Chapter 3

In Examining the Wear Behavior of Polymer Composites Modeling Methods

Ayhan Aytaç[1]

Abstract

The wear behavior of polymer composites is an important issue in industrial applications. When examining the wear behavior of polymer composites, it is important to determine the relationship between parameters such as material properties, surface properties, temperature and wear mechanisms. Various modeling methods have been developed to determine the wear behavior of polymer composites. This article examines the modeling of the wear behavior of polymer composites and reviews existing methods. A general evaluation of studies on modeling the wear behavior of polymer composites is presented.

Studies in the literature generally address various mathematical approaches to describe the wear behavior of polymer composites. In particular, existing approaches to mathematically describe the friction and wear behavior of multicomponent systems are examined. In the studies to be carried out, setting up an experimental setup in a laboratory environment, mathematical modeling or computer-aided simulation modeling can be carried out. However, within the scope of the study, modeling using Finite Element Method (FEM), Artificial Neural Network (ANNs), experimental setup and mathematical modeling were examined. Additionally, the development of new hybrid polymer matrix composites and the study of their wear behavior are also discussed.

1. Introduction

Polymer composites are gaining traction in tribological applications because of unique material characteristics including excellent wear resistance and reduced friction (Abdelbary, 2015; N. K. Myshkin & Kovalev, 2017). Determining the link between characteristics including material

1 Assistant Professor Doctor, National Defense University, Department of Mechanical Engineering, aytac@msu.edu.tr, ORCID ID: 0000-0002-7963-0640

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qualities, surface properties, temperature, and wear processes is crucial for analyzing the wear behavior of polymer composites. To find out how polymer composites wear, several modeling techniques have been created. It is possible to do computer-aided simulation modeling, mathematical modeling, or experimental setup in a laboratory setting. This study looked at mathematical modeling, artificial neural networks (ANNs), finite element method (FEM) modeling, and experimental setting.

Wear in polymer composites is caused by the material in contact with the friction surface interacting with it. The characteristics of polymers indicate that factors including surface energy, elastic modulus, specific heat, thermal conductivity, and operating circumstances affect wear behavior (Abdelbary, 2015). In polymer composites, local fatigue rises with repeated contact during wear (Panda et al., 2017). Research and compilation will be done on studies that predict the wear behavior of polymer composites based on the parameters given in the literature, and the findings will be compared and presented.

2. Factors Affecting Wear Behavior of Polymer Composites

Factors affecting the wear behavior of polymer composites are:

1. Filler Material: The type, size and shape of filler particles can affect the wear resistance of polymer composites (Muhammad, D., & Asaduzzaman, M. 2012).

2. Loading Type: Normal load, sliding speed, vibration amplitude and frequency are important factors that determine the friction and wear behavior of polymer composites (Muhammad, D., & Asaduzzaman, M. 2012).

3. Surface Properties: Properties such as surface roughness, machining and post-machining treatment of polymer composites can affect the wear behavior (Muhammad, D., & Asaduzzaman, M. 2012).

4. Fiber Type: The type of fibers used in fiber-reinforced composites can affect wear resistance. For example, glass fibers can have different effects on wear behavior (Fig. 1) (Sarath et al. 2023).

5. Lubrication: Lubrication condition can affect the wear resistance of polymer composites. Proper lubrication can reduce friction and increase wear resistance.

In order to comprehend and maximize the wear behavior of polymer composites, several elements need to be considered. Researchers are making significant progress in modeling and enhancing the wear behavior of polymer composites in light of these considerations (Han. 1996, Fekete. 2021, Muhammad, D., & Asaduzzaman, M. 2012). The effective parameters influencing the wear behavior include sliding distance, sliding speed, load, volume ratio, and weight ratio, as shown by the analysis of the experiments.

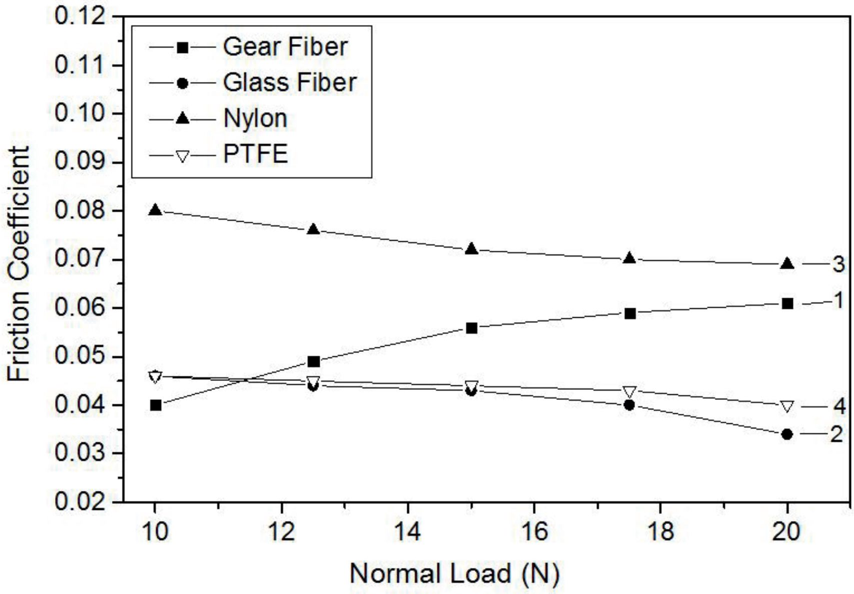

Figure 1. Polymer materials' load-friction coefficient graph, with a sliding speed of 1 m/s (Muhammad and Asaduzzaman, 2012).

Ashby provides a meaningful diagram that locates the polymeric materials with the lowest wear rate and scans the wear rate values (Figure 2). Furthermore, this diagram suggests that the wear rate domain can be expanded by using polymers in applications, especially towards lower values (Ashby. 2017).

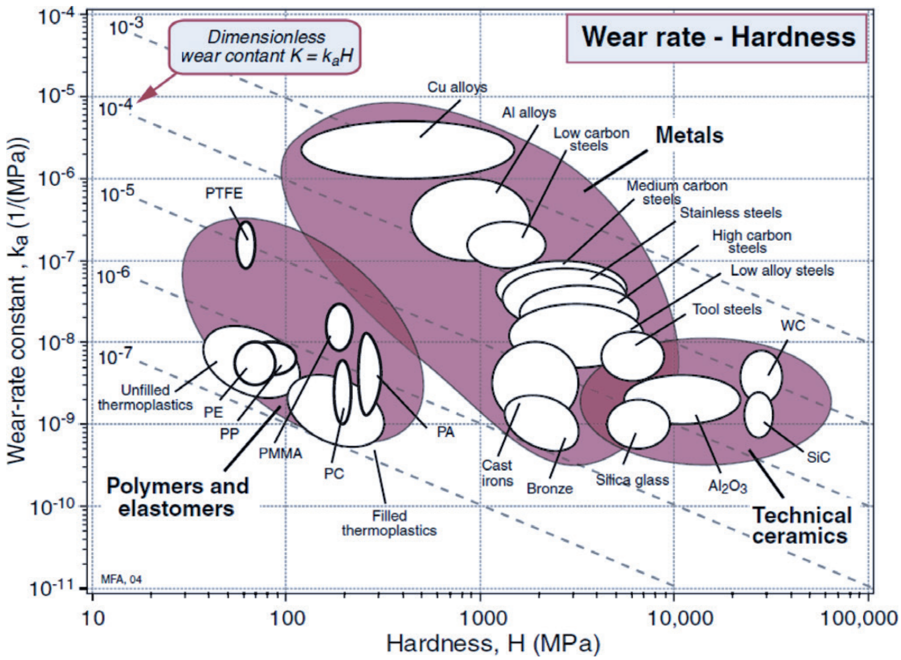

Figure 2. Polymer and polymer composite placement within the hardness-wear rate constant (Ashby, 2017).

3. Development and Wear Behavior of Hybrid Composite Polymers

When created efficiently, the new composite material has a more remarkable durability than it would if each constituent were used alone. Composites are employed in electrical, thermal, and environmental applications in addition to their structural qualities. In general, polymers' mechanical qualities are insufficient for a variety of structural uses. Different polymer matrix materials are used to form hybrid polymer matrix composites, and reinforcements like carbon, glass, or aramid fiber are frequently included as well. Studying the mechanical and wear properties of such composite materials is necessary for their development. (Fig. 3) (Fu et al. 2002).

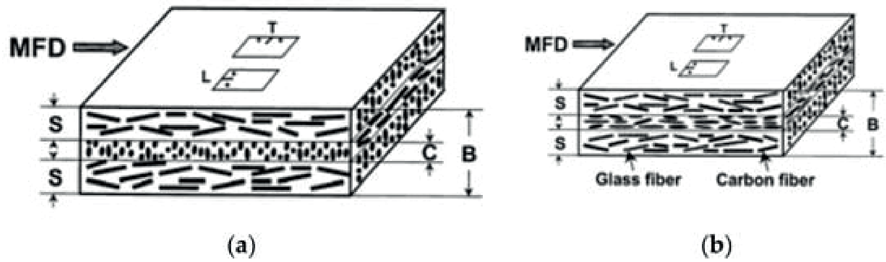

Figure 3. Diagram illustrating the three-layer architectures of hybrid composites with GFs/CFs and single-additive composites (a) (Fu vd. 2002).

To improve the mechanical characteristics and wear resistance of hybrid polymer matrix composites, researchers are experimenting with diverse combinations of matrix and reinforcing materials. These investigations span a broad spectrum, including material selection, production techniques, experimental testing, and modeling.

Karthik and colleagues conducted a study with the goal of creating new hybrid polymer matrix composites with Kevlar and epoxy resin as matrix materials. They used glass and carbon fibers for reinforcement. The hand lay-up method was utilized to prepare laminates made of fiber reinforced polymer matrix composite (FRP). To assess wear characteristics, the samples were put through a L9 Orthogonal Array pin-on-disc wear tester, which is part of Taguchi's Design of Experiments methodology. They used glass and carbon fibers for reinforcement. Increasing the hybrid polymer matrix composite laminate's thickness has improved its wear qualities. This material has numerous uses in the automobile sector and engineering structures (Karthik et al. 2020).

Numerous researchers have studied the following topics: carbon nanotubes (CNTs), rubber particles, nanodiamonds, titanium dioxide, wollastonite, tungsten carbide, graphene oxide, titanium carbide, silicon carbide, silica, and carbon. By adding filler particles like graphite and aluminum oxide, it strengthens epoxy. Researchers have worked on a number of projects to hybridize carbon fiber, polyamide, Kevlar, electrospun polysulfone nanofibers, and shape memory alloy fibers in order to improve the mechanical properties of glass fiber reinforced polymer composites. Better mechanical, thermal, and electrical conductivity characteristics are exhibited by carbon nanofibers and carbon fibers. (Gojny et al., 2006).

In conclusion, the discipline of materials engineering is still conducting research on the creation of hybrid polymer matrix composites and the analysis of their wear behavior. Research in this area helps the materials sector develop novel and cutting-edge applications.

4. Wear Modeling Approaches

4.1. Artificial Neural Network Approach (ANNs)

A computing system called an artificial neural network (ANN) mimics the architecture, or neurons, of a real nervous system. Every input to a neuron has a function that determines its contribution to the next neuron as well as its connectivity strength. For material research and modeling, this network system is recommended; however, it needs a specific amount of findings. (Friedrich et al., 2005). A review of works using the Artificial Neural Network model technique is provided below. Thermoplastics and thermosets augmented with unique fillers—including nanoparticles—are given specific consideration. Using artificial neural networks, attempts are undertaken to forecast wear characteristics and do systematic parameter assessments. ANNS is a new technology that can be used to forecast these materials' wear qualities based on test conditions and composition. Additionally, it makes systematic parameter studies for material optimization using computers possible. (Wear of polymer composites - K Friedrich, R Reinicke, Z Zhang, 2002, n.d.).

Three polymers' erosive wear data—polyethylene (PE), polyurethane (PUR), and an epoxy modified with hygrothermally decomposed polyurethane (EP-PUR)—have been handled by the artificial neural network technique (Zhang et al., 2003). It was shown that the friction coefficient and wear rate values decreased with an increase in the applied load in the study that examined the tribological properties, wear, and friction of ultra-high molecular weight polyethylene under dry sliding and Hank's balanced salt solution lubrication conditions. For the sliding speed values and applied load ranges examined in the study, the dry sliding condition produced the maximum friction coefficient and wear rate values, according to the findings. The study looked at how well artificial neural networks (ANNs) could forecast the material's wear rate values and friction coefficients under various sliding situations, and the findings were consistent with that. (Ermiş & Ünal, 2021).

4.2. Finite Element Method (FEM) Approach

The number of units, lines, regions, or volumes of the elements are initially defined depending on the properties of the tribological system when employing the finite element approach for wear modeling. For this, nodal points are employed. Nodes make it possible to display the amount of tribologically transferred stress. Nodes under a lot of stress also have large density. Linear or nonlinear functions are used to establish experimental conditions during wear. (Abdelbary, 2015). The studies that were done using the finite element method methodology are looked at below.

Finite element analysis has been applied to the study of stress and deformation properties during contact, as well as the determination of material properties. A macroscopic approach that assumes homogeneous, anisotropic material qualities derived from the rule of mixture-type relationships has typically guided the majority of these evaluations. This macroscopic approach's inability to accurately simulate the real-world interaction between the composite's fibers and matrix and its counterpart's asperities is a drawback (Friedrich et al., 2005). P-fiber orientation with respect to the shear direction was examined through the use of anisotropic half-space models. The contact simulation findings are used to approximate the stiffness basis for modeling each individual fiber as an infinite beam on an elastic foundation. These findings indicate a fiber stress brought on by shear and deformation (Ovaert & Wu, 1993). The contact and stress states created when a steel ball was driven into a fiber-reinforced composite were ascertained using a FE micromodel. For N- and P-fiber orientation, the position and distribution of subsurface stresses and strains were investigated. It was discovered that there is significant shear and compression on the surface in the case of N-fiber orientation. When P-fiber orientation is present, the matrix experiences stress of both the shear and compression types, yielding and local plastic deformation, while the fibers' typical deformations include compression and bending (Váradi et al., 1999). The frictional wear process in a polymer-metal contact pair: a numerical modeling approach The FEM model was made using the Abaqus software to show an integrated process and the construction of a numerical tool. The contact pair that serves as the foundation for this work is the contact between an elevator's thermoplastic polyurethane (TPU) guide shoe insert and the matching steel guide. A true simulation of these tests would need a very significant computing time because the tribometer tests required vast travel distances and a huge number of cycles in order to fit and verify the wear model. Thus, testing conducted over a suitable simulation period should be used to simulate the wear process comparable to the distances traveled (Martínez et al., 2012). The wear of polymer composites in friction joints is simulated by calculating temperature and using a mathematical model and an algorithm to solve a physically realistic stress-strain contact problem using a finite element method. The interaction processes at the PCM-counterbody interface, as well as the issue of non-stationary thermal conductivity, have been developed by developing an approach to wear process simulation based on temperature calculation in a surface layer of a polymer composite material (PCM), which takes into account the effect of ambient temperature and its influence on friction and wear process development. It was simulated by using the finite element technique (FEM) to solve a contact interaction problem. When the coefficient of friction for smooth and rough surfaces is compared, it can be shown that wear increases as surface roughness increases, but temperature essentially stays the same. (Bochkareva et al., 2018). Without making any additional heat exchange assumptions, the non-linearity of deformation and contact temperature in polymer composites was calculated by solving a non-stationary heat conduction issue in terms of mechanical-thermal energy conversion and heat loss through convection. The state of finite elements related to a polymer composite's attributes was examined, beginning with the computed temperature. (Bochkareva et al., 2020). At room temperature and a steady speed of 3 m/s, wear testing of three distinct laminated composites carbon fiber, woven glass fiber, and glass fiber reinforced epoxy was carried out on a pin-on apparatus under five different loads of 10, 20, 30, 40, and 50 N. constructed with a disc tribometer. Model of linear elastic finite elements The failure mode in the shear mode and the pin on the disk under dry lubrication were both simulated using FEM. The coefficient of friction can be numerically determined with the use of FEM in measuring friction force. One feature from FEM that is crucial for material description and analytical model work is tensile strength. As a result, an easy tensile test was used to determine it experimentally. The findings indicate that GFRP-R (Glass Fiber Reinforced Polypropylene R-Glass Prepreg) composites have a higher wear rate. (Abdellah et al., 2022).

4.3. Experimental and Mathematical Model Approaches

One can utilize wear behavior modeling developed using mathematical models or experimental setups directly, or one can use it to validate or contrast computer-aided simulations and models. Studies that used this model method were looked at.

A suggested model for abrasive wear of unidirectional fiber-reinforced polymer composites includes two models that illustrate the extremes of cyclic wear behavior, in contrast to steady-state wear, when various components wear at the same rate. This structure, which can be described as quasi-steady-state or cyclic, accommodates changes in the fiber and matrix wear rates. The underlying process has been explained, and it has been noted that this model yields more precise estimates of polymer composites' wear resistance than forecasts made using straightforward linear and inverse mixing rules based on the steady-state model. (Yen & Dharan, 1996). These predictions were compared with two engineering models to estimate the wear rates of thrust bearings made of polymers and dry friction rotating journal bearings. Additionally, it was shown how roughness, roughness orientation, and the development of transfer layers affect wear behavior (Franklin, 2001). The analysis of the study revealed a mathematical expression that uses dimensional analysis and similarity theory to calculate the temperature in the friction zone (T). In turn, the temperature acts as a reference point for forecasting wear. The established model states that it is possible to find the T value for every component in the friction pair. A thorough grasp of a polymer composite's mechanical and thermal properties, as well as its operating conditions, is necessary for the model to be applicable. If the operating parameters and fundamental data of the composites are known, then using the model makes it possible to determine the wear value of friction pairs made of polymer compositesIt is claimed that using models saves a substantial amount of time and money as compared to carrying out real friction wear trials under real conditions. (Tretyakov, 2004). The application of single-track and intersecting etching techniques is investigated to study abrasive wear in polymers. The results of earlier studies were confirmed through scratch and pin-on-disk wear tests on a variety of commercial polymers, indicating a relationship between scratch phenomena and abrasive wear. Interestingly, Sinha et al. found that the traditionally determined scratch hardness did not show any pattern with abrasive wear. (2007). Several influential parameters that could be analytically confirmed were included in a model that was developed in an attempt to create a comprehensive analytical model for predicting the wear of engineering polymers. The wear equations are divided into two categories: abrasive wear and fatigue wear. This is because the two mechanisms of wear work in separate ranges of roughness. It is important to note that, except in cases where melt wear predominates, the E/H ratio assumes a value at which wear is expected to be negligible in most parametric combinations. These predictions are useful in practice and match up well with various engineering polymer trials. (Chowdhury & Chakraborti, 2008). Small-scale roller-on-plate tests were used to compare the friction and wear behavior for polyoxymethylene homopolymers (POM-H) and teflon-doped polyethylene terephthalate (PET/PTFE). Four experimental models are presented to predict tribological data on contact pressure shear rate (pv-value), which is the parameter used to characterize tribological data. Sample geometries and contact deformation, as well as thermal effects (heat generation and dissipation), were taken into account with a new macroscopic geometry model that allows test results in small and large-scale tests. (Samyn & Schoukens, 2008). A description of the wear model, transfer, and their effects on friction is given. The creation and motion of particles as well as the friction-transfer relationship are both explained by the model's unknown parameters. In a linear reciprocating sliding tribometer, where a polymer-coated rod slides in a point contact configuration on a rough metallic roller under high pressure and a large sliding length of 10 mm, the parameters are obtained experimentally. It has been demonstrated that the developed model does a good job of describing how friction changes across multiple cycles. (Boissonnet et al., 2012). By merging Reye's wear model with elastohydrodynamic lubrication theory, a wear model under lubricated conditions was created. According to the wear simulation, HDPE wear rises with increasing sliding speed and normal load but falls with increasing lubricant viscosity and asperity height. The wear model can shorten the time required for wear testing and be used to forecast the long-term wear of polyethylene-based polymers in lubricated settings. (Xu et al., 2018). It has been demonstrated that temperature affects polymer-polymer sliding contacts, and that the choice of materials for static and rotating parts in polymer-polymer contact designs affects the sliding contact life. It has also been demonstrated that application temperature during operation significantly affects longevity. Lastly, a new design approach based on the deformation energy concept is offered, which suggests a wear model because this energy causes changes in the properties of the material. The suggested model is different from current models in that it uses the Peclet number to include the thermal characteristics of materials in contact (Ramesh et al., 2019). Hybrid natural fiber-reinforced polymer composites have emerged as an environmentally friendly alternative to traditional building materials due to their low cost and high strength-to-weight ratio. Response surface method (RSM) was used in the studies. RSM also provided a mathematical model for optimization of sliding wear of hybrid composites. The most suitable composite with optimum values for minimum sliding wear of hybrid composites was found. A fuzzy logic model was also developed for the prediction of sliding wear of hybrid composites based on experimental data. From the results obtained, it was seen that the developed fuzzy model could predict the sliding wear of hybrid composites with 87% accuracy. (A. K. Sinha et al., 2021).

5. Evaluation of Wear in Polymer Matrix Composites

The outcomes are typically assessed through a combination of theoretical modeling and experimental studies. As part of these investigations, material qualities are ascertained, wear resistance is tested, and mathematical models are created. Studies that look at polymer matrix composite materials' wear behavior experimentally exist. It is necessary to investigate the tribological and mechanical aspects of polymer matrix composites' wear and friction characteristics. These kinds of investigations are critical to comprehending how material components interact, assisting in the selection of materials, and assessing their application performance.

Mechanical modeling and the assessment of material parameters are commonly employed in calculations to assess wear in polymer matrix composites. These computations (Sudeepan et al., 2014):

- Friction and wear property calculation: Material properties and mechanical modeling are utilized to determine the friction and wear properties of polymer matrix composites. These models comprise the matrix element, the fibrous zone, and the material's wear outcome.
- Dry sliding wear behavior calculation: The following procedures are used in studies where the wear resistance, material characteristics, and dry sliding behavior of polymer matrix composites are calculated.
- Tribological and mechanical properties: The tribological and mechanical properties of polymer matrix composites are computed by means of mechanical modeling, which establishes the material-instek and coaxial properties and computes the parameters influencing the material's wear and friction properties.
- Polymer matrix composites: The structure and characteristics of these materials, such as reinforcing materials, thermosetting polymers, and other additive materials, are determined using a variety of techniques and computations. The performance of polymer matrix composites in various applications and areas of usage is assessed using this data.

These computations are used to assess polymer matrix composites' wear behavior and enhance their application performance. Furthermore, the performance of the materials in applications is assessed and material selection is guided by these computations (Sudeepan et al., 2014).

6. Conclusion and Evaluation

Low coefficients of friction, strong resistance to abrasion, ease of shaping, and resistance to oxidation or corrosion characterize polymeric materials. Polymer composites are stronger and more rigid than pure polymers because of the presence of reinforcing elements, which enables them to bear heavy loads and stresses. While many thermoset composites may deteriorate or lose their mechanical qualities at high temperatures, other polymer composites have good temperature resistance.

The use of polymeric materials has several benefits, such as low density, resistance to oxidation and tribocorrosion, non-toxic structure, easy shaping, and low cost. It does seem to have certain drawbacks, though, in addition to its positives. Negative temperatures affect polymeric materials differently, and even a slight variation in operating circumstances can have a substantial impact on their tribological characteristics.

Examining classical tribology reveals that it was first created as a discipline for metals. Polymer tribology is dominated by interfaces and various operating circumstances such as thermal heat, contact pressure, and the production of transfer films. Because of this, conventional experimental techniques in this area are modified for use with polymers rather than valid for polymers. The scale and complexity of the system under examination vary, and there are several methods in the literature for assessing the tribological behavior of a pair of polymer-based materials. This makes it evident that a distinct working area is created by a suitable kind of tribo test setup with the right parameters chosen to mirror the material/composite's real-time application.

Polymer composites, because of their special tribological characteristics, are very versatile, and can be customized, have many uses and great potential in the future. The capabilities of polymer composites will be further expanded by ongoing research and development activities and technical advancements, resulting in enhanced performance, sustainability, and new applications in a variety of sectors. Furthermore, the development of hybrid composites has opened up a significant area for tribological research.

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