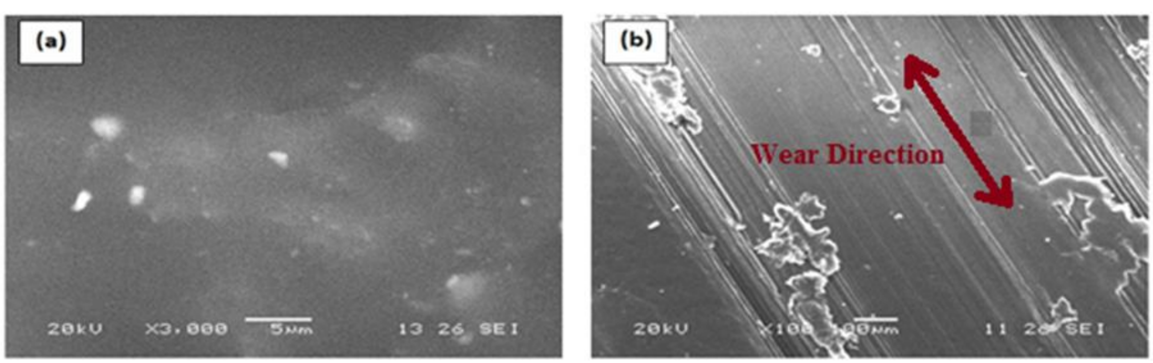


Figure 11: SEM micrographs of worn surfaces of UHMWPE + 2% CB, Load=171.62N, Density=10% and Sliding Velocity=0.12m/s (a) before wear test (b) after wear test.

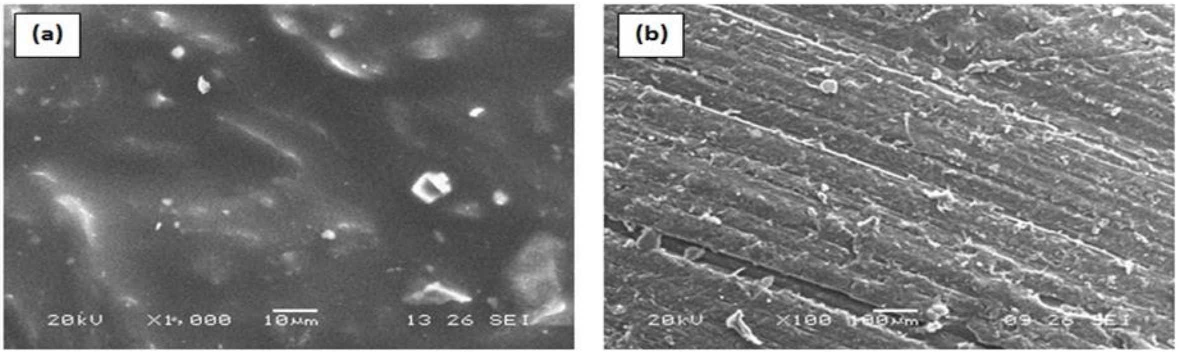


Figure 12: SEM micrographs of worn surfaces of UHMWPE + 2% CB, Load=181.42 N, Density=20% & Sliding Velocity=0.09 m/s (a) before wear test (b) after wear test.

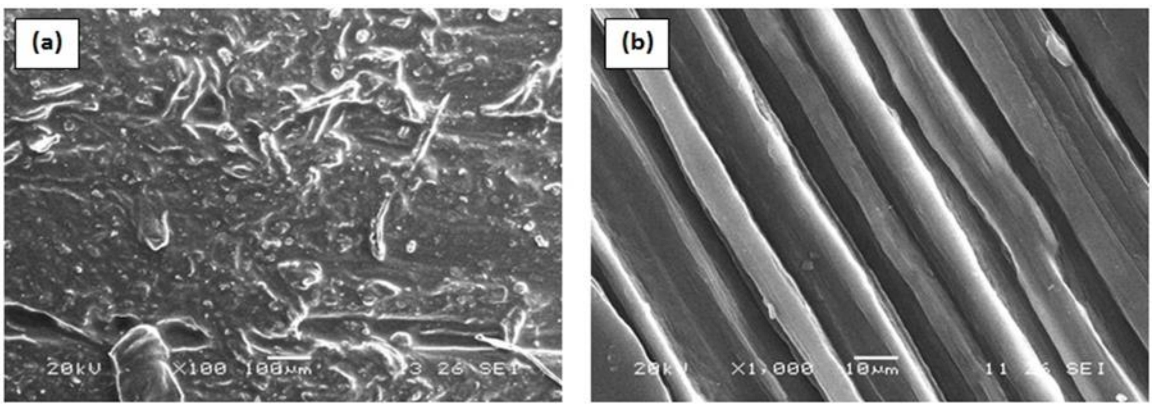


Figure 13: SEM micrographs of worn surfaces of UHMPE, Load=156.91N, Density=10% & Sliding Velocity=0.09 m/s (a) before wear test (b) after wear test

5.0 CONCLUSIONS

Tribological performance of UHMWPE composites can be summarized as follow.

1. For surface texture orientation of equilateral triangle base towards center, specific wear rate is less compared to apex of triangle towards center.
2. It was observed that for 10 % density specific wear rate was less as compared to 20% dimple density. Thus, increase in dimple density has adverse effect on specific wear rate.
3. Worn surface of UHMWPE composites with C.B., shows groove patters perpendicular to sliding direction. As C.B. percentage increases in the UHMWPE composites grooves are flattened indicating less specific wear rate, this is due to formation of transfer layer at the dimpled counter face.

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