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ENHANCING THE INJECTION PROCESS OF GEAR-TYPE COMPONENTS FABRICATED FROM POLYMERIC MATERIALS THROUGH THE ANALYSIS OF DIVERSE FLOW STRATEGIES IN MOLDS

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Abstract: This study investigates the injection molding of polyamide 6.6 reinforced with 30% glass fibers using Moldflow Adviser and SolidWorks Plastics. Key parameters, including fill time, end-of-fill pressure, flow front temperature, cooling time, and fiber orientation, were evaluated. The results demonstrate consistency between the two software packages, highlighting the advantage of SolidWorks Plastics due to its integrated finite element analysis. Accurate fiber orientation prediction proved critical for the performance and durability of polymer gears. The study provides a reliable basis for validating CAE tools in the design and optimization of injection molding processes for industrial applications.

Key words: *PA6.6, SolidWorks Plastics, MoldFlow Adviser, Simulation, Glass Fiber, Injection Molding.*

1. INTRODUCTION

During the Industrial Revolution era, the plastics industry emerged as one of the fastest-growing global sectors, offering practical alternatives to traditional materials such as glass, metal, and ceramics. Thanks to their low weight and chemical stability, plastics are widely used in the production of everyday items. Over the past decade, global demand for plastics has risen sharply—from 204 million tons to nearly 300 million tons per year [1], [2]. Their ability to be easily molded into various shapes and dimensions makes plastic materials especially valuable, with extensive applications, particularly in consumer-goods and packaging [3], the automotive and transport sector, industry and agriculture. Fiber-reinforced polymeric materials are widely used in the automotive sector and many other industries. Incorporating various organic or inorganic reinforcements can make the resulting composites more cost-effective, biodegradable, or mechanically superior [4].

The performance of Glass Fiber Reinforced Polymer (GFRP) composites is of critical importance in both static and dynamic applications. Fiber reinforcement not only enhances the mechanical strength of the polymer matrix but also significantly influences its tribological behavior under both dry and humid conditions.

Within polymeric materials, polyamide (PA)-based composites reinforced with glass fibers (GF) exhibit outstanding mechanical and tribological properties. In particular, PA6.6 is characterized by high strength, stiffness, thermal resistance, and chemical stability. The incorporation of GF further improves these attributes, enabling the use of such composites in components subjected to high loads and wear.

Today, the growing demand for plastic components places significant pressure on manufacturers to produce them at increasingly higher volumes [5].

Selecting the most suitable technology for manufacturing polymer-based parts is a critical task and must take into account the material, dimensions, geometry, and production volume [6].

Injection molding is a fundamental polymer processing technique in which molten polymer is injected into a mold under controlled pressure. This process transforms plastic pellets into three-dimensional parts in a single step [7]. It is recognized as the most widely used and versatile method for the large-scale production of complex plastic components, providing high dimensional accuracy and consistency. The injection molding cycle comprises four main stages: filling, packing, cooling, and ejection [8], [9]. In GFRP materials, injection molding must consider fiber orientation, volume fraction, and dispersion, as these parameters strongly affect the mechanical and tribological performance of the final component [10], [11]. In sample preparation involving thermal softening, the heating time needed to reach molding temperature influences both productivity and energy consumption [12].

Effective process design in injection molding minimizes production issues, shortens time-to-market, lowers development costs, and enhances part quality. This involves machine selection, mold design, cost estimation, and parameter optimization. An appropriate machine must ensure adequate shot size, plasticizing capacity, injection pressure, and clamping force, while accommodating the mold on the platen[13].

Although optimizing design parameters can significantly improve product quality, it is crucial to balance such improvements with efficiency and cost, as an extra emphasis on minimizing deformation, failures, air gap may increase manufacturing complexity and expenses [14]."

Injection mold design requires careful evaluation of multiple parameters during the design stage. In recent years, companies have increasingly adopted computer-aided engineering (CAE) tools to maintain and often enhance product quality [13]. Traditional approaches based on intuition, prior experience, and trial-and-error have proven inefficient, whereas CAE simulation enables engineers to virtually assess alternative designs and materials without consuming physical resources or machine time. MoldFlow Adviser and SolidWorks Plastics support all stages of the injection molding process, assisting part and mold designers, manufacturing engineers, and machine operators. Their application contributes to accelerated time-to-market, reduced production costs, and minimized design and manufacturing errors [13]. Simulation of the injection molding process for such components can be performed using both MoldFlow Adviser and SolidWorks Plastics softwares, which provide accurate and comprehensive information regarding process behavior.

Computer-based simulation methods not only shorten execution time but also generate detailed, interpretable outputs such as weld line formation, air traps, stress concentrations, cooling and filling times of the mold cavity, volumetric shrinkage, and warpage [15]. Examining the resulting data— including flow patterns, velocity variations, and pressure contours presented both visually and numerically—helps identify the optimal processing conditions [16].

Michal Stanek et al. optimized the injection molding process by determining the ideal processing conditions and evaluating the resulting product dimensions, geometry, and properties. Using the Moldflow Plastics Xpert (MPX) system, they investigated optimal injection pressure, packing pressure, and flow velocity, demonstrating its effectiveness for process optimization [17].

Oliaei et al. employed Autodesk Moldflow simulations to optimize warpage and volumetric shrinkage in three different self-prepared biodegradable polymers. Using the Taguchi L27 array to examine the interactive effects of processing conditions, they found that a polylactic acid–thermoplastic polyurethane blend exhibited high resistance to both warpage and shrinkage [18].

Ahmad Zahiruddin et al. employed Moldflow Adviser software to investigate the injection molding behavior comprising polyamide, polyphenylene ether (PPE), and polycarbonate/acrylonitrile butadiene styrene (PC/ABS) blends. By varying process parameters, the influence of molding conditions on these three polymeric materials was evaluated and compared [19].

2. OBJECTIVES OF THE STUDY

The demand for injection-molded components continues to grow steadily. Injection molding is among the most versatile techniques for the large-scale production of plastic parts with precise dimensional tolerances. Within this process, mold design and fabrication remain critical factors.

This study investigates a gear wheel manufactured by injection molding from polyamide 6.6 (PA6.6) reinforced with 30% glass fibers (GFRP), used for automotive applications. Injection-molded plastic gears are increasingly replacing metal counterparts across a broad range of applications, including food processors, industrial, medical, and consumer devices.

In the present study, the design of a plastic gear wheel was carried out using AutoCAD, while the injection molding process and the fabricated part were investigated through simulations conducted with MoldFlow Adviser and SolidWorks Plastics softwares.

This study investigates a series of key parameters associated with the injection molding process by comparing the results generated by two simulation software packages. The objective is to evaluate and compare the predictive capabilities of both tools in order to determine which provides more reliable process parameters for product validation.

3. MATERIALS AND METHODS

The present case study examines a medium-complexity gear wheel, commonly employed in polymeric gear assemblies. The component was modeled in 3D using SolidWorks CAD software, allowing an accurate representation of its geometry and serving as a basis for subsequent analysis and simulation. The geometry and dimensions of the part are illustrated in Fig. 1. The material selected for manufacturing was polyamide 6.6 reinforced with 30% glass fibers (PA6.6-30%GF), a widely applied engineering polymer in high-strength applications, which has also been the subject of our previous investigations Fig. 2 and Fig.3.

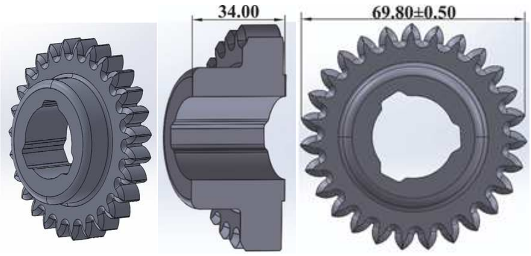
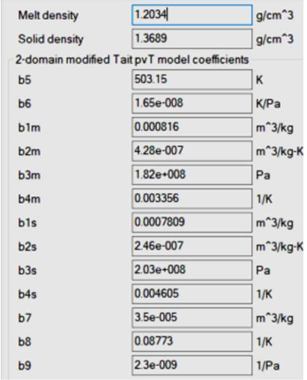


Fig.1. Studied gear wheel.



Melt density	1.2034	g/cm^3
Solid density	1.3689	g/cm^3
2-domain modified Tait pvT model coefficients		
b5	503.15	K
b6	1.65e-008	K/Pa
b1m	0.000816	m^3/kg
b2m	4.28e-007	m^3/kg-K
b3m	1.82e+008	Pa
b4m	0.003356	1/K
b1s	0.0007809	m^3/kg
b2s	2.46e-007	m^3/kg-K
b3s	2.03e+008	Pa
b4s	0.004605	1/K
b7	3.5e-005	m^3/kg
b8	0.08773	1/K
b9	2.3e-009	1/Pa

Fig.2. PA6.6+30%GF rheological characteristics.

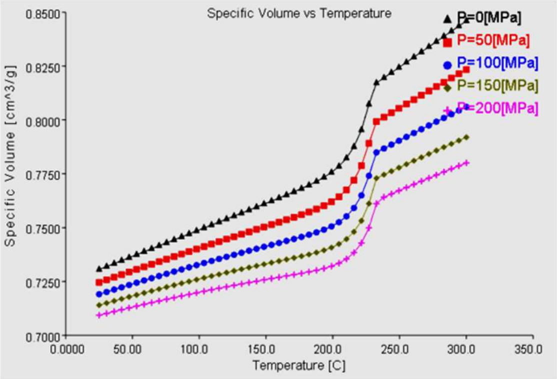


Fig.3. PA6.6+30%GF Specific volume vs temperature.

The orientation and distribution of fibers resulting from the injection molding process were analyzed using SolidWorks Plastics and MoldFlow Adviser softwares to establish correlations between processing parameters and the material's mechanical response. A comparative simulation approach was adopted to investigate material flow within injection molds using both software packages, which are widely applied in mold design and manufacturing. The analysis was performed in a stepwise manner, maintaining the same injection point, and employing the same polymer material for both simulations. Finally, the commune parameters studied were analyzed and the differences between the two scenarios were systematically evaluated.

A significant aspect highlighted in previous studies is the importance of fiber orientation in fiber-reinforced polymer parts produced by injection molding. The placement of fibers should be optimized in regions where critical mechanical properties of the part are affected, particularly in the outer region corresponding to the gear teeth and the tooth flanks that come into contact during operation. This aspect is emphasized through the simulations.

For each simulation, the coordinates of the injection point were identical Fig.4 a and b. These coordinates are shown in Fig.4b, with the following values: X = 1.759 mm, Y = 13.491 mm, Z = -24 mm.

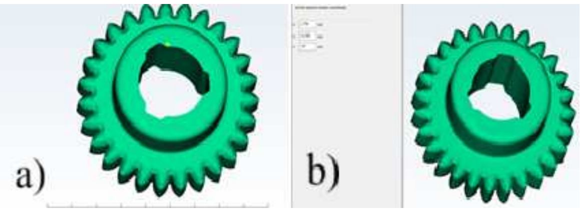


Fig.4. Selection of the injection point. a)SolidWorks Plastics(SWO) ,b) MoldFlow Adviser(MFA).

The required injection pressure was below 66% of the maximum specified limit, indicating adequate process margins. A potential reduction in part thickness could decrease cooling time; however, additional simulations are necessary to confirm mold filling within the defined pressure constraints. When the flow front temperature dropped by more than 10 °C below the melt temperature, risks of incomplete filling, elevated pressure demand, reduced weld line strength, and inferior mechanical performance were observed. Conversely, maintaining the flow front temperature within ±10 °C of the initial melt temperature promoted uniform filling and packing, lowered injection pressure requirements, improved weld line integrity and surface finish, and increased the likelihood of achieving optimal part properties.

The predicted cooling time was defined as the moment when 90% of the part volume reached a temperature below the designated ejection threshold. In standard injection molding operations, cooling typically lasts from a few seconds up to about 60 seconds. However, the simulation results showed that some areas of the part may need more than 60 seconds to cool to the required ejection temperature.

Reducing the overall wall thickness or introducing cores in excessively thick sections can decrease cooling time, promote more uniform temperature distribution, and consequently reduce the overall cycle time.

3.1 Polymer Flow Analysis Using SolidWorks Plastics and MoldFlow Adviser

The analysis was initiated using SolidWorks Plastics. It was observed that, before simulating the flow of the polymeric material within the mold cavity, the software performs a preliminary finite element analysis. This functionality represents one of the key differences between the two software packages considered and constitutes a significant advantage, as it enables results with higher accuracy compared to those obtained with MoldFlow Adviser, where such analysis is not available. For the present simulations, a refined finite element mesh was employed, adjusted according to the capabilities of the available hardware,Fig.5.

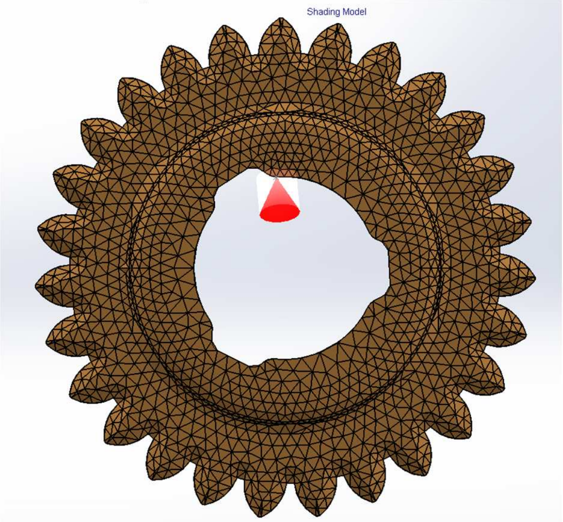


Fig.5. Finite element analysis using SolidWorks Plastics.

Fill time is a key parameter in injection molding, representing the duration needed for the molten polymer to fully occupy the mold cavity. The fill-time plot illustrates how the polymer melt advances through the cavity during the filling phase. In this visualization, blue areas show the initial location of the flow front, while red areas indicate the instantaneous flow front at a given time step or the final filled state, including situations where the software identifies a short shot (Fig. 6, Fig. 7).

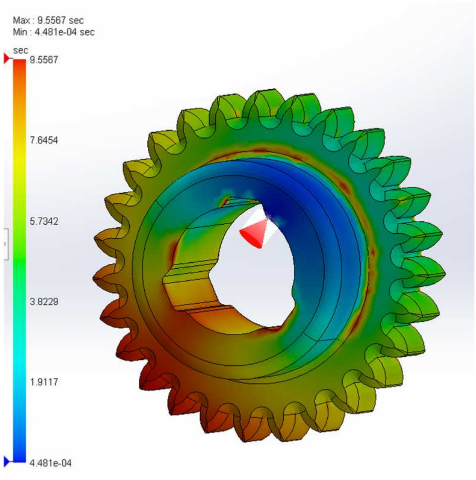


Fig.6. Fill Time, SWP.

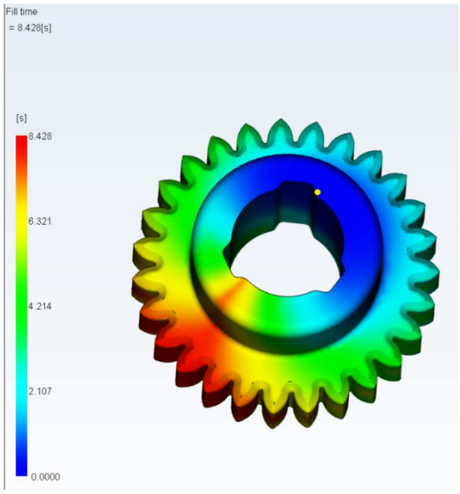


Fig.7. Fill Time, MFA.

Pressure at the end of fill represents the pressure applied by the molten polymer at the precise moment the mold cavity becomes completely filled. This parameter is critical for establishing the injection pressure limit—the maximum pressure the molding machine is capable of delivering. Monitoring this value is essential, as surpassing the machine's pressure capacity can lead to a short shot and incomplete cavity filling. In the present case study, the injection point was located at the center of an asymmetrical handle. The corresponding pressure-at-end-of-fill plot indicated a non-uniform pressure distribution across the cavity. In the second case, relocating the injection point slightly to the right resulted in a more uniform pressure distribution, Fig.8,Fig.9. Achieving balanced end-of-fill pressure throughout the cavity is beneficial, as it improves the effectiveness of packing and cooling across the molded part. Therefore, the injection point should be selected based on end-of-fill pressure plots that demonstrate uniform distribution.

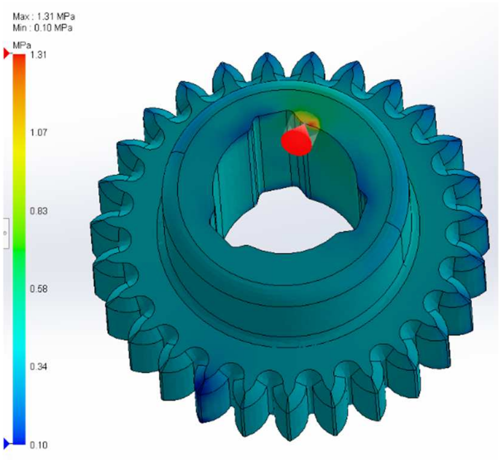


Fig. 8. Pressure at End of Fill, SWP.

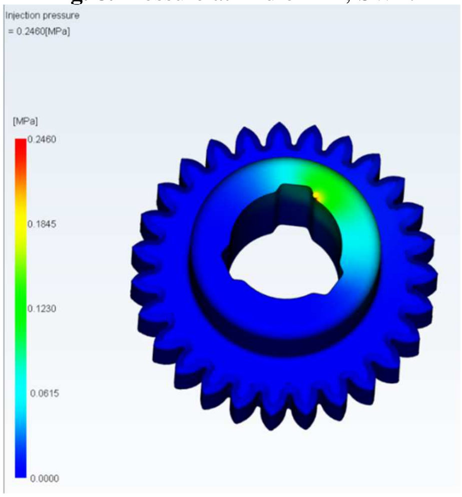


Fig.9. Injection pressure, MFA.

It is important to note that pressure drop is largely governed by flow length, part wall thickness, and melt viscosity. Thin-walled injection-molded components require higher pressures because the reduced cross-sectional area increases flow resistance. When the simulation predicts a short shot, appropriate corrective actions must be implemented.

1. Repositioning the injection location. When the injection point is placed near the end of the part, the effective flow length corresponds to the entire part length. Relocating the injection point toward the center reduces the flow length to approximately half, thereby decreasing injection pressure requirements. Although the melt must advance in two directions, the overall flow resistance is significantly lowered.

2._Adjustment of Fill Time: The fill time was modified to assess its influence on material flow. Reducing the fill time, corresponding to a higher injection speed, generally decreases the viscosity of the molten polymer, thereby facilitating greater flow distances within the mold. It is important to emphasize that shorter fill times can lead to higher injection pressures, shear rates, and shear stresses. The maximum allowable injection pressure is limited by the capabilities of the injection molding machine, while the polymeric materials used also have intrinsic limits with respect to shear rate and shear stress.

3._Modification of Part Wall Thickness: The wall thickness of the part was increased to investigate its effect on injection pressure. This adjustment necessitated the generation of a new finite element mesh and repetition of the flow analysis. While increasing wall thickness reduces the required injection pressure, it also results in longer cooling times and a higher consumption of polymer material.

Temperature at End of Fill represents the polymer melt temperature when the mold cavity is completely filled. This parameter indicates the stability of the melt front, with higher temperatures reflecting ongoing flow and lower temperatures signaling the onset of solidification, which may affect part quality and weld line integrity. At the end of the filling stage, the polymer in contact with the mold cavity solidifies, forming a thin frozen layer that reaches the mold temperature,Fig.10,Fig.11. The thickness of this frozen layer is largely independent of the part wall thickness and is primarily influenced by the temperature difference between the molten polymer and the mold, as well as the thermal conductivity of the material. For the outer surface of the part, the *Temperature at End of Fill* results correspond to the center of the nearest solid mesh cell adjacent to the surface. Consequently, these recorded temperatures are slightly higher than the actual mold wall temperature. This discrepancy diminishes when a finer mesh is employed, providing more cells through the part thickness and improving the accuracy of the temperature distribution.

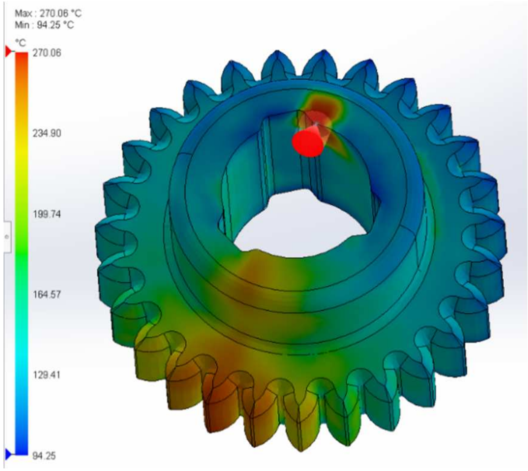


Fig.10. Temperature at End of Fill, SWP.

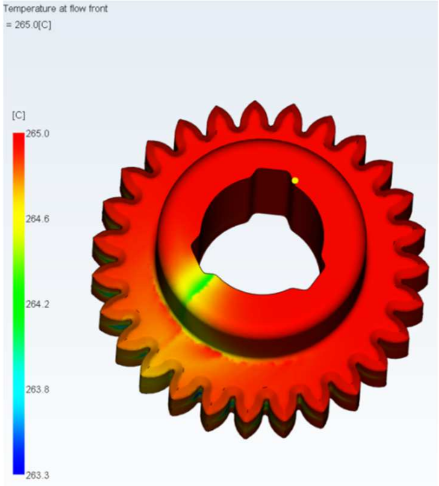


Fig.11. Temperature at Flow Front, MFA.

The purpose of the **cooling stage** is to lower the polymer temperature to the ejection temperature, which corresponds to the deflection temperature under flexural load. Typically, cooling represents about 70% of the total injection molding cycle. Cooling time is primarily affected by the melt and mold temperatures, with higher temperatures generally prolonging the cooling phase. Because polymeric materials exhibit low thermal conductivity, relatively long cooling periods are required. Additionally, cooling time is proportional to the square of the wall thickness, meaning that doubling the thickness results in a fourfold increase in cooling time. To reduce cooling duration, wall thicknesses were designed to be as thin and as uniform as structurally possible (Fig. 12, Fig.13).

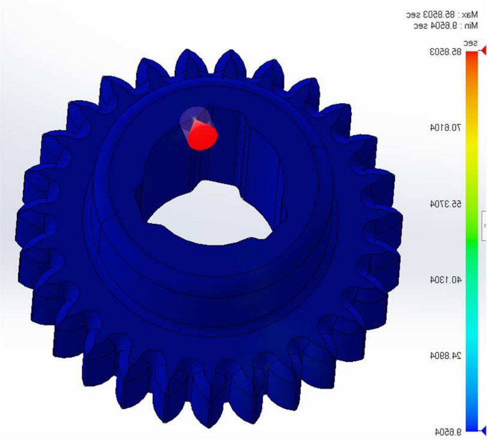


Fig.12. Cooling Time, SWP.

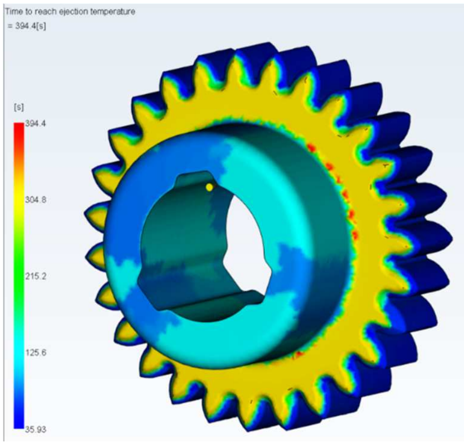


Fig.13. Time to Reach Ejection Temperature, MFA.

Fiber Orientation(GF) is a key factor that directly affects the performance of reinforced polymer parts. The use of specialized software capable of analyzing and visualizing fiber orientation is essential for the design of components with complex geometries, ensuring enhanced strength and optimized structural performance.

Incorporating glass fibers into the polymer matrix substantially improves multiple material properties, including enhanced thermal stability (through an increased heat-deflection temperature), improved dimensional stability (via reduced shrinkage and lower water absorption), and greater resistance to creep and mechanical fatigue.

During the injection molding process, the reinforcing fibers generally orient themselves in the direction of the polymer melt flow, leading to anisotropic mechanical properties. This effect is illustrated in the figures above (Fig. 14, Fig. 15).

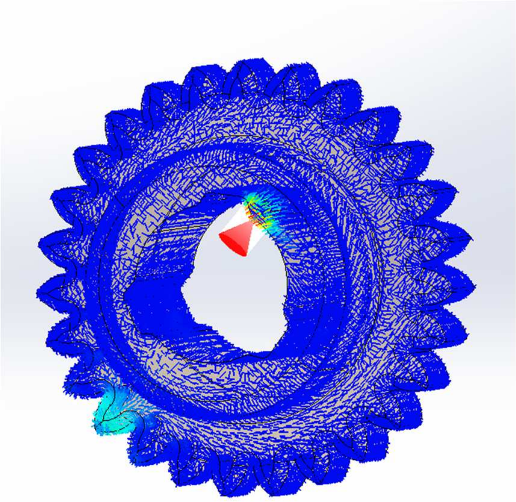


Fig.14. Fiber Orientation, SWP.

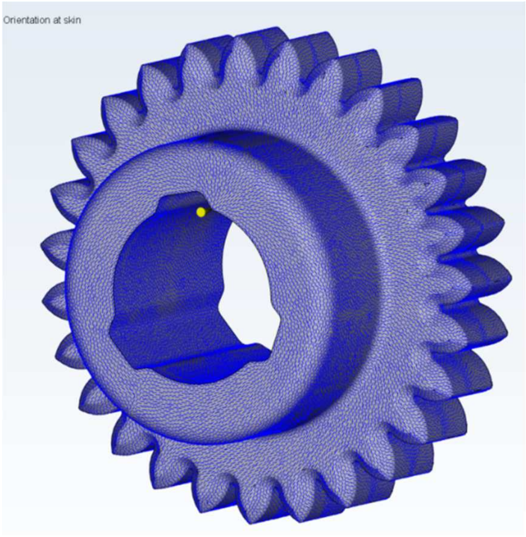


Fig.15. Fiber Orientation, MFA.

Fiber orientation in injection molding is primarily dependent on the melt flow and the geometry of the component. Under steady and linear flow conditions, fibers tend to align uniformly with the flow direction, whereas abrupt changes in the flow path or turbulence—such as at corners or in narrow sections—induce random or transverse orientations.

In lateral mold injection-like this case, distinct fiber orientation patterns were observed: near the gate, fibers aligned mainly with the primary flow direction, while toward the gear tooth extremities, orientation shifted toward a circumferential arrangement. The skin layers, exposed to higher shear rates, show strong fiber alignment with the flow direction, whereas the core region, subjected to lower shear, exhibits a more random or transverse orientation.

Both proposed simulations lead to the aforementioned observations, thereby adding credibility to the results.

Ease of Fill Analysis: The Ease of Fill plot was used to evaluate the ability of the cavity to be completely filled under the specified processing conditions. In this plot, green regions denote areas that can be filled under standard injection pressures, yellow regions indicate areas where the injection pressure exceeds 66% of the machine's maximum capacity, and red regions highlight areas where the required pressure surpasses 90% of the machine's limit. When the simulation was conducted on the part cavity alone (without including the runner system), the presence of yellow or red regions signaled the need for modifications to either the design or the processing parameters. Potential corrective measures include increasing the wall thickness, relocating or adding injection points, modifying the polymer material, or adjusting processing parameters to reduce the pressure required for complete filling, Fig.16, Fig.17.

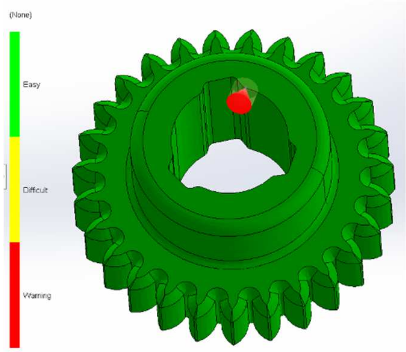


Fig.16. Ease of Fill, SWP.

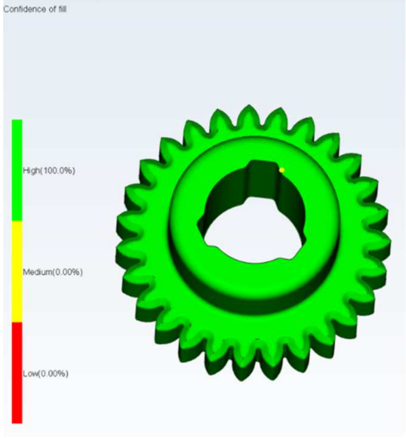


Fig.17. Ease of Fill, MFA.

4. DISCUSSIONS

PA6.6 reinforced with 30% glass fibers is characterized by relatively low melt viscosity, making it a material with good flowability for injection molding and ensuring efficient filling of mold cavities [20].

Accurate prediction of fiber orientation and length distribution allows reliable evaluation of the material's microstructure and mechanical behavior. As fiber orientation strongly governs the strength and durability of polymer gears, precise modeling of these parameters is essential. In this context, the prediction of fiber orientation represents not only a novel but also a highly effective approach for enhancing the overall performance and extending the service life of injection-molded gears, which are characterized by inherently complex orientation patterns.

Greater accuracy in predicting fiber orientation and length distribution allows more reliable estimation of material structure and mechanical behavior.

The table below summarizes the main results obtained from the performed simulations. The software packages used assign different terminology to certain analyses, and their descriptions vary accordingly. For instance, the filling time is designated by the same term in both applications, whereas in the case of cavity pressure analysis, the temperature at the end of the filling stage, and the cooling time, different terms are employed, although they reflect the same process outcomes.

Table 1

Values obtained from simulation.

Considered variables	**Solidworks Plastics**	**Moldflow Adviser**
Fill Time	9.55 [s]	8,42 [s]
Pressure at End of Fill Injection pressure	0.92 [Mpa]	0.24 [Mpa]
Temperature at End of Fill Temperature at Flow Front	270º C	265º C
Cooling Time Time to Reach Ejection Temperature	397.8 [s]	394.4 [s]
Shear Stress at End of Fill	0.15 [Mpa]	-

In SolidWorks Plastics, unlike in MoldFlow Adviser, shear stress is explicitly considered. It represents the shear force exerted on the polymer melt during the injection molding process and constitutes a key parameter for predicting material degradation and the occurrence of visual defects. Elevated shear stress values indicate a potential risk of material degradation, which may compromise the overall quality of the molded part, with higher values typically concentrated near the cavity walls. Moreover, shear stress data can be exported as part of the residual in-mold stress information, enabling further structural analysis within SOLIDWORKS Simulation.

5. CONCLUSIONS

The injection molding behavior of glass fiber–reinforced polyamide was investigated using Moldflow Adviser and SolidWorks Plastics. The influence of processing conditions and key parameters was assessed and comparatively analyzed in both software environments, maintaining identical input values. The results highlight the consistency of the predictions and provide a reliable basis for validating simulation tools in polymer processing. Considering the possibility of performing additional finite element analyses, a feature provided by SolidWorks Plastics, the results obtained demonstrate superior accuracy compared to those generated by MoldFlow Adviser. The main contribution of this research lies in identifying the most suitable software solution for simulating the manufacturing process of a polymeric gear wheel, which is highly relevant for industrial applications. Although the economic aspect related to the acquisition costs of the two software packages was not assessed in this study, it can be stated with confidence that the use of SolidWorks Plastics provides the advantage of an integrated platform, encompassing design, modeling, and process simulation functionalities within a single environment.

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Îmbunătățirea procesului de injectare a componentelor de tip angrenaj fabricate din materiale polimerice prin analiza diferitelor strategii de curgere în matrițe

Studiul analizează procesul de injectare a poliamidei 6.6 armate cu 30% fibre de sticlă utilizând Moldflow Adviser și SolidWorks Plastics. Au fost evaluate parametri cheie: timpul de umplere, presiunea la sfârșitul umplerii, temperatura frontului de curgere, timpul de răcire și orientarea fibrelor. Rezultatele arată consistență între software-uri, evidențiind avantajul SolidWorks Plastics datorită integrării analizei prin element finit. Predicția orientării fibrelor s-a dovedit esențială pentru performanța și durabilitatea roților dințate polimerice. Studiul oferă o bază solidă pentru validarea instrumentelor CAE în proiectarea și optimizarea proceselor de injectare în aplicații industriale.

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