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VARIATION OF MECHANICAL AND TRIBOLOGICAL CHARACTERISTICS OF POLYMER PARTS REINFORCED WITH SHORT GLASS FIBERS

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Abstract: This study examines the mechanical and tribological behavior of polyamide 6.6 (PA6.6), in both neat and short glass fiber-reinforced (30%) forms, produced by injection molding. Tensile tests revealed a ~71.5% increase in mechanical strength for reinforced composites, accompanied by reduced elongation at break. Tribological evaluations using a pin-on-disc tribometer indicated significantly lower friction coefficients and wear rates for glass fiber-reinforced samples. SolidWorks Plastics simulations confirmed the correlation between fiber orientation, processing conditions, and material performance. The combined experimental and numerical approach demonstrates an effective strategy for optimizing the structural and tribological properties of injection-molded PA6.6 components, enabling their reliable application in engineering fields.

Key words: PA6.6, PA6.6-30% GF, reinforced composites, fiber orientation, injection-molded, wear rates

¶ (12 pt)

1. INTRODUCTION ¶ (12pt)

In recent years, **fiber-reinforced polymer composites** have become essential in engineering applications due to their favorable mechanical properties, low density, and versatility in design. Therefore, considerable efforts have been made to replace steel and castings with lighter materials, such as aluminum and polymers[1]. These materials offer critical advantages such as light weight, high specific strength, and improved insulation properties, making them increasingly preferred across automotive, aerospace, and industrial sectors [2-4]. The shift toward lighter materials supports a global strategy to reduce carbon emissions, particularly in the transportation industry, by decreasing structural mass while maintaining or improving performance [2]. Due to the complex behavior of polymeric blends, comprehensive testing and data comparison are essential to prevent material failure and to ensure the selection of the most suitable polymer combination for a specific application.

Among these materials, **polyamide (PA)-based composites** reinforced with **glass fibers (GF)** have demonstrated remarkable mechanical and tribological capabilities. Polyamides, especially PA6.6, exhibit excellent strength, stiffness, thermal resistance, and chemical stability. Reinforcing these matrices with GF further enhances these properties, making them suitable for components that must withstand high mechanical loads and wear conditions. In particular, long and short GF are widely used to improve the mechanical strength and dimensional stability of polyamides without significantly increasing density or compromising processability [5]. For instance, Srinath and Gnanamoorthy demonstrated that adding approximately 20 wt.% GF to nylon 66, when tested against stainless steel (AISI 314), reduced the specific wear rate by ~74% and the coefficient of friction by ~28% [6]. Similarly, Kim et al. reported that a 30 wt.% GF reinforcement against carbon steel (S45C) significantly improved wear resistance and reduced friction [7].

The tribological performance of Glass Fiber Reinforced Polymer (GFRP) composites is critical for dynamic applications. The addition of fibers not only strengthens the polymer matrix but also alters its wear characteristics under dry and humid conditions. Numerous studies have confirmed that the fiber content, environmental exposure, and interfacial bonding significantly influence the frictional behavior and longevity of these materials [8], [9], [10]. Furthermore, environmental conditions can dramatically affect tensile and flexural strength. Wazery et al. observed that the tensile strength of GFRP composites ranged from 28.25 MPa to 78.83 MPa, while flexural strength varied from 44.65 MPa to 119.23 MPa, depending on the fiber content (15–60 wt.%) [8]. Abdullah et al. [10] showed that chopped fiber composites exhibited higher Young's modulus, maximum stress, and yield strength than woven 0/90 composites, underscoring the influence of fiber morphology on mechanical response.

From a processing perspective, **injection molding** remains the most prevalent method for fabricating thermoplastic components. It accounts for more than one-third of total plastic production globally and is preferred due to its short production cycles, excellent surface finish, and ability to produce parts with complex geometries [11]. When applied to GFRP materials, injection molding must account for variables such as fiber orientation, volume fraction, and dispersion, all of which critically influence the mechanical and tribological behavior of the final component [12], [13]. Fibers can serve as heterogeneous nucleants during foaming, leading to smaller, more uniformly distributed cells and improved structural performance [12].

Sinmazçelik and Yılmaz studied the effect of thermal aging on randomly oriented, short-fiber CFRP and GFRP composites, finding that thermal aging did not significantly alter the degree of crystallinity, though it did affect tribological, and mechanical properties [14].

According to Plastics Europe, the automotive industry alone accounts for 8.6% of total European plastic demand, with PA and PP being

the most utilized thermoplastics in the sector [4]. The mechanical behavior of fiber-reinforced composites is governed by the intrinsic properties of the fiber, such as tensile strength and modulus, as well as the fiber–matrix interface, which enables efficient stress transfer [15,16-18]. For PA6.6 matrices, GF is a particularly effective reinforcement due to the high interfacial bonding achieved through fiber sizing treatments, resulting in composites with excellent structural integrity [18].

1.1 Objective of the Study

In the polymer injection molding industry, it is possible to produce components with complex geometries, characterized by high dimensional accuracy and excellent process repeatability. This study investigates a representative mechanical component—a toothed wheel—originally fabricated from polyamide 6.6 (PA6.6) used in the automotive field, whose teeth fail prematurely, under normal loading conditions. To solve this problem, PA6.6 reinforced with 30% glass fiber was chosen as studied material.

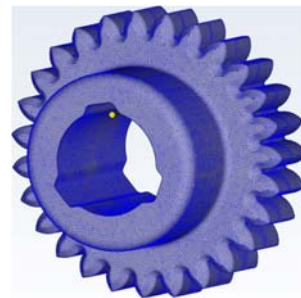


Fig. 1. Studied toothed wheel.

Due to their lightweight and cost-effective nature, plastic gears are increasingly replacing metal gears in low-load applications. Given the substantial mechanical loads to which these components are subjected during operation, the incorporation of glass fiber reinforcement is essential. The reinforcement with glass fiber significantly enhances the material's mechanical properties, enabling the component to withstand and transmit complex and unpredictable loading conditions while maintaining structural integrity. In this context, fiberglass reinforcement is introduced in the form of **whisker-shaped glass fibers** to enhance the

composite's mechanical performance. Whiskers are single-crystal fibers with exceptional crystallographic integrity, characterized by high aspect ratios and minimal internal defects due to their small diameters. As a result, they exhibit mechanical strengths approaching the theoretical limits predicted by elasticity theory.

This composite material is widely utilized due to its enhanced mechanical performance. The objective of this research is to evaluate the effects of glass fiber content (0 wt% and 30 wt%), applied load, and sliding velocity on the mechanical and tribological behavior of injection-molded PA6.6-based glass fiber-reinforced polymer (GFRP) composites. Tribological performance was assessed using a pin-on-disc tribometer, focusing on key parameters such as the coefficient of friction, specific wear rate, and contact temperature. Additionally, fiber orientation and distribution induced by the injection molding process were analyzed to establish correlations between processing conditions and material response, using SolidWorks Plastics.

A simulation-based approach was employed to investigate glass fiber orientation and flow behavior during mold filling. A comparative analysis between reinforced and unreinforced PA6.6 was conducted, considering mechanical properties and tribological performance.

2. MATERIALS AND METHODS

To evaluate the mechanical behavior of PA6.6 in both unreinforced and glass fiber-reinforced forms, test specimens were produced via injection molding, Fig.4, following the dimensional requirements specified by the SR EN ISO 527-2000 standard. The reinforced PA6.6 composite contained 30 wt.% short glass fibers (SGF), with specific characteristics from the Table 1.

The primary objective of preparing the polymeric material specimens was to investigate the evolution of the mechanical properties—and other relevant characteristics—PA6.6 reinforced with 30% GF. The polymer granules utilized in

this study were supplied by the ICEFS Săvinești Research Center, Fig 2.



Fig. 2. a) PA6.6 pellets, b) PA6.6-30%GF.

Bone-shaped and plate specimens for tensile and tribological testing, Fig.4, were produced through melt injection, using an injection molding machine at Monofil Săvinești, Romania, Fig.3.



Fig. 3. Plate injection mould.

Virgin PA 6.6 is white and exhibits excellent physico-mechanical and chemical properties characteristic of engineering-grade polyamides, Fig.2. Its melting temperature, which is 40–60°C higher than that of other polyamides, extends the range of applications for PA6.6-based engineering polymers. PA 6.6 – 30%GF is a polymer composite material that contains short glass fibers with a diameter ranging between 8 and 14 µm, and a length between 1 and 3 mm, Fig.5. It PA 6.6 – 30% GF is black, and additional processing characteristics can be found in Table 1.

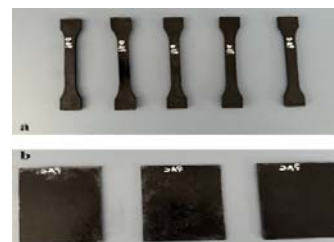


Fig. 4. a) bone shaped and b) plate samples



Fig. 5. GF whiskers[19]

The tribological behavior of PA66 and its glass-fiber-reinforced composite was evaluated under dry sliding conditions using a TRB3 ball-on-disc tribometer (Anton Paar, Graz, Austria). Wear tests were conducted in accordance with ASTM G99–17, ASTM G133, and DIN 50324, ensuring compliance with recognized industrial and research standards.

Prior to testing, all samples and steel balls were thoroughly cleaned with ethyl alcohol to remove surface contaminants. After each test, the specimens were cleaned again and dried before mass and dimensional measurements. Each test was repeated at least three times to ensure statistical reliability. The tribometer was operated with InstrumentX software, which allows precise control of load, speed, and movement, as well as the simulation of contact stress and deformation distribution. After testing, the wear track was scanned 4–5 times for each sample to determine the specific wear rate K (mm^3/Nm).

The software also computed the contact pressure and allowed the post-processing of friction and wear data. 100Cr6 steel was selected as the counterface material due to its high hardness, dimensional stability, and wear resistance.

The ball was positioned at a 10 mm track radius, generating a consistent circular wear path. The tests were performed at a constant sliding speed of 300 rpm for 30 minutes, under ambient conditions of 23 °C and 58–60% relative humidity, within a class 1:1000 cleanroom environment.

Table 1. GF whiskers characteristics

Property	Typical Value / Range	Unit	Remarks
Crystal Structure	Amorphous (for glass) or Single-crystal-like	–	Glass whiskers exhibit high structural integrity and minimal defects
Diameter	0.8 – 14	μm	Smaller than conventional fibers
Length Aspect Ratio (L/D)	1 – 3 20 – 200+	mm –	Yields a high aspect ratio Critical for effective stress transfer
Tensile Strength	3 – 7	GPa	Near-theoretical values due to defect-free structure
Young's Modulus	70 – 90	GPa	Higher than unreinforced thermoplastics
Density	~2.5	g/cm^3	Typical for E-glass mater

The tribological specimens were prepared as circular discs with a diameter of 50 mm and a thickness of 2 mm, which were brought into contact with a 6 mm diameter 100Cr6 steel ball, Fig.6.



Fig. 6. Tribometer and tested specimens

3. Uniaxial Tensile Test of Specimens

The test involves applying a tensile force to a specimen until it breaks in order to determine the desired mechanical characteristics. Tensile tests were performed on a uniaxial tensile testing machine type Instron 3366, Fig.7, located in the Mechanical Testing Laboratory of the Department of Materials Strength at the Technical University of Cluj-Napoca.

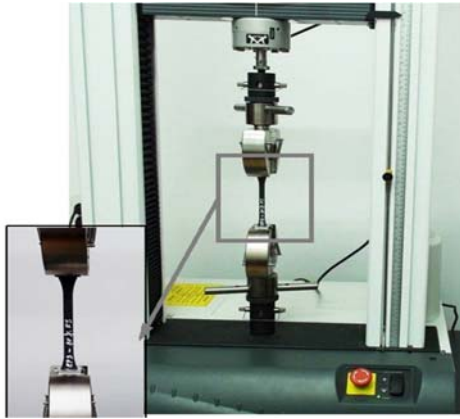


Fig. 7. Instron 3366 Tensile Testing Machine

The determination method involves applying a load along the main axis of the test specimen at a constant rate, continuing either until the specimen breaks or until a predefined load or elongation value is reached. For the tensile tests, a minimum of five specimens were used for each of the two materials under investigation. The **universal testing machine** allows real-time plotting of the applied force versus elongation. When testing multiple specimens consecutively, the machine is capable of storing the data recorded from previous trials.

At the end of the testing sequence, it enables the calculation of the **average tensile strength**, among other mechanical parameters.

Figures 8,9 illustrate the force–elongation response obtained from tensile testing of the injection-molded PA 6.6 and PA 6.6–30% GF specimens.

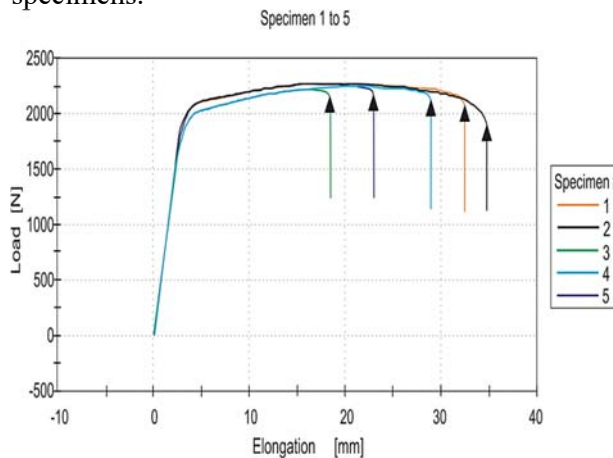


Fig. 8. PA 6.6 non-reinforced Load diagram– Elongation

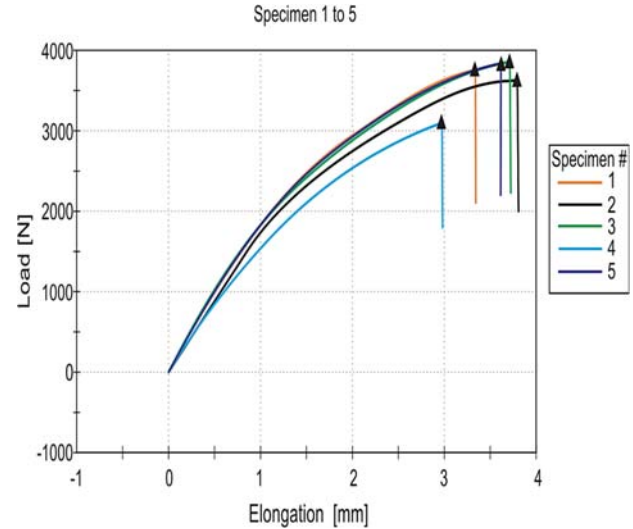


Fig. 9. PA 6.6 with 30% SGF Load diagram – Elongation

A comprehensive overview of the average values for applied load, elongation, and tensile strength for both material types is provided in Table 2.

Table 2. Tensile tests results for PA 6.6 non-reinforced and PA 6.6-30 %GF

Material	Load [N]	Elongation [mm]	Tensile strength [MPa]
PA 6.6 non-reinforced	2262	32.36	56.5
PA 6.6 30 wt.%SGF	3878	3.63	96.9
P-value	<0.001	0.001	<0.001

The two graphs indicate that, although the elongation of the non-reinforced specimens is significantly greater—reaching several tens of millimeters—the force required to fracture the samples is substantially higher in the case of the reinforced materials. It can be observed that reinforcing polyamide with glass fibers leads to a **significant increase in tensile strength**. The molded products made from glass fiber-reinforced polymeric materials (PA 6.6 – 30% GF) exhibit a mechanical behavior **comparable to that of thermosetting materials** under tensile loading conditions. Furthermore, it can be stated that as the degree of reinforcement increases, the **flow time of the polymer material during tensile testing is significantly reduced**. Following the tensile testing of specimens made from PA 6.6 – 30% GF, the average recorded elongation was 3.63 mm,

while the mean tensile force at break reached a value of 3878 N. The maximum tensile strength value recorded for the extruded product made from **PA 6.6 – 30% GF** was found to be **nearly twice as high** as that of the extruded product made from unreinforced PA 6.6, Fig.10.

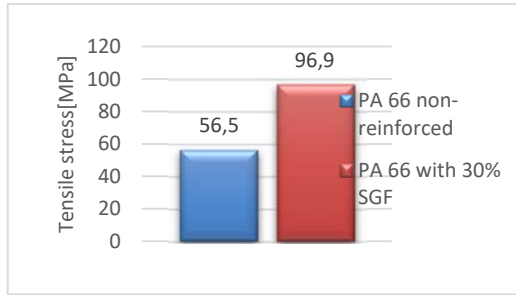


Fig. 10. Maximum tensile strength

PA6.6 exhibits a distribution more distinct for each sample, with plateaux of stress, at approximately 40 MPa for the lowest test speed in the yield zone and at approximately 50 MPa for the other test speed

The reinforced material exhibited a **71.5%** increase in mechanical strength compared to the unreinforced counterpart, Fig.10. Reinforcement of the plastic material results in a significant reduction in elongation. For certain applications, this property is critical, necessitating an optimal balance between the mechanical strength of the component and its capacity for elastic deformation during service[20].

3.1 Wear testing of materials

The tribological evaluation primarily aimed to characterize abrasive wear, material transfer, and the thermal stability of the friction pairs. Throughout the tests, the coefficient of friction was continuously monitored, and the wear rate was calculated to assess the tribological performance of the investigated materials. To gain a comprehensive understanding of the wear mechanisms, the experimental conditions were documented, and the occurrence of material transfer between the contacting bodies was analyzed.

At a low applied load of 5 N, both PA6.6 and PA6.6-GF30% exhibit a clear running-in period followed by a steady-state regime, Fig.11. The coefficient of friction (COF) for unreinforced

PA6.6 increases progressively from ~ 0.055 to **0.66**, with pronounced fluctuations caused by micro-asperity interactions and adhesive wear. In contrast, PA6.6-GF30% shows a higher initial COF (~ 0.28) due to direct fiber–steel contact, but stabilizes more rapidly at **~ 0.52** , indicating improved frictional stability.

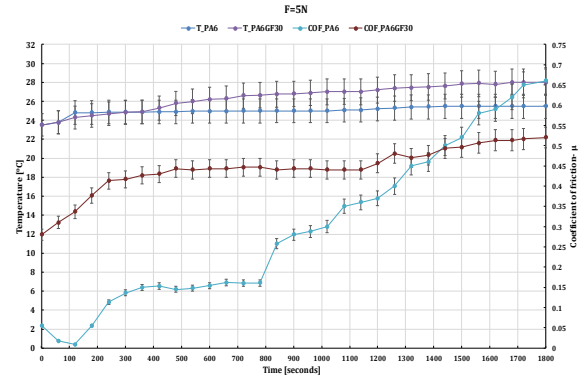


Fig. 11. Coefficient of friction(COF) for applied load of 5 N

The local interface temperature increases moderately from ~ 23.5 °C to ~ 28 °C, remaining well below any level that could induce thermal softening of the polymer. The presence of glass fibers ensures better load distribution, reducing frictional instability and promoting a more uniform wear process. At 10 N, the COF decreases for both materials, following the typical trend of polymer composites under moderate loads, Fig.12.

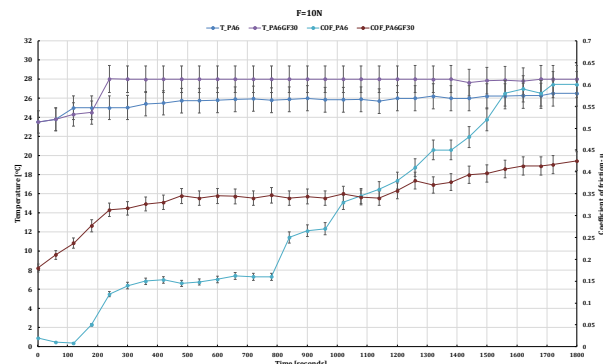


Fig. 12. COF for applied load of 10 N

PA6.6 stabilizes at a COF of ~ 0.60 , while PA6.6-GF30% reaches ~ 0.425 , showing reduced friction and fewer fluctuations during the steady-state regime. The running-in phase is shortened, and the local temperature increases to 26–28 °C, more stable for the fiber-reinforced sample due to improved energy dissipation. The

increase in normal load enhances the real contact area, limits micro-sliding, and favors a more stable tribological regime, for PA6.6-GF30% .

At the maximum tested load of 15 N, the beneficial effect of 30% glass fiber reinforcement is most evident, Fig.13.

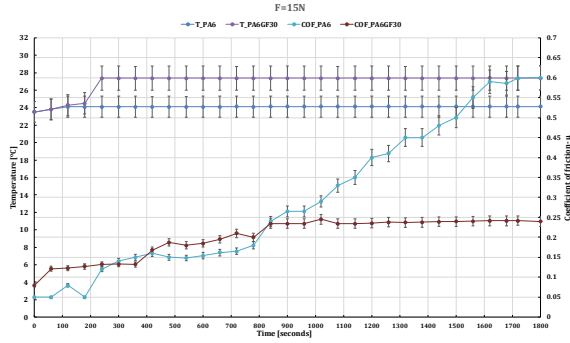


Fig. 13. COF for applied load of 15 N

Unreinforced PA6.6 maintains a COF of ~ 0.60 , with minor fluctuations, whereas PA6.6-GF30% reaches a very low COF of ~ 0.24 . The fibers play a critical role in transferring the load, reducing matrix deformation, and stabilizing sliding, which translates to lower friction and improved wear resistance. The analysis of the specific wear rate K and the Hertzian contact pressure provides further insight into the tribological mechanisms, Fig.14. Unreinforced PA6.6 exhibits the highest wear rate across all loads (from $4.72 \times 10^{-5} \text{ mm}^3/\text{Nm}$ at 5 N to $3.99 \times 10^{-5} \text{ mm}^3/\text{Nm}$ at 15 N), reflecting its lower load-bearing capacity and susceptibility to adhesive and abrasive wear.

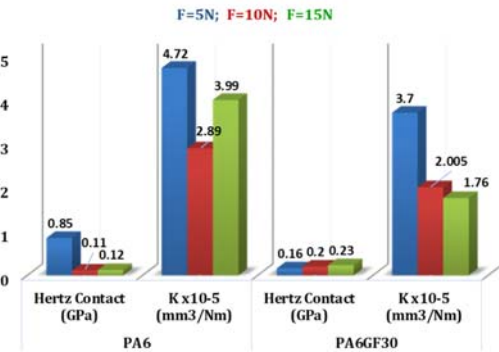


Fig. 14. Values for specific wear rate K and the Hertzian contact pressure

In contrast, PA6.6-GF30% shows a consistently lower wear rate ($3.70 \times 10^{-5} \rightarrow 1.76 \times 10^{-5} \text{ mm}^3/\text{Nm}$), confirming

its superior wear resistance. The lower Hertzian contact pressures for PA6.6-GF30% (0.16–0.23 GPa) compared to PA6.6 (0.85–0.12 GPa) indicate a more uniform load distribution and reduced localized stress, which limit surface damage and material loss. Overall, the combination of low COF, reduced wear rate, and favorable contact conditions demonstrates the enhanced tribological performance of PA6.6 reinforced with 30% glass fibers.

3.2 Simulation of glass fiber flow during injection moulding

This study utilizes **SolidWorks Plastics**, an advanced computational simulation platform, to analyze and optimize the injection molding process prior to mold fabrication. The software models the filling phase of the mold cavity, incorporating transient heat transfer between the molten polymer and the metallic mold, as well as changes in viscosity during cooling and partial solidification. Simulation parameters are defined through either a guided wizard—facilitating the selection of mesh type, thermoplastic material properties, and injection gate locations—or manual configuration for greater control. Within **SolidWorks Plastics**, the part and mold geometries are created, and the simulation data are analyzed focusing on temperature distribution, heat transfer rates, and cooling time under transient thermal loading. A particular focus of this research is the prediction and control of glass fiber (GF) orientation during molding since a favorable alignment of fibers in the gear's tooth structure can substantially enhance its tribological behavior.

The higher the prediction quality of the fiber orientation and length distribution of this software, the more accurate a prediction of the material structure and the resulting mechanical behavior can be made [21].

According to the theory, the flow rate—derived from the translatory movement of the screw—and the melt temperature—controlled by the temperatures of the heating tapes—in the injection molding process have a significant

influence on the resulting fiber orientation in the test specimens.[22].

To enable a meaningful comparison between the fiber orientation in the injection-molded test specimens and the simulation results, the simulation parameters are carefully aligned with those of the actual injection molding process, Fig.15.

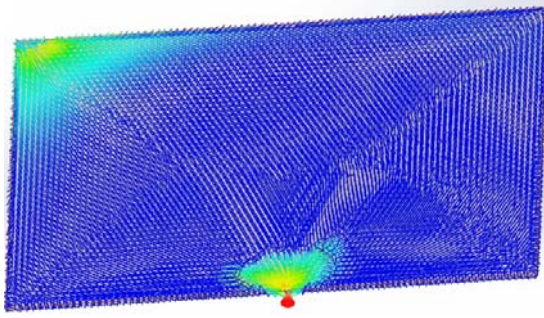


Fig. 15. GF fill orientation during injection molding

We know that the addition of glass fiber can effectively increase the structural strength of the part; if the glass fiber content is higher, the flow during filling can be controlled by the design of the gate, which can increase the structural strength of the part.

The melt flow in injection molding processes promotes the alignment of reinforcing fibers in the direction of material flow, driven by entrainment within the velocity field of the polymer melt. Under conditions of steady and linear flow, fibers tend to exhibit a high degree of alignment uniformity. Conversely, in regions where the flow path undergoes abrupt directional changes or experiences turbulence—such as at sharp corners or narrow sections—fiber orientation may become random or deviate perpendicular to the principal flow direction.

In this case, of lateral mold injection, distinct fiber orientation domains are observed. Proximal to the gate, fibers predominantly align with the primary flow vector, whereas toward the extremities of the gear teeth, orientation frequently transitions toward a circumferential arrangement, Fig.15.

Across the thickness of the molded part, a characteristic core–shear structure is often present. The skin layers, subjected to higher shear rates, exhibit fibers strongly aligned with the flow direction, while the central core,

exposed to reduced shear, displays a more random or transverse orientation. Zones in which fiber orientation is unfavorably aligned relative to the applied mechanical stresses are prone to act as crack initiation sites, thereby reducing the structural integrity of the component.

4. DISCUSSIONS

The experimental and numerical findings confirm the substantial influence of glass fiber reinforcement and fiber orientation on the performance of injection-molded PA6.6 components. Incorporating 30 % fiber glass fibers nearly doubles the tensile strength compared to neat PA6.6, with a mean breaking force of 3878 N, but also reduces elongation at break from several tens of millimeters to an average of 3.63 mm. This reflects the common stiffness–ductility trade-off in fiber-reinforced thermoplastics, where enhanced load-bearing capacity comes at the expense of deformability.

Tribological tests revealed that PA6.6GF30 % consistently outperforms neat PA6.6 in terms of COF stability, wear resistance, and Hertzian contact pressures. At 5 N, reinforced samples show a higher initial COF due to fiber–counterface contact but stabilize more quickly; at 10 N and 15 N, they maintain lower steady-state COF values (0.425 and 0.24, respectively) with reduced fluctuations. Specific wear rates are significantly lower for PA6.6GF30 % across all loads, confirming improved load distribution and suppression of adhesive and abrasive wear mechanisms.

SolidWorks Plastics simulations accurately replicate the observed fiber orientation patterns. High-shear skin layers exhibit strong alignment along the melt flow direction, while the low-shear core presents a more random orientation. This layered orientation structure influences mechanical behavior: fibers aligned with the principal stress direction contribute to higher tensile strength, whereas unfavorably oriented fibers can act as crack initiation sites. Simulation–experiment correlation validates the predictive model, enabling its use for process optimization.

By adjusting parameters such as gate position, injection speed, and holding pressure in simulation, fiber alignment in critical gear tooth regions can be improved, enhancing both mechanical strength and wear resistance. The combined use of **material reinforcement** and **simulation-guided process control** thus provides an effective approach for manufacturing polymer gears with superior structural integrity and tribological performance.

5. CONCLUSIONS

The conducted experimental and numerical analyses demonstrate that incorporating 30% glass fiber reinforcement into PA6.6 substantially enhances tensile strength—nearly doubling it compared to neat PA6.6—while reducing elongation at break, confirming the inherent stiffness–ductility trade-off typical of fiber-reinforced thermoplastics. Tribological testing under dry sliding conditions revealed that glass fiber reinforcement leads to a lower and more stable coefficient of friction, reduced wear rates, and improved load distribution, all without inducing significant thermal softening during operation. SolidWorks Plastics simulations accurately predicted fiber orientation patterns observed experimentally, particularly the layered skin–core structure, and confirmed that fiber alignment relative to the stress direction plays a decisive role in mechanical performance. The close correlation between simulated and experimental results validates the potential of CAD-based process optimization for improving the mechanical and tribological properties of injection-molded components.

These findings open avenues for further research aimed at refining fiber orientation control through advanced gate design, optimized injection parameters, and real-time monitoring of mold filling. Future studies could explore the influence of different fiber volume fractions, alternative reinforcement materials, and complex gear geometries on performance, as well as the long-term durability of reinforced components under cyclic loading or in lubricated conditions. Such investigations would not only

deepen the understanding of structure–property relationships in fiber-reinforced polymers but also provide industry with predictive tools for manufacturing high-performance polymer gears and other precision components with extended service life.

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Variația caracteristicilor mecanice și tribologice ale pieselor polimerice ranforsate cu fibre scurte de sticlă

Acest studiu investighează comportamentul mecanic și tribologic al poliamidei 6.6 (PA6.6), în formă pură și ranforsată cu 30% fibre de sticlă scurte, obținute prin injecție. Testele de tracțiune au arătat o creștere de aproximativ 71,5% a rezistenței mecanice la materialul ranforsat, însoțită de reducerea alungirii la rupere. Evaluările tribologice efectuate cu tribometrul pin-on-disc au evidențiat o scădere semnificativă a coeficientului de frecare și a ratei de uzură pentru compozitele ranforsate. Simulările realizate cu SolidWorks Plastics au confirmat corelația dintre orientarea fibrelor, condițiile de proces și performanța materialului. Rezultatele demonstrează că îmbinarea testării experimentale cu analiza numerică oferă o abordare eficientă pentru optimizarea proprietăților componentelor injectate din PA6.6.

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