Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 44 No.4 (2023)

"Enhanced Wear Characteristics of UHMWPE Composite Reinforced with Nano ZnO: Experimental Investigation and Microstructural Analysis"

H S Yeshvantha[1]*, Chethan D[2], Kiran Kumar N[3], Yuvaraja Naik[4], Ravi Kumar M[5], AJK Prasad[6]

[1]**Department of Mechanical Engineering, Sir M Visvesvaraya Institute of Technology, Bengaluru,India- 562157*
[2]*Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, Bengaluru, India- 560064*
[3]*Department of Mechanical Engineering, Vemana Institute of Technology,Bengaluru, India- 560034*
[4]*Department of Mechanical Engineering, Presidency University,Bengaluru, India- 560064*
[5] *Department of Mechanical Engineering, S J C Institute of Technology, Chikkaballapur, India- 562101*
[6]*Department of Mechanical Engineering, Sir M Visvesvaraya Institute of Technology, Bengaluru,India- 562157*

Abstract
This work aims to study how Ultra-High Molecular Weight Polyethylene (UHMWPE) composites reinforced with various concentration of nano ZnO (2.5%, 5%, 7.5%, 10%, and 12.5%) wear under dry conditions. The track radius was maintained at 50 mm during the wear tests, which were run for a total of 660 seconds under various load and sliding speed conditions. With the intention of examining the impact of nano ZnO on the wear properties of the composite, the wear parameters examined include specific wear rate, wear loss, and coefficient of friction (COF). The findings show that adding nano ZnO causes specific wear rate, wear loss, and COF to decrease. The UHMWPE composite's wear resistance gets better as the amount of nano ZnO rises. Due to the increased load-bearing capacity offered by the nano ZnO reinforcement, specific wear rate, wear loss and COF have decreased. Nano ZnO particles serve as a protective barrier, minimising wear by decreasing contact between the sliding surfaces. The results also show that greater applied loads and sliding speeds tend to increase the values of wear rate, wear loss and COF. The contact pressure and frictional forces become more intense along with the increase in load and speed, which results in more material removal and more resistance to sliding motion. Reduced groove diameters and plastic flow, as shown by microstructural examination of the worn surfaces, point to increased load-bearing capacity and deformation resistance. Nano ZnO strengthens the composite matrix and makes it easier for a smoother wear surface to develop, which in turn increase the total wear resistance of the PMC.

Keywords**:** *UHMWPE, Zno, Wear rate, Wear loss, CoF*

1. Introduction

UHMWPE has high wear-resistance, toughness, durability, and biocompatibility. Therefore, it is commonly used as a bearing material with ceramic or metallic counter surfaces in joint arthroplasty [1,2] UHMWPE's significance for achieving outstanding performance in total joint arthroplasties is unquestionable [3,4]. For long-term clinical applications, its tribological performance and lifetime are key aspects [5,6]. However, UHMWPE implants have limited life due to their wear complications. When the UHMWPE is used in the periprosthetic environment it induces osteolysis followed by loosening of the implant. This implant loosening is joined with fatigue causes the aseptic loosening which ultimately causes the implant's failure. [7,8,9,10]. Many methods such as improving cross-linking [11,12,13,14], or crystallinity percentage [15,16,17,18] through irradiation [19], surface modification through plasma treatment [20,21], or introducing effective textures [22,23], and reinforcements with particles or fibers [24,25,26] have been used for enhancing properties of UHMWPE.

An important method to enhance the properties of UHMWPE is the reinforcement with polymers [27]. Many reinforcing materials such as zinc oxide particles, glass, carbon nanoparticles, and others have been employed to improve the wear resistance of UHMWPE. Blending HDPE and UHMWPE in a 50:50 ratio enhanced both processability and mechanical properties, with a 200% increase in strain at break compared to neat resins. This synergy improved toughness and fracture behaviour, as confirmed by scanning electron microscopy analysis [28]. This study unveiled phase separation in UHMWPE/HDPE composites with carbon nanofibers (CNFs), impacting tribological properties. Microscopic analysis revealed distinct microstructures, with CNFs residing predominantly in the HDPE phase. The addition of CNFs reduced wear rates in UHMWPE/HDPE blends, suggesting that HDPE might not be ideal for processing UHMWPE composites due to its influence on wear resistance [29]. Exploring UHMWPE/PET composites for improved artificial joint wear resistance, this study delved into their rheology, thermal traits, and sintering dynamics for optimized processing. It unveiled a distinct crystallization mechanism, elevated viscosity, and advanced sintering behavior, with surface area dynamics predominating over viscous flow during coalescence, contrasting the Eshelby-Frenkel model [30]. Intriguingly, the study unveils a remarkable 150% boost in strain energy density, a 140% increase in ductility, and up to 25% higher tensile strength in high-strength, high-modulus UHMWPE films with just a 1 wt% addition of multiwalled carbon nanotubes (MWCNTs). Tensile and Raman spectroscopic analyses suggest that MWCNTs enhance chain mobility in UHMWPE, accounting for these significant improvements [31]. This study focuses on enhancing UHMWPE/PET composite performance through chromic acid etching of UHMWPE. The modified composites displayed superior impact properties due to enhanced polymer-fiber interfacial bonding and improved fiber dispersion. Notably, pre-modification of UHMWPE led to enhanced wear resistance, uncovering microploughing and fatigue-related microcracking as the primary wear mechanisms through morphological analysis of worn samples [32]. This research addresses the need for dynamic contact measurement in complex polymeric systems by developing a composite sensor material. Morphological analysis through FESEM and AFM revealed the formation of CB-containing channels within UHMWPE, while mechanical testing showed no significant difference in elastic modulus compared to pure UHMWPE. Remarkably, under dynamic compressive loading, the electrical resistance of CB/UHMWPE composites decreased significantly, highlighting their potential as dynamic contact sensors without the need for high-shear mixing [33]. This study investigates wear and creep resistance in a composite comprising UHMWPE and HDPE reinforced with varying MWCNT concentrations (0.2-2 wt%). The research explores the impact of nitric acid pre-treatment on wear resistance, using ball-on-prism tribometer tests against different steel types. Results indicate that MWCNTs enhance wear performance, reducing the specific wear rate, though challenges in achieving nanotube homogeneity within the matrix suggest further refinement is required [34]. A biocompatible UHMWPE composite, reinforced with nano-sized hydroxyapatite (HA) particles, was successfully fabricated for biomedical purposes. The HA particles, at a 0.5 volume fraction, were uniformly dispersed in the UHMWPE matrix, while hot drawing aligned the polymer chains. The resulting composite displayed a remarkable tensile strength of 100 ± 22 MPa, comparable to cortical bone, and exhibited significant bioactivity by promoting calcium phosphate precipitates in simulated body fluid—an encouraging development for biomedical applications [35]. This study involved the creation of Nano-TiO2/UHMWPE composites, followed by gamma ray irradiation at varying doses. Hardness measurements and wear tests against CoCrMo alloy were conducted in a knee simulator with saline lubrication. Examination of worn surfaces via optical microscopy, along with IR and XRD analysis, indicated that the addition of nano-TiO2 and radiation dose reduction effectively reduced the wear rate in the UHMWPE composites [36]. In the quest to prevent implant failures and osteolysis, the study sought to enhance UHMWPE's tribological properties through carbon nanotube (CNT) incorporation. Chemically treated CNTs were uniformly blended with UHMWPE via ball milling, resulting in compression-molded sheets. Tribological assessments in a ball-on-plate tribometer unveiled distinct wear patterns and friction coefficients between the polymer and nanocomposites. Notably, the introduction of CNTs led to a significant reduction in wear volume and wear coefficients, showing a linear relationship with sliding distance [37]. This study explored zinc oxide (ZnO) reinforced UHMWPE composites, with treated and untreated ZnO particles, prepared using hydraulic hot pressing. The research investigated the influence of ZnO loading on tensile properties and antibacterial performance. Tensile modulus improved with increased ZnO content, while tensile strength and elongation at break decreased compared to pure UHMWPE. Both treated and untreated ZnO-filled

UHMWPE exhibited antibacterial activity against E. coli, with better inhibition observed in the treated ZnO-filled UHMWPE, while showing slight inhibition against S. aureus [38].

Inorganic particles such as alumina [39], silica [40] or hydroxyapatite [41], have been reported for improving wear and mechanical performance.It is important to note that the filler loadings, filler–matrix interaction, dispersion of the fillers in the composites, type of fillers, filler's size and shape are crucial in determining the wearbehaviour of the composites [42]. ZnO was used as the filler in this research since it exhibits excellent mechanical [43], electrical conductivity and anti-bacterial properties [44-46]. The capability of ZnO in reducing bacterial infection displays its potential to be used for medical applications. Subramani et al. [47] reported that the excellent anti-bacterial property of ZnO/PP composites is its effectiveness against two different human pathogenic bacteria, the Staphylococcus aureus and the klebsiella pneumonia. Chang et al. [48] also reported that UHMWPE filled with ZnO showed active inhibition towards Escherichia coli and slight inhibition for S. aureus. ZnO, as filler in polymer matrix composites, has also been studied by various researchers in enhancing the mechanical and tribological properties [49-53]. Although numerous researches have used ZnO-reinforced polymeric material to improve its tribological properties, the implementation of microand nano-scale ZnO in UHMWPE composite has not been extensively studied. The addition of ZnO into the UHMWPE would not only enhance the tribological properties, but also induces additional anti-bacterial properties, which may be useful in biomedical applications such as implant materials, surgery devices and wound-healing materials [54].

Few review articles [55,56,57] have been published to correlate the mechanics and morphology of UHMWPE with its wear and mechanical properties. In one review [58], the influence of CNT and graphene as reinforcements for UHMWPE is evaluated. In a few review articles [59], other advances in UHMWPE for improving wear and mechanical performance are discussed. The elsewhere research on other PMCs have also reported on the mechanical, thermal wear behaviour of composites. This study delves into the thermal and mechanical properties of vinyl ester/glass composites with varying carbon black reinforcements. Differential scanning calorimetry, X-ray diffraction, tensile and flexural testing, along with SEM analysis, were employed for analysis. Notably, a 4% carbon black incorporation into the vinyl ester composite demonstrated a remarkable 30% improvement in tensile strength, 35% in hardness, 45% in flexural strength, 66% in flexural modulus, and 44% in interlaminate shear strength compared to other carbon black percentages [60]. Another study aimed at assessing thermal and mechanical properties of vinyl ester/glass composites, incorporating varying percentages of carbon black using experimental methods. Analysing factors like glass transition temperature, TGA, degradation temperature, hardness, flexural strength, and more, the research employed techniques including differential scanning calorimetry, X-ray diffraction, and mechanical testing. Notably, a 4% carbon black addition to the vinyl ester composite resulted in significant improvements: 30% higher tensile strength, 35% increased hardness, 45% enhanced flexural strength, 66% boosted flexural modulus, and a 44% increase in interlaminate shear strength, compared to other carbon black percentages [61]. However, in such articles, many studies on other polymeric materials are considered for supporting the evidence and there is a lack of clarity regarding the optimal values of the effective methods. In this work an attempt is made to evaluate the wear characteristics of UHMWPE composites reinforced with nano ZnO under dry wear conditions. The novelty of this work lies in its specific focus on UHMWPE composite reinforced with nano ZnO, the comprehensive evaluation of multiple wear parameters, the investigation of various nano ZnO percentages, and the microstructural analysis of wear surfaces. These aspects contribute to advancing the understanding of the wear behaviour of UHMWPE composites and provide insights for the development of high-performance wear-resistant materials.

2. Experimentation

2.1Materials used

The UHMWPE with GUR 4120 grade which is in powder form with molecular weight of 5 x 106 gmol-1 with density of 0.93 g/cm^3 and the other chemicals utilized in the study are procured from Rajdeep Associates, Bangalore. Nano ZnO was prepared using solution process as mentioned in the article [59].

2.2 Sample preparation

After synthesizing the ZnO reinforcements the UHMWPE ceramic oxide mixture was transferred to the multi-cavity die placed on wooden slabs in a table-top hydraulic press. The die was heated using band heaters and insulated with cera-wool blanket covered by a glass fibre cloth. A digital temperature indicator connected to an iron-constantan thermocouple measured the temperature during the hot compression moulding process. Pressure was applied using a bottle hydraulic jack, monitored with a pressure gauge. UHMWPE composites were prepared at 130°C±2°C for 90±2 minutes. After reaching the specified pressure and temperature, compression was continued for the designated time. The power supply was turned off, and upon reaching room temperature, the die was opened, and the samples were carefully removed and stored in labelled, sealed covers.

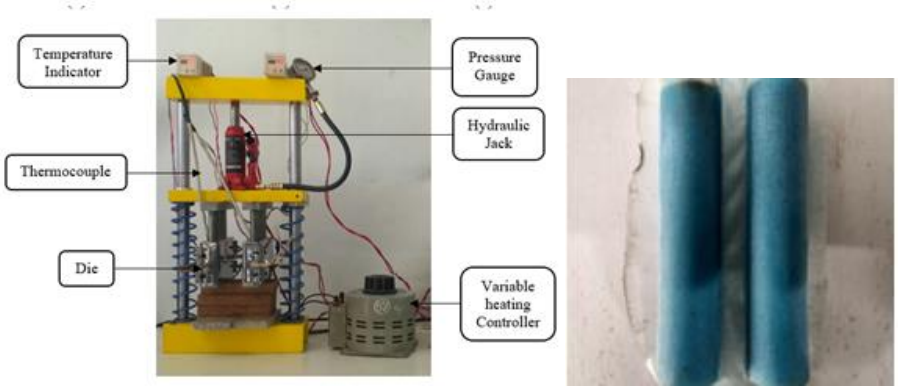

Fig 1: Compression moulding setup and prepared UHMWPE composite

2.3 Density and Porosity measurements

The density of fabricated composites is measured using a digitized density tester based on the Archimedes principle. It works by submerging the composite sample in a liquid with a specified density and observing the force of buoyancy on the sample. Readings are accurate because of digital interface, which also does away with the necessity for manual computations. This testing procedure is effective and trustworthy and aids in figuring out the density of the composites, which is important for judging their performance and quality.

Fig 2: Digitized density tester

2.4 Hardness measurement

To evaluate the produced composites for their hardness Vickers hardness tester was used. The test is commonly used to evaluate the durability of various substances. This procedure involves making an imprint into the specimen using a diamond indenter in the shape of a square-based pyramid. Using the measured diagonal lengths of the imprint and the applied force and area of the impression, a hardness value can be determined. Testing the composites' hardness allows us to analyse their indentation resistance and judge how well the reinforcement contributed to the material's improved hardness.

Fig 3: Hardness tester with loaded sample

2.5 Tribological Characterization

The dry wear test was conducted using the Ducom pin-on-disc friction and wear monitor model TR201LE. Testing time was considered as 660 seconds with different loads of 10N, 20N, and 30N, sliding at speeds of 50, 100, and 150rpm on a track having a constant radius of 50mm. Using the pin-on-disc test setup, characteristics of wear and friction may be determined by simulating sliding contact between two surfaces. By altering the load and sliding speed, the wear performance of the materials may be assessed in a variety of scenarios.

Fig 4: (a) POD wear test machine with sample, (b) wear and friction monitor, (c) Samples

2.6 Microstructural Characterization

The microstructural evaluation of the composites was carried out using various analytical techniques. Scanning Electron Microscopy (SEM) coupled with Energy-Dispersive X-ray Spectroscopy (EDX) was employed for elemental analysis of both the powders and the composite samples. This allowed for the identification and quantification of the constituent elements present in the materials. X-ray Diffraction (XRD) analysis was performed to determine the crystallographic structure of the composites and assess any phase changes or crystalline modifications. The Scherer equation was applied to analyse the particle size of the composites based on the XRD data. Additionally, Dynamic Light Scattering (DLS) was utilized to determine the size of the reinforcement particles in the composites. These comprehensive techniques provided valuable insights into the microstructure, elemental composition, crystallographic structure, and particle size distribution of the composites, contributing to a deeper understanding of their properties and performance. Also, SEM images of wear surfaces are taken to analyse the wear behaviour of the prepared samples.

3. Results and Discussions

3.1 Microstructural Characterization

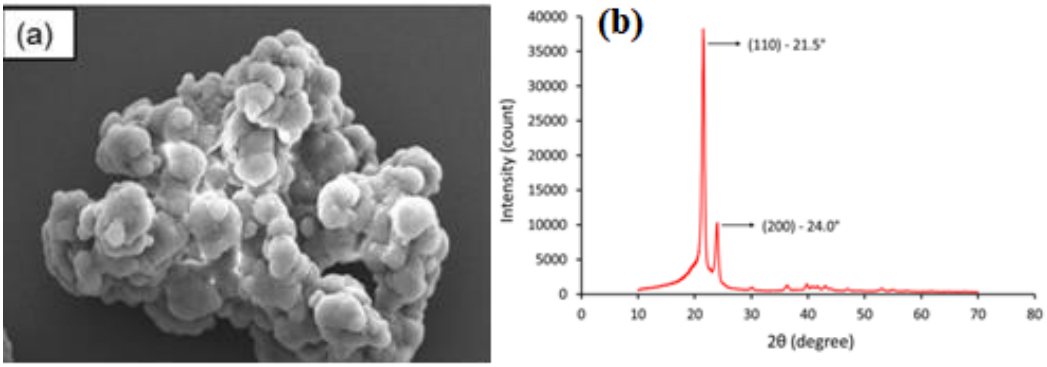

Fig 5: (a) SEM image of UHMWPE, (b) XRD pattern of UHMWPE

Upon microstructural evaluation using SEM (fig 5 a), it is evident that the smaller UHMWPE particles exhibited a significant degree of agglomeration, forming secondary particles that appeared rounded in shape. Close inspection of the microstructure revealed the existence of fibrils. Furthermore, the particles displayed a non-porous nature, and a complex structure was evident. This unique arrangement enhances the UHMWPE's ability to pack into a regular structure, thereby improving its overall surface characteristics. These findings contribute to a improved knowledge of composite's microstructure and its potential impact on its mechanical properties.The XRD pattern of UHMWPE (fig 5 b) reveals the existence of two different phases, indicating its semi-crystalline nature. The first phase corresponds to the amorphous region, while the second phase is characterized by orthorhombic crystalline structure. Notably, two sharp peaks were observed at 21.5 degrees and 24 degrees, corresponding to the (110) and (200) crystallographic planes, respectively. These peaks indicate the presence of well-defined crystalline regions within the UHMWPE structure. The identification of these phases provides valuable insights into the material's crystallographic structure and aids in understanding its mechanical and thermal properties.

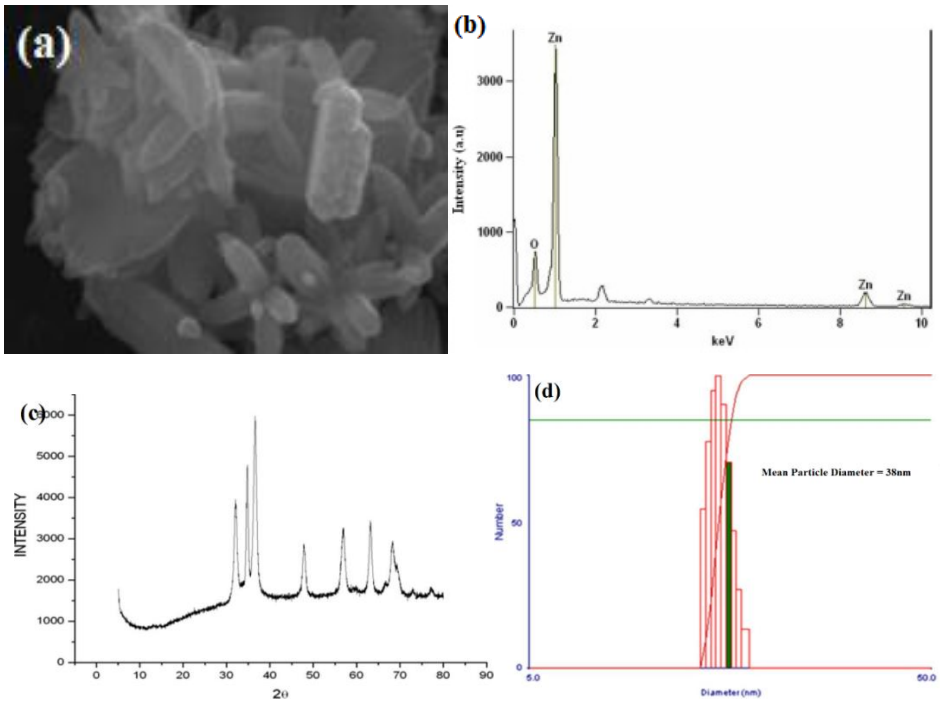

Fig 6: (a) SEM image of ZnO particles, (b) Elemental characterization of nano ZnO, (c) XRD pattern of nano ZnO, (d) Nano ZnO particle size distribution

SEM analysis (fig 6 a) revealed that the ZnO particulates exhibited a pure form, appearing as visually appealing white-coloured nanoparticles. Detailed observations at a magnification of 50,000X captured the distinct

morphology of flower-like and capsulated particles. The size of the synthesized nanoparticles was estimated to be averaged at 41 nm. The SEM images also displayed clustering of particles, indicating homogeneity in size and a reduction in particle size because of the method of synthesis used. Additionally, EDAX was used in elemental analysis (fig 6 b), confirming the presence of zinc (Zn) and oxygen (O) elements in the nano ZnO powder without any detectable impurities.The X-ray diffraction (XRD) pattern of the ZnO powder (fig 6 c) demonstrated a close match with the indexed peaks of bulk ZnO, confirming its purity. The XRD patterns corresponded to the characteristic Wurtzite hexagonal structure of ZnO, in accordance with the JCPDS card number: 01-079-0205. No impurity peaks were detected within the detection limit of XRD analysis, further affirming the high purity of the produced ZnO powder.The ZnO nanoparticles size (average), determined using the Scherer formula, was calculated to be 40 nm. The particle size distribution, depicted in Figure 6d, showed a range of 30-50 nm with a mean size of 40 nm for the ZnO nanoparticles. These findings provide comprehensive information about the morphology, elemental composition, crystal structure, and particle size distribution of the synthesized ZnO nanoparticles.

.2 Density and Porosity Results

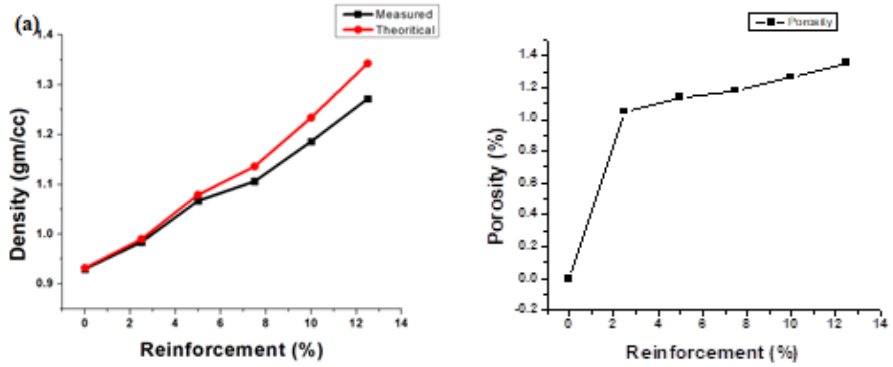

Fig 7: (a) Variation of density, (b) Variation of porosity with variation in reinforcement

Figure 7a shows a rising trend in the produced composites' density. The increased density of the nano ZnO particles in comparison to UHMWPE may be the reason for the rise in density of composites with the inclusion of nano ZnO reinforcement. More of these higher density particles are integrated into the composite material as the amount of nano ZnO grows, increasing the density overall. The observed densities (0.93, 0.984, 1.067, 1.106, 1.186, and 1.272gm/cc) are in line with the increasing amounts of micro ZnO reinforcement (respectively 0%, 2.5%, 5%, 7.5%, 10%, and 12.5%). This pattern demonstrates that the concentration of nano ZnO directly affects the density of the composites, leading to greater overall densities when more nano ZnO is added.PMCs with higher densities may have better wear resistance. Because of the denser composite structure, improved resistance to material loss and degradation during frictional contact, durability and service life are boosted. Nevertheless, this rise in density is accompanied by an equal rise in porosity. The observed porosity values (1.048%, 1.137%, 1.179%, 1.265%, and 1.357%) show that the material contains void spaces. The existence of agglomerates or spaces between the particles, poor mixing or distribution of the reinforcing particles, and inadequate compaction during production are considered to be the causes that might cause this rise in porosity. Despite the general increase in density, these effects cause void spaces to be introduced, leading to greater porosity. While increasing porosity can have a negative impact on the mechanical qualities of composites, it can also have positive effects in some applications, such as better damping characteristics or improved acoustic properties. In light of the particular requirements and planned usage of the composite material, the connection between density and porosity should be carefully examined.

3.3 Hardness Results

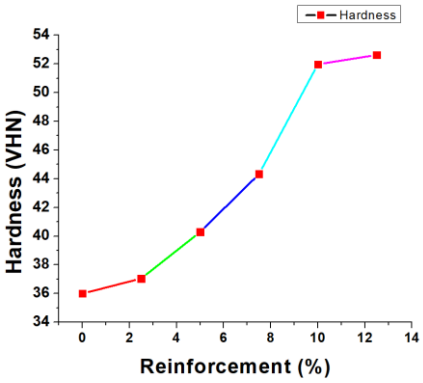

Fig 8: Hardness of composites with different composition

The hardness values of the composites increase with increasing the percentage of reinforcement (nano ZnO). The measured hardness values are: 36, 37.05, 40.29, 44.33, 51.98, and 52.63, correspondingly (0-12.5%), for the various compositions. The inclusion of the strengthening nano ZnO particles within the fabricated UHMWPE composite is the main reason for the intensification of hardness. Comparatively, nano ZnO is a harder material than UHMWPE, and as the amount of nano ZnO reinforcement grows, so does the composite's total hardness. This is so because the inclusion of tougher particles increases the material's resistance to deformation and indentation. During a hardness test, the nano ZnO particles that were disseminated and incorporated into the UHMWPE matrix acted as barriers that prevented an indenter from penetrating the material. More obstacles are present in the material as nano ZnO concentration rises, increasing hardness values and indentation resistance. The composite is successfully strengthened by the reinforcing particles, which also improve the composite's resistance to applied pressures. It is vital to note that the hardness is significantly influenced by the distribution and dispersion of the micro ZnO particles inside the composite matrix. Higher hardness ratings come from more uniform particle dispersion, which improves load transmission and overall reinforcement. Whereas, insufficient particle dispersion or clustering may result in regional differences in hardness and lower overall hardness levels.

3.4 Wear test results

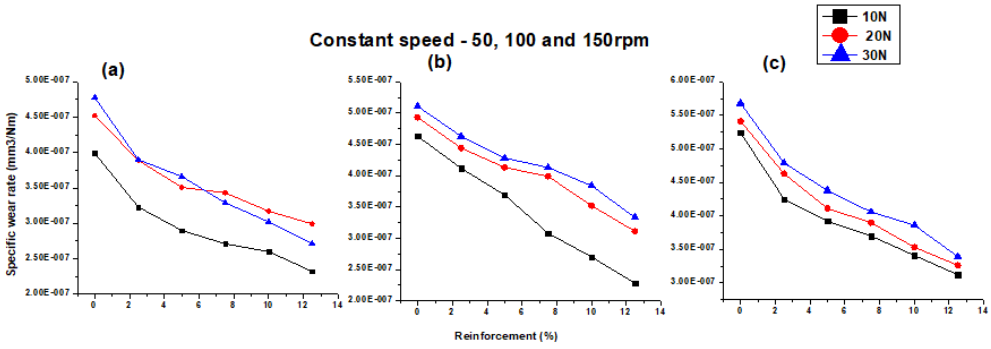

Fig 9: Wear rate for different composite composition at different loading and speed conditions

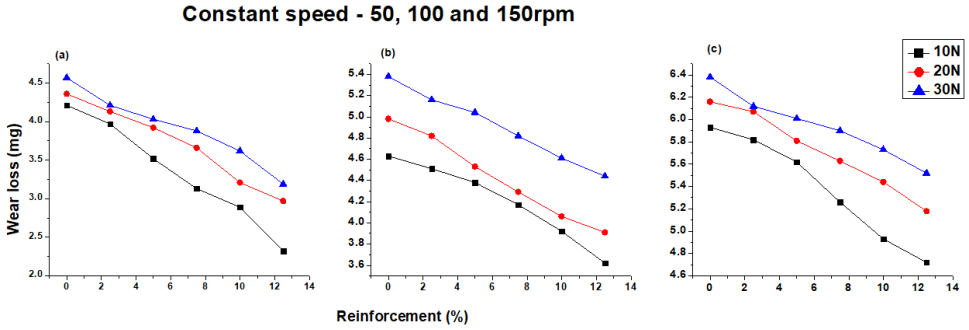

Fig 10: Wear loss for different composite composition at different loading and speed conditions

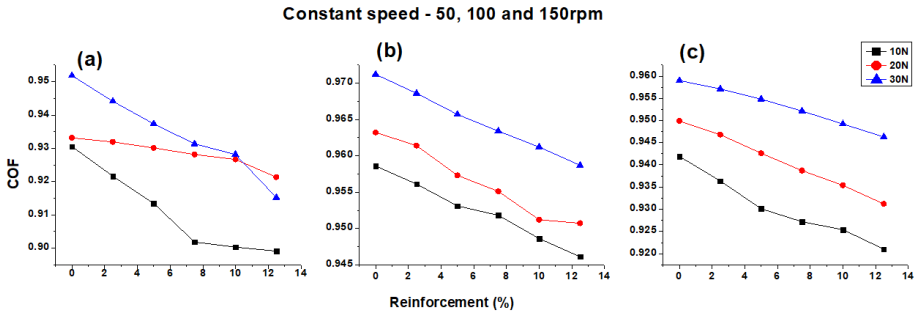

Fig 11: COF for different composite composition at different loading and speed conditions

The reduction of the composite specific wear rate, wear loss, and coefficient of friction (COF) is greatly aided by the inclusion of nanoscale ZnO reinforcement. In terms of specific wear rate, the findings of 12.5% nano ZnO have the lowest values, which are 2.32E-7, 2.99E-7, and 2.71E-7mm3/Nm (for 50rpm), 2.28E-7, 3.11E-7, and 3.33E-7mm3/Nm (for 100rpm), and 3.12E-7, 3.26E-7, and 3.39E-7mm3/Nm (for 150rpm), for 10, 20, and 30N load, respectively. Additionally, 12.5% nano ZnO reinforced composites show the lowest weight loss values, with values of 2.32, 2.97, and 3.19 mg for 50 rpm, 3.62, 3.91, and 4.44 mg for 100 rpm, and 4.72, 5.18, and 5.52 mg for 150 rpm. With values of 0.8991, 0.9213, and 0.9152 (for 50 rpm), 0.921, 0.9312, and 0.9463 (for 100 rpm), and 0.9461, 0.9507, and 0.9587 (for 150 rpm), the COF values are likewise shown to be lowest with 12.5% nano ZnO reinforcement. Through a number of processes, nano ZnO reinforcement increases the composite wear resistance. First off, the use of nano ZnO particles improves the composite's ability to support loads, minimising contact between sliding surfaces and lowering wear. As a protective barrier, the reinforcement minimises material removal during sliding contact. A smoother wear surface is formed as a result of the use of nano ZnO reinforcement, which also lowers frictional forces and wear debris production. As seen in the test results, this results in a decreased specific wear rate and wear loss. The lubricating action of the nano ZnO particles might also be responsible for the drop in COF. The nanoparticles function as solid lubricants to lower friction and stop overheating when sliding surfaces come into contact. Whereas, larger applied loads and sliding speeds tend to increase all the three parameters considered (specific wear rate, wear loss, and COF). A larger load increases the material removal and contact pressure, which raises the wear rate and wear loss. Similar to how increasing sliding speed increases heat production and frictional forces, greater COF is the outcome.At lower load and speed, adhesive wear predominates, characterized by the transfer of material between the mating surfaces. As the load and speed increase, abrasive wear becomes prominent, caused by the cutting and ploughing action of hard particles on the composite surface. Additionally, at higher load and speed, fatigue wear has occurred due to repeated loading and unloading cycles.The wear transition observed in the test results indicates a shift from adhesive wear to abrasive wear as the load and speed increase. This transition is reflected in the increasing values of specific wear rate, wear loss, and COF with higher load and speed conditions.

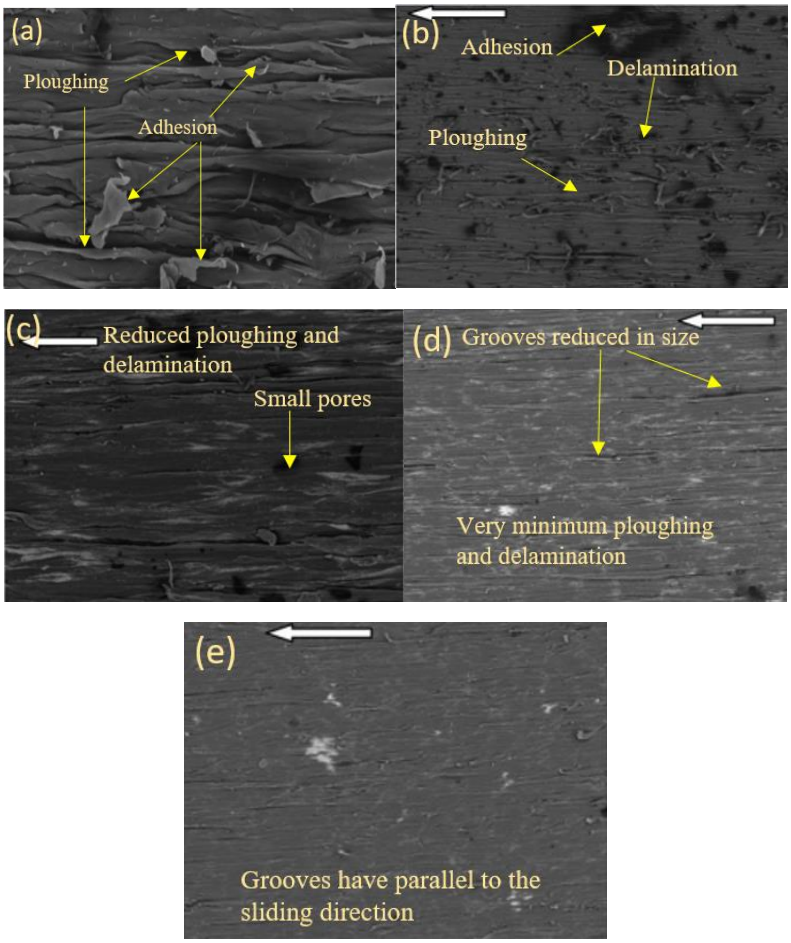

Fig 12: Wear surfaces of UHMWPE composites with (a) 2.5% nano ZnO, (b) 5% nano ZnO, (c) 7.5% nano ZnO, (d) 10% nano ZnO, (e) 12.5% nano ZnO

The SEM images of UHMWPE composites with varying percentages of nano ZnO reinforcement (2.5%, 5%, 7.5%, 10%, and 12.5%) reveal important insights into the wear behaviour of the composites.For the composite with 2.5% nano ZnO, the images show significant ploughing and adhesion on the surface. This can be attributed to the limited reinforcement content, which results in weaker reinforcement-matrix interaction. As the reinforcement percentage increases to 5% and 7.5%, the ploughing and adhesion effects are observed to reduce. This indicates improved reinforcement-matrix bonding, where the nano ZnO particles effectively resist the penetration and adhesion of the counterface.Furthermore, in the composite with 10% nano ZnO, the ploughing and adhesion effects are significantly reduced, indicating a stronger reinforcement-matrix interface. The higher reinforcement content provides a greater number of reinforcement particles that effectively reinforce the composite matrix, leading to a reduction in ploughing and adhesion.In the composite with 12.5% nano ZnO, the SEM images show negligible ploughing and adhesion effects. This can be attributed to the high percentage of nano ZnO reinforcement, which results in a dense distribution of reinforcement particles throughout the composite matrix. The increased number and uniform dispersion of nano ZnO particles enhance the load-bearing capacity of the composite, reducing the occurrence of ploughing and adhesion.The groove size and the presence of pores in the different compositions are also noteworthy. As the nano ZnO reinforcement percentage increases, the groove size tends to decrease. This indicates improved load-bearing capacity and resistance to material deformation. Additionally, the presence of pores is observed to decrease with higher nano ZnO content, indicating better compaction and reduced porosity in the composite structure.Finally, it is observed that the grooves on the wear surface become parallel to the sliding direction in the composites with higher nano ZnO content. This can be attributed to the enhanced reinforcement-matrix bonding and the presence of a greater number of nano ZnO particles that act as barriers, limiting the material flow and causing the grooves to align

with the sliding direction.Therefore, the increase in hardness values of the composites with higher nano ZnO content correlates with the improved wear performance observed in the wear test results. The enhanced hardness contributes to the overall wear resistance of the composites, resulting in lower specific wear rates, weight losses, and COF.

4. Conclusion

By analysing the results obtained after experimentation the following conclusions can be made accordingly:

The addition of nano ZnO reinforcement increased the density of the composites while also introducing porosity due to inadequate dispersion or void formation during fabrication process.The hardness of the composites improved with higher percentages of nano ZnO reinforcement, attributed to the harder nature of the particles and their effective reinforcement within the matrix.

Nano ZnO reinforcement significantly reduced the specific wear rate, wear loss, and coefficient of friction of the composites, enhancing their wear resistance through improved load-bearing capacity, reduced material removal, and solid lubrication effects. SEM analysis of wear surfaces showed reduced ploughing and adhesion effects with increased nano ZnO content, indicating stronger reinforcement-matrix bonding. Decreased groove size and pore presence demonstrated improved load-bearing capacity and compaction.

In conclusion, the addition of nano ZnO reinforcement to UHMWPE composites offers significant improvements in microstructure, mechanical properties, and wear performance. The findings contribute to a better understanding of the composite's behaviour and provide valuable insights for the development of high-performance polymer nanocomposites.

5. References

[1] Ruggiero A., D'Amato R., Gómez E., Merola M. Experimental comparison on tribological pairs UHMWPE/TIAL6V4 alloy, UHMWPE/AISI316L austenitic stainless and UHMWPE/AL2O3 ceramic, under dry and lubricated conditions. *Tribol. Int.* 2016;96:349–360.

[2] Brach Del Prever E.M., Bistolfi A., Bracco P., Costa L. UHMWPE for arthroplasty: Past or future? *J. Orthop. Traumatol.* 2009;10:1–8.

[3] Gomez-Barrena E., Puertolas J.-A., Munuera L., Konttinen Y.T. Update on UHMWPE research From the bench to the bedside. *Acta Orthop.* 2008;79:832–840

[4] Guedes R.M. A viscoelastic model for a biomedical ultra-high molecular weight polyethylene using the time–temperature superposition principle. *Polym. Test.* 2011;30:294–302.

[5] Hirakawa K., Bauer T.W., Stulberg B.N., Wilde A.H., Secic M. Characterization and Comparison of Wear Debris from Failed Total Hip Implants of Different Types*. *J. Bone Jt. Surg.* 1996;78:1235–1243.

[6] Sychterz C J., moon K H., hashimoto y., terefenko k.m., engh c.a., bauer t.w. Wear of Polyethylene Cups in Total Hip Arthroplasty. A Study of Specimens Retrieved Post Mortem*. *J. Bone Jt. Surg.* 1996;78:1193–1200.

[7] Zeman J., Ranuša M., Vrbka M., Gallo J., Křupka I., Hartl M. UHMWPE acetabular cup creep deformation during the run-in phase of THA's life cycle. *J. Mech. Behav. Biomed. Mater.* 2018;87:30–39.

[8] Zhou J., Chakravartula A., Pruitt L., Komvopoulos K. Tribological and Nanomechanical Properties of Unmodified and Crosslinked Ultra-High Molecular Weight Polyethylene for Total Joint Replacements. *J. Tribol.* 2004;126:386.

[9] Sethi R.K., Neavyn M.J., Rubash H.E., Shanbhag A.S. Macrophage response to cross-linked and conventional UHMWPE. *Biomaterials.* 2003;24:2561–2573.

[10] Eddoumy F., Addiego F., Celis J.P., Buchheit O., Berradja A., Muller R., Toniazzo V., Ruch D. Reciprocating sliding of uniaxially-stretched ultra-high molecular weight polyethylene for medical device applications. *Wear.* 2011;272:50–61.

[11] Lewis G. Properties of crosslinked ultra-high-molecular-weight polyethylene. *Biomaterials.* 2001;22:371–401.

[12] Park K., Mishra S., Lewis G., Losby J., Fan Z., Park J.B. Quasi-static and dynamic nanoindentation studies on highly crosslinked ultra-high-molecular-weight polyethylene. *Biomaterials.* 2004;25:2427–2436.
[13] Fu J., Ghali B.W., Lozynsky A.J., Oral E., Muratoglu O.K. Wear resistant UHMWPE with high toughness by high temperature melting and subsequent radiation cross-linking. *Polymer (Guildf.)* 2011;52:1155–1162.
[14] Atwood S.A., Van Citters D.W., Patten E.W., Furmanski J., Ries M.D., Pruitt L.A. Tradeoffs amongst fatigue, wear, and oxidation resistance of cross-linked ultra-high molecular weight polyethylene. *J. Mech. Behav. Biomed. Mater.* 2011;4:1033–1045.
[15] Kanaga Karuppiah K.S., Bruck A.L., Sundararajan S., Wang J., Lin Z., Xu Z.-H., Li X. Friction and wear behavior of ultra-high molecular weight polyethylene as a function of polymer crystallinity. *Acta Biomater.* 2008;4:1401–1410.
[16] Fouad H., Mourad A.-H.I., Barton D.C. Effect of pre-heat treatment on the static and dynamic thermo-mechanical properties of ultra-high molecular weight polyethylene. *Polym. Test.* 2005;24:549–556.
[17] Lewis G., Fencl R.M., Carroll M., Collins T. The relative influence of five variables on the in vitro wear rate of uncrosslinked UHMWPE acetabular cup liners. *Biomaterials.* 2003;24:1925–1935.
[18] Bruck A.L., Kanaga Karuppiah K.S., Sundararajan S., Wang J., Lin Z. Friction and wear behavior of ultrahigh molecular weight polyethylene as a function of crystallinity in the presence of the phospholipid dipalmitoyl phosphatidylcholine. *J. Biomed. Mater. Res. Part B Appl. Biomater.* 2010;93B:351–358.
[19] Di Y., Gang X., Chunhua C. The effect of gamma irradiation on the tribological properties of UHMWPE composite filled with HDPE. *J. Thermoplast. Compos. Mater.* 2014;27:1045–1053.
[20] Zhang J. Surface modification of ultra-high-molecular-weight polyethylene by argon plasma. *J. Thermoplast. Compos. Mater.* 2014;27:758–764.
[21] Liu H., Pei Y., Xie D., Deng X., Leng Y.X., Jin Y., Huang N. Surface modification of ultra-high molecular weight polyethylene (UHMWPE) by argon plasma. *Appl. Surf. Sci.* 2010;256:3941–3945.
[22] Kovalchenko A., Ajayi O., Erdemir A., Fenske G., Etsion I. The effect of laser surface texturing on transitions in lubrication regimes during unidirectional sliding contact. *Tribol. Int.* 2005;38:219–225.
[23] Etsion I. Improving Tribological Performance of Mechanical Components by Laser Surface Texturing. *Tribol. Lett.* 2004;17:733–737.
[24] Chang N., Bellare A., Cohen R., Spector M. Wear behavior of bulk oriented and fiber reinforced UHMWPE. *Wear.* 2000;241:109–117.
[25] Ge S., Wang S., Huang X. Increasing the wear resistance of UHMWPE acetabular cups by adding natural biocompatible particles. *Wear.* 2009;267:770–776.
[26] Plumlee K., Schwartz C.J. Improved wear resistance of orthopaedic UHMWPE by reinforcement with zirconium particles. *Wear.* 2009;267:710–717.
[27] Ferreira A.E., Ribeiro M.R., Cramail H., Lourenço J.P., Lorenzo V., Pérez E., Cerrada M.L. Extraordinary mechanical performance in disentangled UHMWPE films processed by compression molding. J. Mech. Behav. Biomed. Mater. 2019;90:202–207.
[28] Lim K.L.K., Ishak Z.A.M., Ishiaku U.S., Fuad A.M.Y., Yusof A.H., Czigany T., Pukanzsky B., Ogunniyi D.S. High density polyethylene/ultra high molecular weight polyethylene blend. II. Effect of hydroxyapatite on processing, thermal, and mechanical properties. J. Appl. Polym. Sci. 2006;100:3931–3942.
[29] Wood W., Li B., Zhong W.-H. Influence of phase morphology on the sliding wear of polyethylene blends filled with carbon nanofibers. Polym. Eng. Sci. 2010;50:613–623.
[30] Rezaei M., Ebrahimi N.G., Kontopoulou M. Thermal properties, rheology and sintering of ultra high molecular weight polyethylene and its composites with polyethylene terephthalate. Polym. Eng. Sci. 2005;45:678–686.
[31] Ruan S.L., Gao P., Yang X.G., Yu T.X. Toughening high performance ultrahigh molecular weight polyethylene using multiwalled carbon nanotubes. Polymer (Guildf.) 2003;44:5643–5654.
[32] Rezaei M., Shirzad A., Golshan Ebrahimi N., Kontopoulou M. Surface modification of ultra-high-molecular-weight polyethylene. II. Effect on the physicomechanical and tribological properties of ultra-

high-molecular-weight polyethylene/poly(ethylene terephthalate) composites. J. Appl. Polym. Sci. 2006;99:2352–2358.

[33] Clark A.C., Ho S.P., LaBerge M. Conductive composite of UHMWPE and CB as a dynamic contact analysis sensor. Tribol. Int. 2006;39:1327–1335.

[34] Xue Y., Wu W., Jacobs O., Schädel B. Tribological behaviour of UHMWPE/HDPE blends reinforced with multi-wall carbon nanotubes. Polym. Test. 2006;25:221–229.

[35] Fang L., Gao P., Leng Y. High strength and bioactive hydroxyapatite nano-particles reinforced ultrahigh molecular weight polyethylene. Compos. Part B Eng. 2007;38:345–351.

[36] Xiong D., Lin J., Fan D., Jin Z. Wear of nano-TiO2/UHMWPE composites radiated by gamma ray under physiological saline water lubrication. J. Mater. Sci. Mater. Med. 2007;18:2131–2135.

[37] Zoo Y.-S., An J.-W., Lim D.-P., Lim D.-S. Effect of Carbon Nanotube Addition on Tribological Behavior of UHMWPE. Tribol. Lett. 2004;16:305–309.

[38] Chang B.P., Akil H.M., Nasir R.M., Nurdijati S. Mechanical and Antibacterial Properties of Treated and Untreated Zinc Oxide filled UHMWPE Composites. J. Thermoplast. Compos. Mater. 2011;24:653–667. doi: 10.1177/0892705711399848.

[39] Senatov F.S., Gorshenkov M.V., Kaloshkin S.D., Tcherdyntsev V.V., Anisimova N.Y., Kopylov A.N., Kiselevsky M.V. Biocompatible polymer composites based on ultrahigh molecular weight polyethylene perspective for cartilage defects replacement. J. Alloys Compd. 2014;586:S544–S547.

[40] . Xiong D.S., Wang N., Lin J.M., Zhu H.G., Fan D.L. Tribological Properties of UHMWPE Composites Filled with Nano-Powder of SiO2 Sliding against Ti-6Al-4V. Key Eng. Mater. 2005;288–289:629–632.

[41] Macuvele D.L.P., Nones J., Matsinhe J.V., Lima M.M., Soares C., Fiori M.A., Riella H.G. Advances in ultra high molecular weight polyethylene/hydroxyapatite composites for biomedical applications: A brief review. Mater. Sci. Eng. C. 2017;76:1248–1262.

[42] X.S. Xing, R.K.Y. Li, Wear behavior of epoxy matrix composites filled with uniform sized sub-micron spherical silica particles, Wear 256 (2004) 21–26.

[43] C. Subramani, S.T. Mhaske, A.A. Kathe, P.V. Varadarajan, P. Virendra, V. Nadanathangam, Functional behaviour of polypropylene/ZnO soluble starch nanocomposites, Nanotechnology 18 (2007) 385702.

[44] L. Zhang, Y. Ding, M. Povey, D. York, ZnO nanofluids—a potential antibacterial agent, Progress in Natural Science 18 (2008) 939–944.

[45] Y. Liu, L. He, A. Mustapha, H. Li, Z. Hu, M. Lin, Antibacterial activities of zinc oxide nanoparticles against Escherichia coli O157:H7, Journal of Applied Microbiology 107 (2009) 1193–1201.

[46] N. Padmavathy, R. Vijayaraghavan, Enhanced bioactivity of ZnO nanoparticles—an antimicrobial study, Sci Technol Adv Mater 9 (2008) 1–7.

[47] B.P. Chang, H.M. Akil, R.M. Nasir, S. Nurdijati, Mechanical and antibacterial properties of treated and untreated zinc oxide filled UHMWPE composites, Journal of Thermoplastic Composite Materials 24 (2011) 653–667.

[48] Y. Wang, J. Shi, L. Han, F. Xiang, Crystallization and mechanical properties of T-ZnOw/HDPE composites, Materials Science and Engineering A 501 (2009) 220–228.

[49] S. Wacharawichanant, S. Thongyai, A. Phutthaphan, C. Eiamsam-ang, Effect of particle sizes of zinc oxide on mechanical, thermal and morphological properties of polyoxymethylene/zinc oxide nanocomposites, Polymer Testing 27 (2008) 971–976.

[50] S. Wang, S. Ge, D. Zhang, Comparison of tribological behavior of nylon composites filled with zinc oxide particles and whiskers, Wear 266 (2009) 248–254.

[51] F. Li, K.A. Hu, J.L. Li, B.Y. Zhao, The friction and wear characteristics of nanometer ZnO filled polytetrafluoroethylene, Wear 249 (2001) 877–882.

[52] J. Shi, Y. Wang, Y. Gao, H. Bai, Effects of coupling agents on the impact fracture behaviors of T-ZnOw/PA6 composites, Composites Science and Technology 68 (2008) 1338–1347.

[53] Sobieraj M.C., Rimnac C.M. Ultra high molecular weight polyethylene: Mechanics, morphology, and clinical behavior. *J. Mech. Behav. Biomed. Mater.* 2009;2:433–443.

[54] AJK Prasad, Yeshvantha HS, Chandrakant Ashok T, Jagannadh G, Basavaraj. Studies on Wear Characteristics of Ultra-High Molecular Weight Polyethylene (UHMWPE) Nano composities containing Nano ZnO. Elsevier Materials Today: Proceedings, 2018; 5: ISSN 2214-7853.

[55] Lewis G. Properties of crosslinked ultra-high-molecular-weight polyethylene. *Biomaterials.* 2001;22:371–401.

[56] Pruitt L.A. Deformation, yielding, fracture and fatigue behavior of conventional and highly cross-linked ultra high molecular weight polyethylene. *Biomaterials.* 2005;26:905–915.

[57] Puértolas J.A., Kurtz S.M. Evaluation of carbon nanotubes and graphene as reinforcements for UHMWPE-based composites in arthroplastic applications: A review. *J. Mech. Behav. Biomed. Mater.* 2014;39:129–145.

[58] Bracco P., Bellare A., Bistolfi A., Affatato S. Ultra-High Molecular Weight Polyethylene: Influence of the Chemical, Physical and Mechanical Properties on the Wear Behavior. A Review. *Materials.* 2017;10:791.

[59] Baena J., Wu J., Peng Z. Wear Performance of UHMWPE and Reinforced UHMWPE Composites in Arthroplasty Applications: A Review. *Lubricants.* 2015;3:413–436.

[60] Geetanjali S. Guggari,S. Shivakumar,R. Nikhil,G. A. Manjunath,Asif Afzal,C. Ahamed Saleel.Experimental investigation of mechanical properties of Acrylonitrile Butadiene Styrene (ABS) based polymer for Submersible pumps . *IOP Conference Series: Materials Science and Engineering*, 2021, doi:10.1088/1757-899x/1065/1/012035.

[61] Geetanjali S. Guggari, S. Shivakumar, G. A. Manjunath, R. Nikhil, Alagar Karthick , Abhilash Edacherian, C. Ahamed Saleel, Asif Afzal, S. Prasath , and B. Saleh. Thermal and Mechanical Properties of Vinyl Ester Hybrid Composites with Carbon Black and Glass Reinforcement, Hindawi, *Advances in Materials Science and Engineering*, Volume 2021, Article ID 6030096, 7 pages, https://doi.org/10.1155/2021/6030096.