TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 69, Issue I, March, 2026

A TRIBOLOGICAL STUDY OF HIGH-PERFORMANCE POLYMERS USED TO MANUFACTURE PLASTIC GEARS

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Abstract: *This paper discusses the use of high-performance plastics in worm gear manufacturing, focusing on polyphenylsulfides (PPS), polyvinyl fluorides (PVDF), polyetherimides (PEI), polyethersulfone (PES), and polysulfones (PSU). These materials offer excellent mechanical, thermal, and electrical properties, including wear resistance, dimensional stability, and chemical resistance. The article evaluates the potential of these materials in the worm gear industry, highlighting their advantages over traditional materials like light weight, corrosion resistance, and mechanical performance. The research analyzes the characteristics of these materials and proposes ways to improve gear system performance. The study highlights the advantages of these materials in sectors like the chemical, pharmaceutical, and electrotechnical industries, emphasizing their potential to enhance efficiency and durability of mechanical systems.*

Key words: *High-Performance Polymers, Plastic gears, Tribological Analysis, Friction coefficient, Wear Resistance.*

1. INTRODUCTION

In the present context, plastic gears have gained significant importance in various industries, serving as essential components in power transmission and motion. Used in a variety of applications, they have become increasingly prominent due to corrosion resistance, mechanical performance, and versatile applicability. This paper provides an overview of the evolution of traditional materials used in gear manufacturing.

The objectives of this research are clearly defined, aiming to deepen understanding and advance the technology associated with plastic gears. The study seeks to provide a detailed perspective on the characteristics of the materials used and proposes methods to enhance the performance of geared systems.

The document will address topics such as the current state of plastic gears, justification for the research, contributions and innovations introduced, proposed objectives, and obtained results. This structural approach facilitates the comprehension and assimilation of the presented information.

2. LITERATURE REVIEW

The necessity of this study arises from identifying significant gaps in specialized literature related to the use of high-performance polymers in plastic gears. The study is essential to address these deficiencies, offering a clearer perspective on the potential of these materials in plastic gears production. Emphasis is placed on the need for improving materials used in gears manufacturing, considering the continuously evolving technological and industrial requirements.

In [1], the study focuses on the technical characteristics of polymer gears gears, such as wear and fatigue resistance. The authors recommend experimental optical analysis of tooth bending during dentition instead of traditional numerical methods. The authors used two image processing methods, which confirmed the good correlation with the finite element analysis results.

The study [2] highlights the possibilities of using plastics such as POM (Polyoxymethylene), PA6 (Polyamide 6), PA66 (Polyamide 66), PEEK (Polyetheretherketone)

Received: 27.01.26; **Similaritie**s: 17.02.26: **Reviewed**:19.02./28.02.26: **Accepted** 19.03.26.

and reinforced plastics in tires due to their properties such as wear resistance, low noise, and low production costs. However, the temperature and precision challenges of cast gears are known. The goal was to develop advanced polymeric power transmission components for mechatronic applications that required a materials database and test system to support design decisions. S gears offer better properties compared to involute gears, including lower contact pressure and lower sliding and friction losses.

In the following three referenced works by the Institute of Polymer Technology (LKT), innovative in-situ testing methodologies for plastic gears are discussed. Reference [3] introduces a system measuring tooth deformations using time differences between rotary encoder indexing pulses, revealing the significant impact of temperature on deformation compared to rotation frequency or speed. Experimental strains surpass calculated values, prompting a suggested modification to the VDI 2736 guideline for more accurate future applications. Paper [4] presents a new testing methodology for steel and plastic bicycles, analyzing time differences in encoder pulses to evaluate elastic and permanent deformation. While results show a strong correlation with established pulse tests, system design introduces displacement due to angular displacements. Research [5] details an in-situ method for measuring deformations and wear in polymer gears. Initially validated on PA66 and PBT gears, the approach involves analyzing time differences in encoder pulses to isolate effects such as elastic and plastic deformation, thermal expansion, and wear. The new test system enhances understanding of wear and deformation behavior in steel and polymer gears, allowing for a comprehensive analysis of different loading conditions over time, considering both transmission torques and rotation speeds.

In their research [6], the authors propose a vibration-based gears wear diagnosis method with the aim of creating effective techniques to evaluate the effect of wear on gears performance. The gears state vector derived from the tooth rotation signals, including the sideband ratios of the gears harmonics. Experimental results demonstrate the effectiveness of these vibration indicators, which can also detect other defects such as tooth cracks or axle imbalances due to their effect on gear vibrations.

In reference [7], a novel non-invasive methodology for diagnosing and classifying levels of uniform gear wear through infrared thermography is presented. This approach includes the calculation of statistical features from temporal signals in thermal images. Linear discriminant analysis is employed for dimensionality reduction, and an artificial neural network is utilized for automatic fault diagnosis. The method undergoes evaluation in experiments spanning from a healthy state to three levels of uniform wear severity (25%, 50%, and 75%). Notably, the innovation lies not only in the utilization of infrared thermography but also in its correlation with elements of machine learning and artificial intelligence. The results, which were compared with classical condition monitoring approaches based on vibration analysis, reinforce the effectiveness of the proposed methodology.

In reference [8], the article offers a thorough overview of research on straight-toothed polymer gears, emphasizing their notable enhancements in power and motion transmission. This improvement is attributed to their characteristics, including light weight, lower inertia, and silent operation in contrast to metal gears. The review encompasses diverse aspects such as the range of polymers and compounds utilized, operating conditions, design features, tooth modification techniques, models, simulation studies, hybrid gears, tribological properties, manufacturing methods, and failure modes. Comprehensive coverage renders this review valuable for researchers in the field.

In [9], the authors investigate how the grinding thickness assignment affects the various parameters during shape grinding of 20Cr2Ni4A gears. The study focuses on surface morphology, grinding temperature, microstructure, surface roughness and microhardness variations. The results show that the grinding temperature is affected by a significant depth of rough grinding, leading to thermal softening and a decrease in microhardness. The surface roughness is affected by the thickness assignment in the last two passes. Microstructural analysis shows that the removal thickness of 0,02 mm during fine polishing is not enough to remove the roughness of the previous pre-polishing, resulting in visible defects on the surface. The proposed repair strategy is validated during practical production, demonstrating good surface quality and geometric accuracy.

The paper [10] proposes an innovative gear fault diagnosis method based on deep learning and audio signal analysis and addresses the limitations of vibration-based methods and traditional acoustic approaches. The method uses an end-to-end convolutional neural network (CNN) to directly process raw signals in the time and frequency domains without requiring service planning. It also integrates multichannel information from different microphones. The experimental results show excellent performance compared to traditional gears fault diagnosis methods that include feature design. The article concludes with a dataset of publicly available audio signals for gear failure diagnosis, contributing to the advancement of research in this area.

The materials chosen for gears influence their kinematics and operation, an aspect highlighted in papers [11] and [12].

In this context, our research highlights original contributions and innovative aspects regarding the use of high-performance polymers in the context of plastic gears. Special attention is given to the unique perspective and innovative approach adopted within the study, emphasizing the distinctiveness of this research.

3. MATERIALS AND METHODS

3.1 Materials

In this section, an extensive description is provided regarding the high-performance polymers that are the focal point of this study.

The polymers investigated include polyphenylsulfides (PPS), polyvinyl fluorides (PVDF), polyetherimides (PEI), polyethersulfone (PES), and polysulfones (PSU). Each material is carefully examined, highlighting its unique properties, strengths, and areas of use. The reasons for the selection of specific polymers are explained in detail, focusing on their unique contribution to the study.

Polyphenylene Sulfide (PPS):

Polyphenylene sulfides (PPS) stand out due to their remarkable mechanical strength, providing durability and rigidity. These properties make them suitable for applications involving significant mechanical loads, such as the manufacturing of plastic gears.

Another distinctive feature of PPS is its excellent thermal stability. Their ability to withstand elevated temperatures without compromising mechanical properties gives them advantages in applications where heat generation is constant.

PPS is known for its exceptional chemical resistance. This feature makes PPS-based plastics suitable for aggressive industrial environments where corrosive chemicals may be present.

Polyvinyl Fluoride (PVDF):

PVDF stands out for its corrosion resistance, dimensional stability, and durability. However, consideration must be given to limitations arising from specific production processes and associated costs.

PVDF offers notable thermal stability, making it suitable for applications where exposure to elevated temperatures is constant. This characteristic makes it attractive in the manufacture of gears intended for demanding industrial environments.

Previous studies have highlighted the tribological performance of PVDF, including its wear resistance and ability to maintain efficient lubrication during operation.

Polyetherimide (PEI):

Polyetherimides (PEI) are distinguished by their wear resistance, making them suitable for applications where gears are subjected to significant frictional loads.

The dimensional stability of PEI is crucial in the context of manufacturing plastic gears, where tight tolerances and precision are critical for optimal system operation.

PEI is often preferred in applications requiring resistance to elevated temperatures, such as in the chemical or aerospace industries.

Polyethersulfone (PES) and Polysulfone (PSU):

PES and PSU offer remarkable mechanical properties, such as tensile strength and hardness, contributing to the overall performance of plastic gears.

These plastic materials are known for their ability to withstand elevated temperatures without compromising structural integrity.

PES and PSU are appreciated for their resistance to a wide range of chemicals, enhancing the durability of plastic gears in diverse industrial environments.

The specific selection of these polymers in this study is based on their different properties. PPS provides a remarkable balance between mechanical strength and thermal stability. PVDF contributes to its resistance to chemicals and PEI stands out for its thermal and dielectric properties. PES and PSU complete the mix with a balance of mechanical resistance and thermal stability. This careful selection of materials is a unique and essential contribution to the study of plastic actuator development.

This rational and analytical approach to polymers is essential for understanding the role of individual materials in research and for the subsequent substantiation of the results obtained.

3.2 Research methods

CAD Modeling and Design:

A computer-aided design (CAD) software was employed to create precise 3D models of plastic gears according to project specifications. Rigorous analysis of geometry and dimensions was conducted to ensure accuracy and compliance.

For the execution of the part, the 3D model of the gear was made. The drawings were made in the CAD design program Catia V5 (figure 1).

The study involved conducting tests on an actual gear designed in CATIA and manufactured from Polyamide PA6 with a diameter of ϕ275x50mm. This ensures that the tests were performed on a real-world, functional gears made on one of the materials under investigation, including polyphenylsulfides (PPS), polyvinyl fluorides (PVDF), polyetherimides (PEI), polyethersulfone (PES), and polysulfones (PSU). The use of gear in the experiments ensures the relevance and applicability of the study's findings to practical gear systems made from the specified high-performance materials.

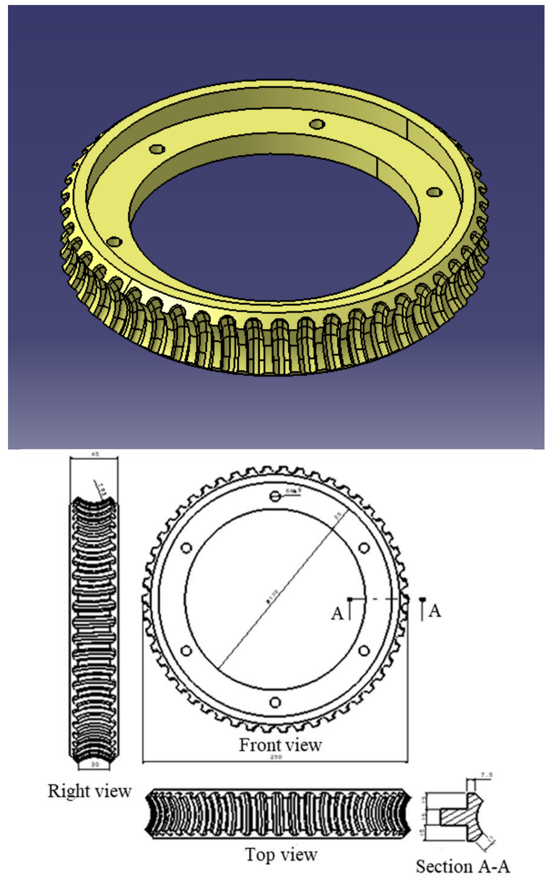


Fig. 1. Gear model

Material Selection and Preparation:

The properties of the studied PA6 are presented below:

Mechanical properties:

- Tensile strength: 79 MPa (DIN EN ISO 527-2);
- Modulus of elasticity (tensile test): 3300 MPa (DIN EN ISO 527-2);
- Tensile strength at yield: 78 MPa (DIN EN ISO 527-2);
- Elongation at yield (tensile test): 4% (DIN EN ISO 527-2);
- Elongation at break (tensile test): 130% (DIN EN ISO 527-2);
- Flexural strength: 100 MPa (DIN EN ISO 178);

- Modulus of elasticity (flexural test): 2900 MPa (DIN EN ISO 178);
- Compression strength: 24/41/86 MPa (EN ISO 604);
- Compression modules: 2700 MPa (EN ISO 604);
- Impact strength (Charpy): n.b. kJ/m (DIN EN ISO 179-1eU);
- Notched impact strength (Charpy): 7 kJ/m (DIN EN ISO 179-1eA);
- Shore hardness D: 79 (DIN EN ISO 868)

Thermal properties:

- Glass transition temperature: 45°C (DIN EN ISO 11357);
- Melting temperature: 221°C (DIN EN ISO 11357);
- Service temperature short term: 160°C;
- Service temperature long term: 100°C;
- Thermal expansion (CLTE) 23-60°C, long.: 12 x 10^{-6} K (DIN EN ISO 11359-1;2);
- Thermal expansion (CLTE) 23-100°C, long.: 13 x 10^{-6} K (DIN EN ISO 11359-1;2);
- Specific heat: 1.6 J/(g·K) (ISO 22007-4:2008);
- Thermal conductivity: 0.37 W/(K·m) (ISO 22007-4:2008);

Electrical properties

- Surface resistivity: 10 Ω (1);
- Volume resistivity: 10 Ω·cm (1);
- Dielectric strength: 31 kV/mm (ISO 60243-1);
- Resistance to tracking (CTI): 600 V (DIN EN 60112);

Other properties:

- Water absorption 24h / 96h (23°C): 0.3% / 0.6% (DIN EN ISO 62);
- Flammability (UL94): corresponding to HB (DIN IEC 60695-11-10).

CNC Machining with Haas Mini Mill:

The CNC Haas Mini Mill was utilized for mechanical machining operations, including turning and cutting. This machine-managed process ensured precision and efficiency in shaping plastic gears.

The CNC machine works on a 3-axis system offering superior quality.

The equipment has a spindle that develops a power of 5,6 Kw and a speed of 6000 rpm.

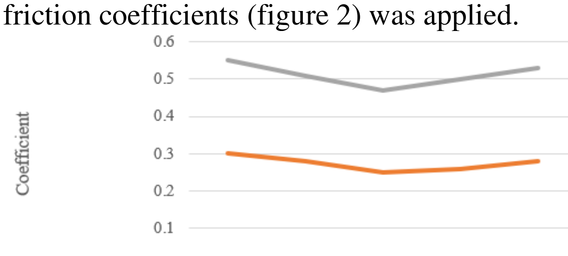
Tribological Testing:

Tribological tests, such as Pin-on-Disk and Ball-on-Disk tribometry, are used to evaluate the friction behavior and wear resistance of plastic gears under conditions that simulate real-world applications.

The comprehensive tribological tests using a Pin-on-Disk apparatus to intricately examine the tribological behavior of Polyamide (ϕ275x50mm), were conducted.

Also, the determination of friction coefficient under various conditions was conducted.

A range of forces between 5 N and 15 N to investigate their influence on static and dynamic friction coefficients (figure 2) was applied.



	Applied Force (N)	5	7	10	12
Dynamic Friction Coefficient	0.25	0.23	0.22	0.24	0.25
Static Friction Coefficient	0.3	0.28	0.25	0.26	0.28

Fig. 2. Friction coefficient vs. applied force graph

At 10 N, the initial static friction coefficient was 0,3, evolving to 0,25 in the first 1000 cycles and stabilizing thereafter.

Next the wear resistance and abrasion analysis was conducted. Here, it is monitored material loss over 5000 cycles, measuring a minimal loss of approximately 0,01 mm² on the Polyamide disk (figure 3).

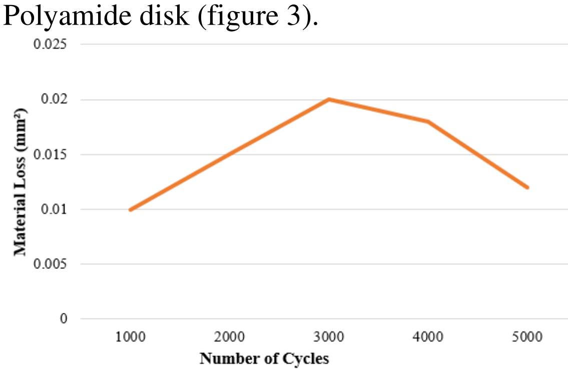


Fig. 3. Variation of material loss during tests

Abrasion analysis revealed negligible abrasion, highlighting notable wear resistance.

Then the sliding speed effect was studied.

The sliding speed between 0,05 m/s and 0,2 m/s to investigate its influence on tribological behavior varied (figure 4).

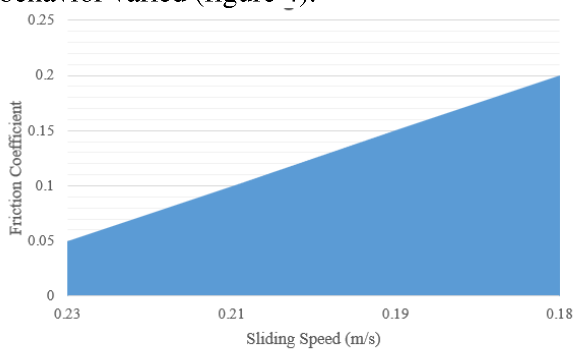


Fig. 4. Sliding speed effect graph

Results indicated a reduction in the friction coefficient at lower speeds and a slight increase at higher speeds.

Calculation and Tolerance Application:

Plastic-specific tolerances are calculated and applied considering factors such as the coefficient of thermal expansion. The goal is to ensure the dimensional stability and operability of plastic gear.

In our study the polyamide plastic gear is intended for an industrial application that involves significant temperature variations, ranging from -20°C to 80°C.

The coefficient of thermal expansion for polyamide is 120 x 10^{-6}. The calculation of thermal expansion:

$$\Delta T = 80°C - (-20°C) = 100°C \quad (1)$$

$$\Delta Diameter = \alpha \cdot Diameter \cdot \Delta T \quad (2)$$

$$\Delta Diameter = (120 \cdot 10^{-6}) \cdot 275 \cdot 100 \quad (3)$$

$$\Delta Diameter \approx 3{,}3mm \quad (4)$$

Given the anticipated thermal variation and to ensure the functionality and reliability of the Polyamide gear, it is proposed to apply tolerances of ±1,5mm for the diameter dimension.

Minimum Tolerated Diameter=Initial Diameter - Tolerance = 275mm - 1,5mm = 273,5mm

Maximum Tolerated Diameter=Initial Diameter + Tolerance = 275mm + 1,5mm = 276,5mm

This analysis highlighted the risk of significant thermal expansion under extreme temperature conditions. In cases of extreme thermal variations, issues related to mechanical interferences and overall gear performance may arise.

To manage the impact of thermal expansion, consideration could be given to integrating composite materials with lower coefficients of thermal expansion. Additionally, implementing a cooling system or thermal dispersion features can help maintain temperatures within acceptable limits.

This detailed analysis emphasizes the importance of correctly applying tolerances in the design of plastic gears, especially in the context of extreme thermal variations. In an initiative-taking approach, the design team can implement technological and material solutions to ensure optimal performance and durability in diverse environmental conditions.

Verification through Precise Measurements:

Detailed measurements are taken to verify that the plastic gears meet predetermined specifications. These include dimensional accuracy checks and surface quality assessments.

Measured dimensions and thickness are consistent with the initial CATIA design and fall within the specified tolerance.

The gears surface exhibits aesthetic and functional qualities in line with ISO 9001:2015 standards.

So, the rigorous verification process confirms that the Polyamide gears are precisely manufactured and meet all designed specifications, ensuring performance and reliability.

4. RESULTS AND DISCUSSIONS

In this study, significant results have been obtained regarding the tribological properties and wear behavior of the tested polymer within the context of plastic gears. Tribological tests were conducted on a polyamide gear with a diameter of ϕ275x50mm, employing Pin-on-Disk tribometer to simulate real-world application conditions.

The following findings pertain to the tribological properties and wear behavior of polymers underscore the importance of material selection and precise design in plastic gears applications.

Utilizing the Pin-on-Disk tribometer, the friction coefficient under various conditions was determined. At a force of 10 N, the initial static friction coefficient was 0,3, evolving to 0,25 in the first 1000 cycles and stabilizing thereafter.

The variation in the friction coefficient indicated a decrease at lower speeds and a slight increase at higher speeds.

Wear resistance analysis revealed minimal material loss of approximately 0,01 mm² on the polyamide disk over 5000 cycles.

Abrasion analysis highlighted negligible abrasion, emphasizing notable wear resistance.

Sliding speeds varied between 0,05 m/s and 0,2 m/s to investigate their influence on tribological behavior.

Results indicated a reduction in the friction coefficient at lower speeds and a slight increase at higher speeds.

Coefficients of Friction (COFs) for Polyamide gears were measured during tribological tests. At 10 N, the initial static friction coefficient was 0,3, evolving to 0,25 in the first 1000 cycles. Wear scar diameters were monitored, revealing a minimal material loss of approximately 0,01 mm² over 5000 cycles.

Tribological tests involved varying sliding speeds between 0,05 m/s and 0,2 m/s. Temperature conditions ranged from -20°C to 80°C, simulating industrial applications.

The tests specifically focused on Polyamide gears (ϕ275x50mm). The number of samples used was five. The results indicated stability in the friction coefficient after 1000 cycles and minimal material loss over 5000 cycles, suggesting consistency in performance.

The lubricants have not been a part of the testing conditions.

5. CONCLUSIONS

This research aimed to enhance plastic gear technology by analyzing high-performance polymers like PPS, PVDF, PEI, PES, and PSU, revealing their unique characteristics and practical applications.

This study significantly contributes to plastic gears by identifying and characterizing high-performance materials, emphasizing the importance of careful material selection and the advantages of each polymer. The use of Pin-on-Disk tribometry testing methods provides relevant results.

This research explores high-performance materials used in plastic gears, filling gaps in specialized literature. It provides a comprehensive perspective on their behavior under various operating conditions. The findings also offer valuable insights for designing and manufacturing plastic gears, thereby optimizing their performance in industrial applications.

Future research should explore the interactions between polymeric materials and specific operating environments, improve testing methodologies, and extend analyses to a broader range of materials. Additionally, investigating the variable impact of lubricants on tribological behavior could be interesting.

In conclusion, this research provides an innovative and detailed perspective on high-performance materials used in plastic gears, offering essential information for the development and optimization of these materials in practical applications. By achieving the set objectives and highlighting significant contributions, this work serves as a solid foundation for future research in the field of plastic gears.

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Un studiu tribologic asupra materialelor plastice performante în fabricarea angrenajelor melcate

Această lucrare analizează utilizarea materialelor plastice performante utilizate în fabricarea angrenajelor melcate, concentrându-se pe cu accent pe polifenilsulfizi (PPS), polivinilfluorizi (PVDF), polieterimizi (PEI), polictersulfoni (PES), și polisulfoni (PSU). Aceste materiale oferă proprietăți mecanice, termice și electrice excelente, precum rezistență la uzură, stabilitate dimensională și rezistență chimică. Articolul evaluează potențialul acestor materiale în industria angrenajelor melcate, evidențiind avantajele lor față de materialele tradiționale, cum ar fi greutatea redusă, rezistența la coroziune și performanța mecanică. Cercetarea analizează caracteristicile acestor materiale și propune modalități de îmbunătățire a performanțelor sistemelor de angrenaje. Studiul evidențiază avantajele acestor materiale în sectoare precum industria chimică, farmaceutică și electrotehnică, subliniind potențialul lor de a spori eficiența și durabilitatea sistemelor mecanice.

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