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Tribological Behaviour of PTFE based Composite Materials with Different Filler Materials: A Combine Numerical and Experimental Approach

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Abstract

This study investigates the tribological behaviour of Polytetrafluoroethylene (PTFE) composites reinforced with various fillers, utilizing the Archard wear model to analyse wear mechanisms and predict wear rates. PTFE is widely recognized for its excellent chemical resistance and low friction, but its inherent wear resistance is relatively poor. To enhance its tribological properties, fillers such as glass fibres, carbon fibres, bronze, and graphite were incorporated into the PTFE matrix. In the present study, fillers materials chosen were carbon, graphene, bronze, MoS_2 and based material selected as PTFE. The load range sliding velocity range considered between 60 N to 180 N and 1 m/s to 5 m/s for both Archard wear model based numerical simulation. However experimental validation of the result was performed using Pin-on-Disc test setup under dry sliding conditions. The wear volume was measured, and the Archard wear coefficient was determined for each composite experiment. It is observed that fillers significantly improve the wear resistance of PTFE. Among the fillers, graphite showed the most substantial reduction in wear rate due to its solid lubricating properties, while glass fibres enhanced the mechanical strength, thereby reducing the wear volume. The Archard wear model provided a robust framework for understanding the wear mechanisms in these composites. The model's predictions were in synchronisation with the experimental data, demonstrating its applicability in estimating the wear behaviour of filled PTFE. The findings suggest that by selecting appropriate fillers and optimizing their concentrations, the wear performance of PTFE can be significantly enhanced, making it suitable for a broader range of engineering applications. This study contributes to the development of high-performance PTFE-based composites and underscores the importance of using predictive models like Archard's to design materials with superior tribological properties

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Keywords: Archard wear, PTFE, filler, composite material, pin-on-disc

INTRODUCTION

Polytetrafluoroethylene (PTFE) is a common material used for tribological applications due to its exceptional self-lubricating capacity, low friction coefficient, and chemical inertness.[1] PTFE has an excellent average density of 2.2 g/mm3, excellent resistance to corrosion, and a low coefficient of friction of 0.01. However, its wear resistance is low, limiting its use in high-stress or abrasive conditions. Hence, to overcome the problem, fillers such as bronze, mica, glass, alumina, MoS_2, and Poly-ether-ether-ketone (PEEK) ~~are~~ added to improve the wear characteristics of PTFE.[2] It is observed that, these fillers not only improve wear resistance, but also mechanical and thermal characteristics, making

PTFE composites ideal for use as seals, bearings, gears, and medical implants. Researchers found that the tribological behaviour of the composite is influenced by filler type, size, distribution, and operational conditions. For example, graphite minimize friction due to their natural lubricating characteristics, whereas bronze increase load-carrying capacity and wear resistance. The complex behaviour of the tribo-system requires a combination of experimental investigations and numerical simulations that examine the effects of various variables systematically. [3-5]

Tribological study has traditionally employed experimental methods to evaluate wear and friction in materials. However, these studies are time-consuming, resource-intensive, and often possess constraints regarding identifying factors influencing wear mechanisms. Archard's law provides an effective framework for wear prediction by taking into consideration of key elements like applied load, sliding distance, material hardness etc. [6] When two surfaces interact under the influence of different operating conditions, material loss that occurs is a critical aspect in tribological analysis. Prediction of the wear using distinct wear mechanisms helps in estimating component's reliability under several working conditions. Adhesive wear deals with the material transfer between the interacting surfaces, which is evaluated using Archard model in combination with finite element analysis (FEA). Robinowicz equation and discrete element method can simulate abrasive wear and predict the wear rate based on material properties and contact geometry. Corrosive wear uses empirical model which incorporate different environmental as well as material conditions however electrochemical process can be simulated using numerical models. In fatigue wear, FEA is used to analyse stress concentration and fatigue crack initiation and growth, which further in conjunction with fracture mechanics principles estimates wear rate Various predictive models are developed by the researchers, however, Archard wear model is one of the most prominently used model for adhesive wear prediction due to simplicity and its scope with broader spectrum of the material and operating conditions. Over the periods, the Archard's model has been used for predictive analysis of tribological problems. [7-10] Simple adhesion model states that volume loss of a material V_w is a result of surface interaction proportional to the applied load (F_n)and sliding distance travelled (L). Also, it has been observed that less wear occurred when hardness of material increases. The Archard model provides a foundational equation relating wear volume to load, sliding distance, hardness, and an empirical wear coefficient. [11-12]

$$V_w = K\frac{Fn*L}{H}$$

Where K is wear coefficient, the above equation is taken into consideration for solving finite element model.

The Archard model is simple and effective, however, it fails to address the complexities of tribo-system like material behaviour, environmental constraints as well as multiscale interactions. Numerical modelling, particularly finite element analysis (FEA) in conjunction with Archard's wear model, has emerged as an efficient way to supplement experimental research. These models allow researchers to simulate wear process, predict outcome under various operating circumstances, and optimize material design before physical testing.[13] It is observed that, for wear simulation FEA is an extremely versatile and powerful tool. Under dynamic load and environmental conditions, FEA gives comprehensive analysis of stress distribution, deformation and wear development. It enables the researchers to investigate local wear phenomenon and understand the wear mechanism in better aspects. The studies reflect those predictive capacities of the wear model are improved by combining Archard's law with FEA. It is also evident that adaptive meshing approaches refine computing resources in high-stress or wear areas, resulting in more accurate results at lower computational costs. FEA-based models help in better understanding of wear progression over time, which provides insights into the long-term performance of materials and systems. [13-14]

Despite the advancements in numerical and machine learning-based wear models, experimental validation remains a critical step to ensure their accuracy and reliability. Numerical models and simulations must align with experimental data to be effective in practical applications. Several studies

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have highlighted the importance of experimental validation in wear modelling. For example, researchers have validated FEA-based wear predictions against experimental results, achieving error margins as low as 5%. [15] Such validations underscore the importance of combining computational and experimental approaches to develop robust and reliable wear models. This paper highlights the use of Archard wear model in conjunction with FEA for predictive wear analysis of PTFE composite filled with 20% glass.

MATERIAL AND METHODS

Materials

For this study, PTFE filled with 20% glass was chosen for wear testing. This is a common and practical glass content for PTFE composites, offering a good balance between mechanical properties and processing ease.[2] Higher volume fraction of glass increases wear resistance of the composite but negatively impact the friction and self-lubricating properties. The specific material used was sourced from HM Polymers in Pune, and its composition is detailed in *Table 1.* The wear samples carefully machined from the procured material. The machining is carried out with precision to ensure dimensional accuracy and uniformity of the test samples. Each cylindrical sample have a length of 32 mm and diameter of 10 mm, conforms the requirements of the standard pin holders used in wear testing apparatus.

PTFE + 20% glass composite is used for the study, the corresponding material properties are represented in *Table 2.* FEA model is incorporated with these material properties for accurately simulating the model. The reliability prediction of the model is largely governed by defining these material properties.

Modelling

FEA is used to predict the wear behaviour of PTFE + 20% glass using pin on disc model. The said model is designed in SOLIDWORKS shown in *Fig. 1.* and then simulated using ANSYS 2021 R2 workbench. The disc made up of AISI 304 stainless steel is used, which shows outstanding corrosion resistance and formability with strength. Analysis of Archard Wear model shown in *Fig. 2* is done in ANSYS through steps like material selection, meshing, defining contact and loading conditions and lastly analysing the results. [16-17] Archard's wear law equation was taken into consideration while solving the analysis. Archard's wear model basically focuses on contact surfaces and it does not consider the roughness of surface. The loss of material was calculated by loss of height of pin after experimentation. As maximum volume loss occurs on pin side which is made of polymer composite material against metallic surface.[18] Therefore, disc stiffness behaviour given as rigid and pin's stiffness behaviour given as flexible.

Table 1. Composition of PTFE Composite.

Composition	Volume fraction (%)	
	PTFE	***Glass***
1	80	20

Table 2. Properties of PTFE + 20% glass

S no.	Property	Unit	PTFE + 20% glass
1	Density [2]	gm/cc3	2.15 - 2.2
2	Tensile Strength [2]	kgf/cm²	180 – 260
3	Compressive Strength [2]	kgf/cm²	45 – 55
4	Impact Strength [2]	J/cm	1.2 - 1.3
5	Hardness [2]	Shore D	58 - 62
6	Coefficient of friction Static [2]		0.01 – 0.12

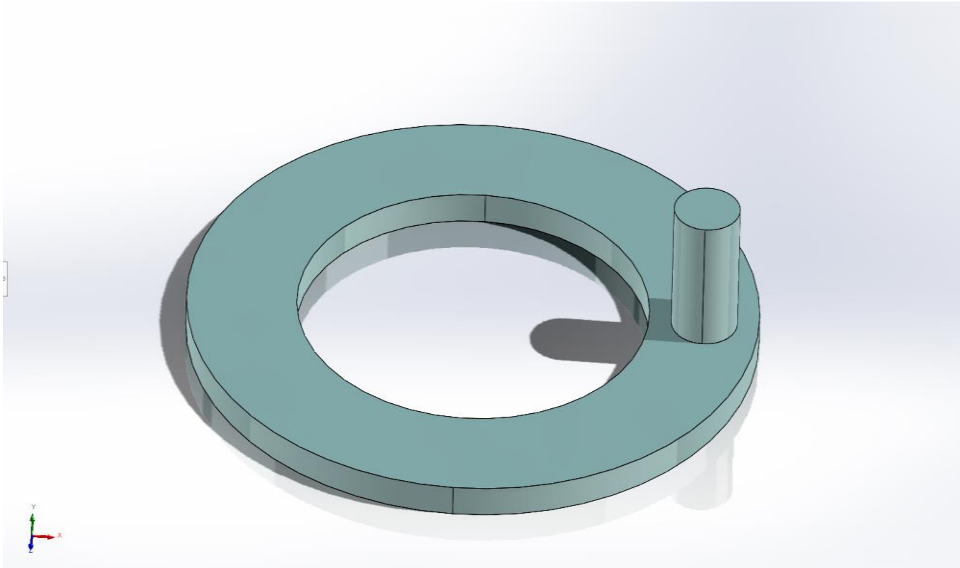

Figure 1. Pin on disc model in SOLID WORKS.

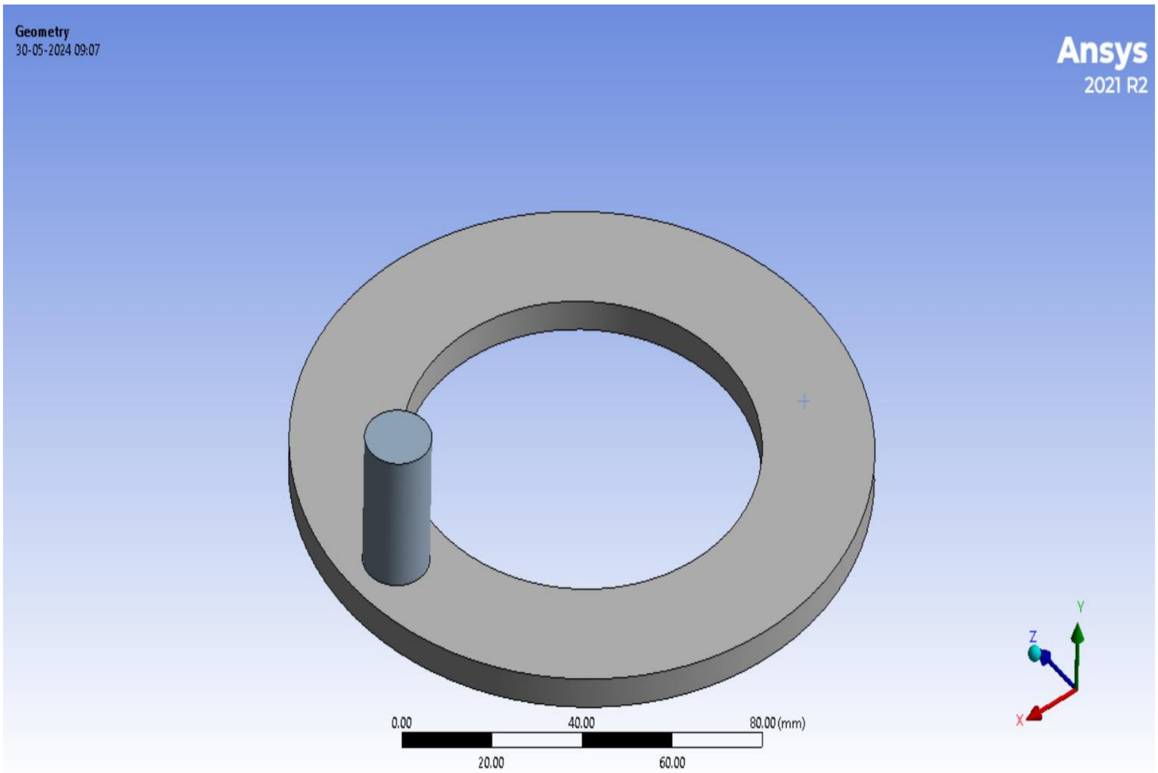

Figure 2. Pin on disc model in ANSYS.

Contact Definition

Frictional contact is defined between the disc and pin to accurately simulate the experimental conditions in ANSYS Workbench shown in *Fig. 3*. The disc and pin are applied with ground joints to restrict their motion to specific degrees of freedom. The vertical motion of the pin is restricted by applying a translational joint to the pin as shown in *Fig. 4*, while a revolute joint was applied to the disc to enable its rotational motion as shown in *Fig. 5.* The pin is modelled as a flexible body to concentrate on the deformation of the pin, while the disc was considered as a rigid body. The low coefficient of friction between the two components, frictional contact with asymmetric behaviour is defined. The detection method was set to nodal normal to the target, aligning with the applied force on the pin.[19]

Additionally, the trim contact option was disabled to allow for aggressive stiffness updates, which helped to accelerate convergence and reduce simulation time.

Meshing

The meshing is done using auto-meshing capabilities of ANSYS mechanical APDL. The 3D elements shown in *Fig. 6.* are meshed with a combination of tetrahedral and hexahedral elements. The tetrahedral elements easily conform the complex geometry whereas hexahedral elements are used in regular shape for better accuracy.[20] Total 3680 elements are created each to form 3D discretization of the geometry, with 8686 nodes the displacement and other variables are calculated. Element growth rate is 1.2 which indicates that the element can progressively increase in size by 20% along the critical zone. The mesh elements are nearly isotropic with the aspect ratio of 0.8. The mechanical APDL solver ensures that the requirements for accuracy and convergence are effectively achieved.[21] The simulation is applying gradual load with 5 steps, which helps in capturing the nonlinearities of the system. The simulation is executed with minimum time step of 0.05 to maximum of 0.1 second to speed up the simulation with maintain the accuracy.

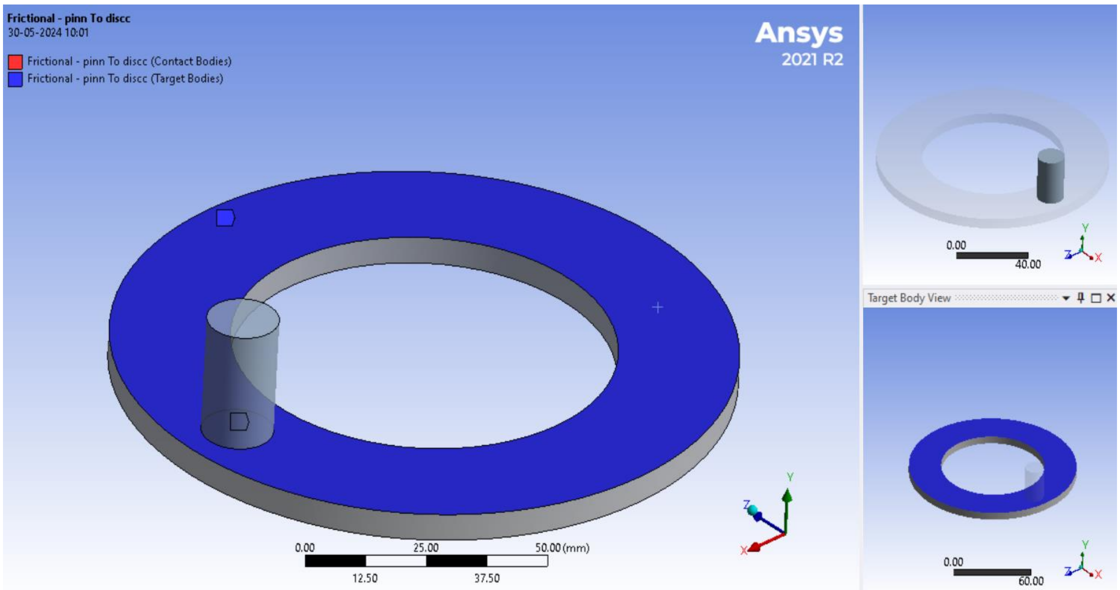

Figure 3. Frictional contact - pin and disc.

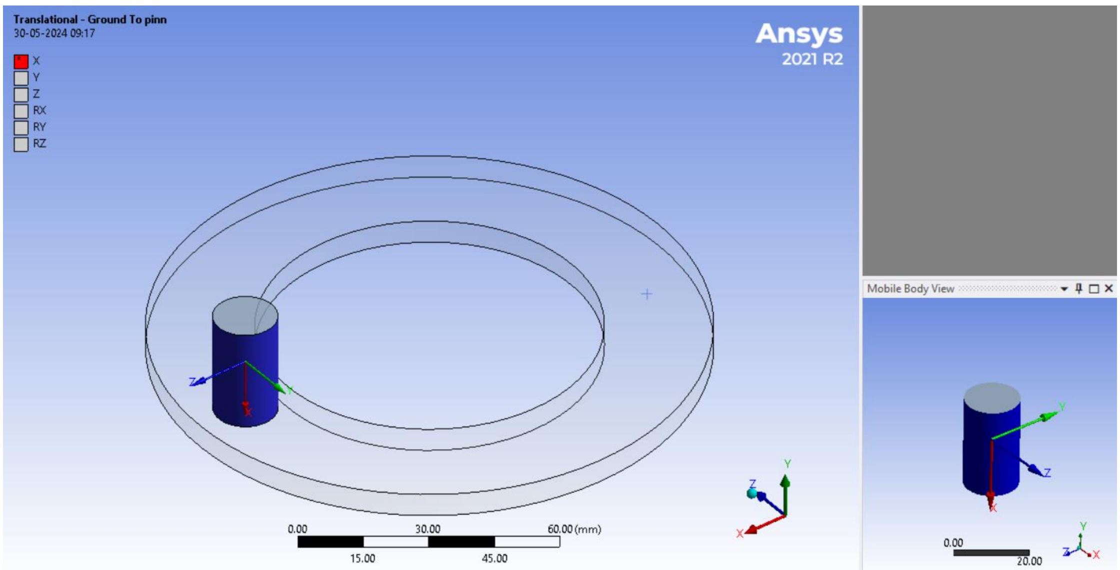

Figure 4. Translation motion of pin.

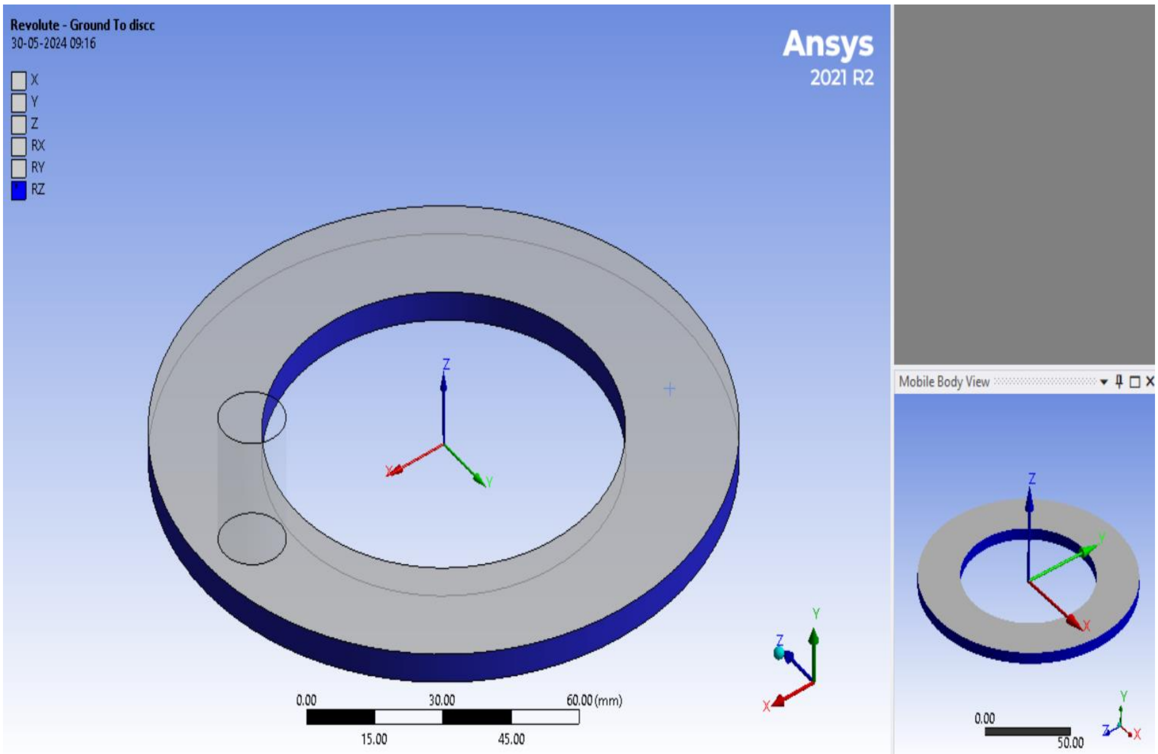

Figure 5. Revolute motion of disc.

SIMULATION DETAILS

Material properties of the contacting surfaces are defined in ANSYS with appropriate modules for structural analysis. Analysis settings, such as element types (like solid elements for structural analysis, wear elements for wear prediction), mesh density, and solver options are configured. Archard wear model is implemented within the analysis software, considering the wear equation and wear rate calculation. The Archard wear coefficient K is defined as 0.988 x 10^{-4} as well as respective material properties of the contacting surfaces are added in the software.

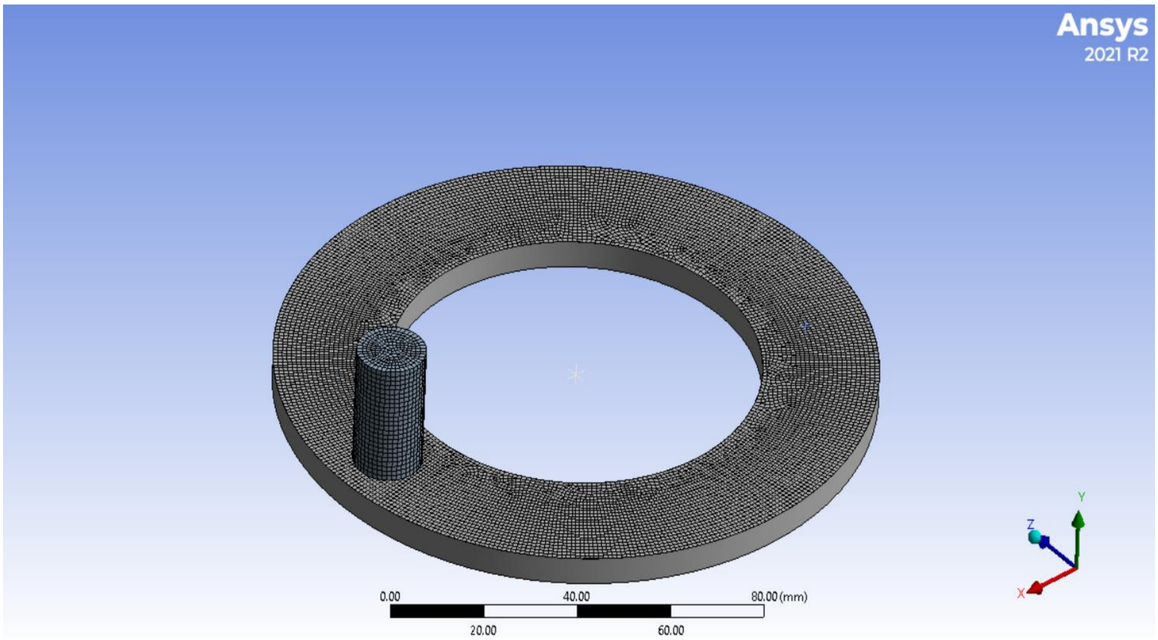

Figure 6. Meshing of CAD model.

The wear model outputs incorporated to predict volume loss.[22] The behaviour of the material under different operating conditions like applied load (60N -180N), sliding velocity (1m/s – 5 m/s) and sliding distance (1000m – 5000m) are investigated. The obtained results validated through sample experiments to ensure the accuracy and predictability of the simulation model. Boundary conditions given for any model to get accurate and compatible to real conditions.[23] In this analysis, pin motion is restricted only along Y direction hence applied translational joint to pin ensuring the contact between the disc and pin as shown in *Fig. 7.*

The disc is given rotational motion along Y direction as shown in *Fig. 8.* The specified load is applied on the pin in the normal direction on the disc surface. Once the load is applied by the pin onto the disc, the disc is rotated, resulting in the pin being displaced from its original position according to the specified inputs.

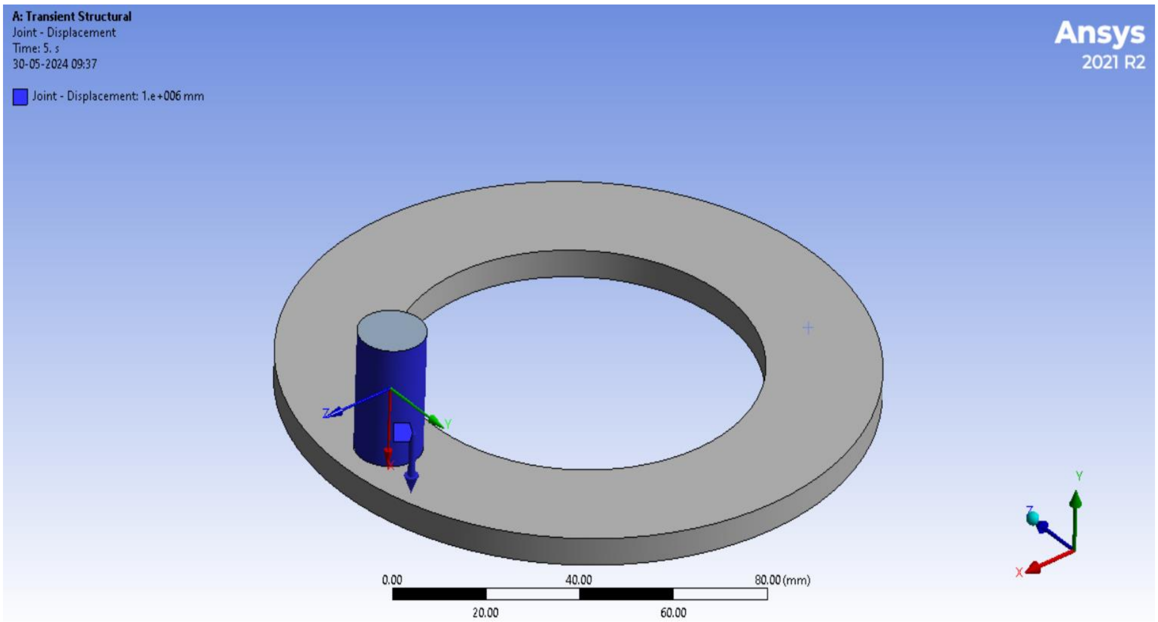

Figure 7. Displacement of the pin.

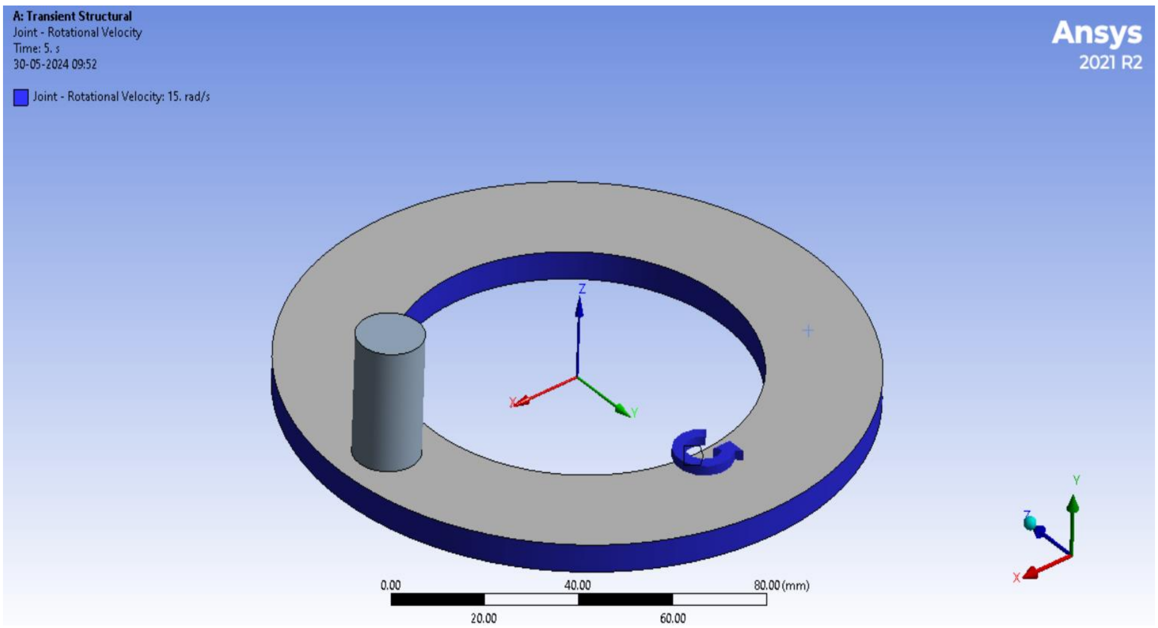

Figure 8. Rotational velocity of the disc.

RESULTS AND DISCUSSIONS

Design of Experiment (DOE) is used to minimizes the number of experiments/ trails maintain data integrity. For this study, L25 orthogonal array for the experiment design. The operating conditions like load, sliding velocity and sliding distance are selected each with five levels. The total number of experiments are divided into simulation and validation. Total 20 experiments are selected for simulation and remaining 5 experiments for validation. The validation experiments are performed on pin on disc wear testing machine with specified input conditions. The detailed matrix for simulation and experiment is shown in *Table 4*.

The volume probe in Archard's wear analysis is related to estimating the material volume loss due to wear shown in *Fig. 9.* It provides a mathematical framework to estimate the wear volume subjected to different operating parameters like load, sliding distance and sliding velocity as well as hardness and Archard wear coefficient. It considers the interaction between the surfaces in contact. It provides insights into how the material is detached from the contacting surface; it also assesses the wear damage.[24] In Archard wear model, material hardness and wear coefficient vary across the surface which is taken care of by the volume probe. It enables us to understand the wear process in a better way, helping in refining the Archard based prediction. Volume probes can be implemented in FEA simulations to calculate wear volume iteratively based on stress distributions, sliding distances, and contact areas. Using FEA, Archard's law is integrated as a subroutine to estimate the incremental material removal during sliding, with the volume being "probed" over the simulation time.[25] These measurements help calculate the volume of material removed to validate Archard's predictions. The simulation results shown in *Table 3.* confirms that weight loss increases with increase in the load. It is observed that at 60 N load with sliding distance of 1000m the weight loss is 0.00048825g whereas if load increases to 180 N with sliding distance of 2000m weight loss increases to 0.0019755g. This confirms the trend between load and material degradation in connection with Archard law. It is evident from the results that the increase in sliding velocity at lower-level weight loss increases, however, at higher velocities with reduction in friction weight loss reduces for constant applied load. It is also observed that the weight loss has a strong positive correlation with the sliding distance. If the sliding distance increased from 2000 to 4000 m with constant load of 90 N the weight loss increased from 0.00083295 g to 0.001296 g. The higher load (120 N) and sliding distance (5000m) weight loss observed is more as compared to the lower combination of the load and sliding distance.

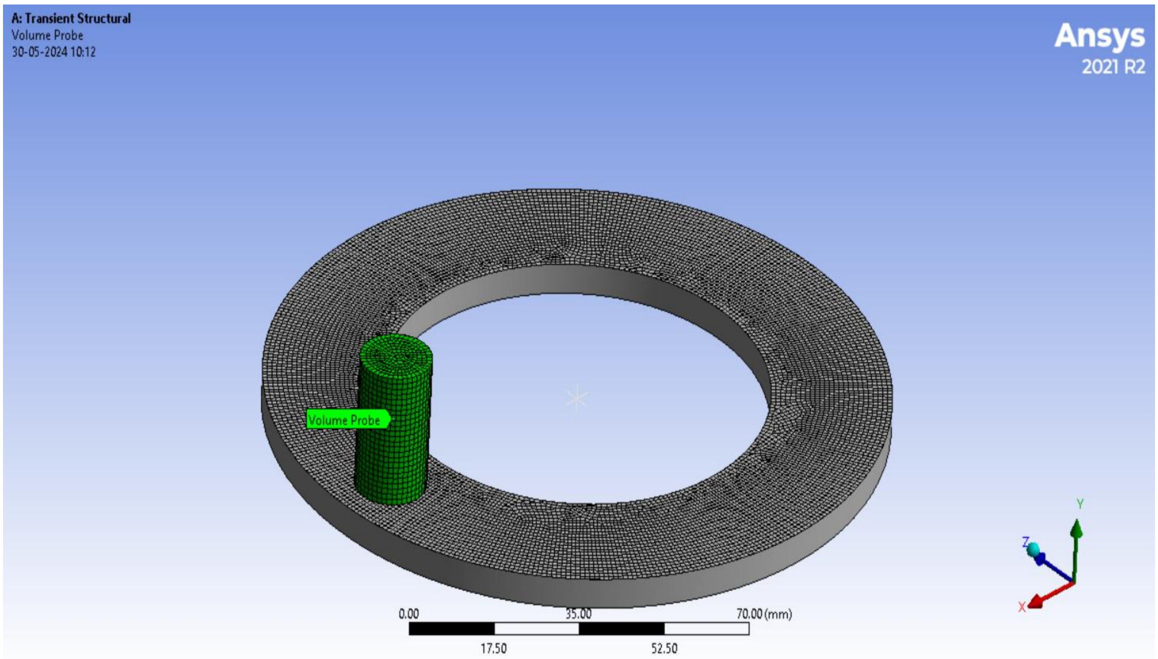

Figure 9. Volume probe.

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Table 3. Simulation and Validation Results.

Experiment run	Load (N)	Sliding velocity (m/s)	Sliding distance (m)	Weight loss(gm)	
Simulation experiments					
1	60	1	1000	0.00048825	
2	60	2	2000	0.0005355	
3	60	3	3000	0.0015345	
4	60	4	4000	0.0003375	
5	90	1	2000	0.00083925	
6	90	3	4000	0.001296	
7	90	4	5000	0.001458	
8	90	5	1000	0.0005625	
9	120	1	3000	0.000612	
10	120	3	5000	0.001431	
11	120	4	1000	0.00078975	
12	120	5	2000	0.00189	
13	150	1	4000	0.00132975	
14	150	2	5000	0.00048825	
15	150	3	1000	0.0010305	
16	150	5	3000	0.001053	
17	180	1	5000	0.00135675	
18	180	2	1000	0.00071325	
19	180	3	2000	0.0019755	
20	180	4	3000	0.0010125	
Validation experiments					
Experiment Run	**Load (N)**	**Sliding velocity (m/s)**	**Sliding distance (m)**	**Weight loss (gm)**	
				FEA approach	***Experimental method***	***% Error***
1	60	5	5000	0.0030126	0.002875	4.567483
2	90	2	3000	0.00122	0.0013	6.557377
3	120	2	4000	0.0007	0.0006475	7.5
4	150	4	2000	0.00111	0.00105	5.405405
5	180	5	4000	0.000601	0.000562	6.489185

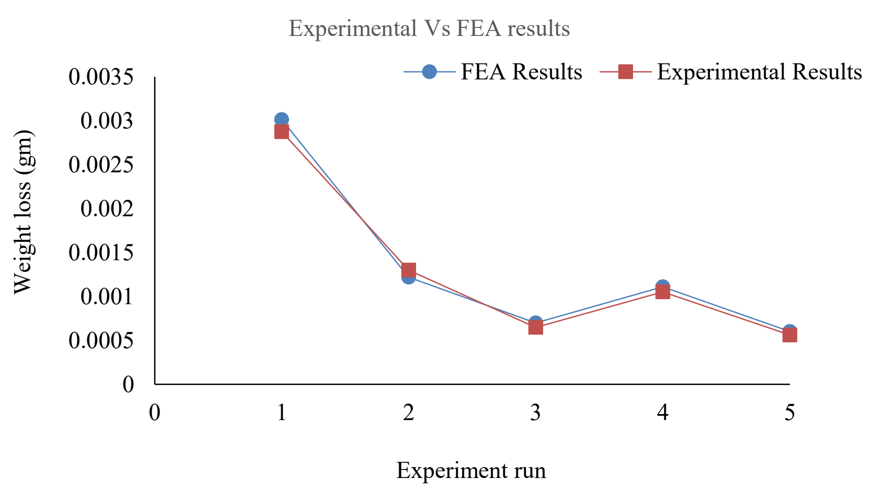

Figure 10. Experimental and FEA simulation comparison.

Fig. 10. indicates that both FEA simulation and experimental approach provide close alignment. The percentage error ranging from 4.57 to 7.5% shows good agreement between both methods. The higher error may be due to the assumptions regarding material properties or boundary conditions similarly the variable conditions of surface roughness and interface temperatures during actual experimentation can also have the impact on outcome. [25-27] The experiment and FEA simulation predictions validate the effectiveness of the FEA approach for predictive analysis of tribo-systems and proves to be an effective tool before conduction of actual experiments

CONCLUSIONS

The present study, the Archard wear model in conjunction with FEA is used for predictive analysis of wear behaviour of glass filled PTFE composite under various tribological conditions. The volume probe incorporated in the model is helpful refining the predictions by dynamically considering the parameters like applied load, sliding distance and sliding velocity. The material removal process is effectively simulated using the model which gives valuable insights of the tribo-system which reduces need of extensive experimental trails. FEA model amalgamated with Archard's equation found capable to investigate the wear volume depending on the stresses which enhance the predictive accuracy of the model. This method is proven to be dependable and cost-efficient solution for wear analysis. Following conclusions can be derived from the above study

a. The study reveals that the Archard wear law shows the reliability for predicting the wear behaviour across the varying tribological conditions. The FEA framework in conjunction with Archard law takes into consideration the dynamic factors providing the better understanding of wear mechanism. It is evident from the results that applied load and sliding distance show a strong positive correlation with wear, however, sliding velocity shows a negative influence on the wear behaviour of the material.
b. The validation experiments conducted using pin on disc wear testing machine shows a strong agreement with the simulation results. The percentage error ranges from 4.57% to 7.5% shows the accuracy and reliability of the simulation framework emphasizes it use for predictive analysis. The results are aligned with Archard's law confirms the utility of this model for application of various industrial applications.

FUTURE SCOPE

The present study focuses on use of Archard wear model for predictive tribological analysis of PTFE composites. The future studies may focus on incorporating different models like abrasive and corrosive wear model which can provide more comprehensive insights of PTFE wear mechanism. Similarly, incorporation of machine learning approach for predictive analysis which can effectively estimate wear behaviour of composite materials

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