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Article

Optimal Determination of Reinforcement Ratios for Injection Molded Engineering Components: A Numerical Simulation

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Abstract

In this work, the influence of the glass fiber on the behavior of the injection molding process of a PA6-based AR15/M4 grip was investigated in a numerical way. The process was realistically modeled using Autodesk Moldflow Insight at different percentages of glass fiber (0%, 15%, 30%, 45%). Simulation results were evaluated such as the temperature distribution, flow time, pressure drop, pumping power, volumetric shrinkage and warpage displacement. Findings indicate that with 15% glass fibers, the material had the shortest fill period (0.62 s), minimal pressure drop (0.0061 MPa) and the lowest power consumption (0.000433 kW), indicating maximum flow efficiency. On the other hand, a 30% GF setup had the largest volumetric shrinkage (17.76% at most) and warpage (Y: 1.213 mm), even though it had better thermal conductivity. The 45% GF material produced the least amount of shrinkage and distortion but necessitated a greater energy consumption compared to 30% GF. Overall, the 15% GF grade provided the highest average of process efficiency and dimensional accuracy, therefore, it is the most appropriate grade for precision molded firearm components.

Keywords: glass fiber; injection molding; PA6; shrinkage; warpage

1. Introduction

Over the last couple of years, glass fiber reinforced thermoplastic composites have been utilized increasingly in the areas of engineering and construction, owing to their unique combination of thermal stability, high specific strength and molds that permit optimal execution. The volumetric accuracy of such polymeric composites, produced preferably in the form of polyamide 6 (PA6), contributes to their widespread application in the automotive, defense and consumer products sectors. That is why their popularity has increased significantly in these industries. However, shifting the liquid filling pattern for complexly shaped parts like firearm grips, structural shells or brackets in the case of injection molding of plastics has been a very flexible design but still difficult engineering problem.

Budiyantoro, C. et al. concluded in their study that polyamide 6 composite is one of the advanced materials widely utilized for its lightweight and high-strength properties [1]. Zhou, S. et al. stated that injection molding technology is the most important among all those that are used for the production of polymer components in various fields such as automotive, electronics, and aerospace. The nature of the final product is heavily affected by the distribution of the filler materials and the flow conditions during the molding process. Thus, it is very important both for academic research and industrial applications to know the relationship between the processing conditions, the material structure, and the properties of the final product [2]. Angulo, C. et al. reported that the mechanical performance of composites varies significantly depending on the processing methods employed and the fiber content. This effect has led to a notable increase in tensile strength. These findings highlight the critical importance of manufacturing processes and material composition in determining the performance of composite materials [3]. In the injection molding of PA6/CF

composites, the reinforcement materials used substantially enhance mechanical performance by increasing the degree of crystallinity and viscoelastic properties. In this context, Herrmann et al. demonstrated in their study that accurately predicting fiber orientation plays a crucial role in understanding the mechanical behavior of the material and in optimizing the molding process [4]. Juhász et al. investigated the influence of carbon-based nanoparticles in hybrid composite systems and demonstrated that the incorporation of basalt fibers and carbon additives enhances their interaction with the matrix phase, thereby providing superior mechanical properties [5]. Similarly, in a study conducted by Li et al., it was reported that PP/PTFE composite foams produced via microcellular injection molding exhibited notable improvements in both surface appearance and impact resistance during mold opening [6]. These findings support the influence of highly oriented structures on mechanical performance. Wu et al. examined the distribution of carbon fibers in the injection weld line region and the reinforcement effect at the interface, emphasizing that a uniform fiber distribution and high orientation significantly enhance the structural integrity, particularly in PA6 composites [7]. Considering these findings, it is essential to understand not only the material behavior but also the configuration of the injection molding equipment used in such processes. In the present study, the general layout and functional units of the injection molding machine are shown in Figure 1, which served as the basis for the simulations and analyses described in the following sections.

In composite materials produced by injection molding, fiber orientation plays a decisive role in mechanical performance. Zhan et al. revealed that the flexural behavior of short glass fiber-reinforced PEEK composites is directly related to fiber orientation. They demonstrated that in such composites with layered structures, orientation has a significant effect on flexural performance [8]. Hirsch et al. validated, through both numerical simulations and experimental data, the structural behavior observed during the injection molding process of thermoplastic composites reinforced with short and continuous fibers. Their results showed that short fiber orientations have a direct influence on the mechanical properties of the final product [9]. In a study conducted by Karl et al., the flow-fiber coupling effect during mold filling was examined in detail, and it was determined that this interaction could lead to variations of up to $\pm 30\%$ in orientation ratios and more than $\pm 10\%$ in stress fields [10]. Dogossy et al. demonstrated that fiber orientation in thick-walled composite parts can be predicted with high accuracy using finite element analysis. These analyses revealed how variations in fiber orientation affect mechanical performance [11]. Chauhan, V. et al. investigated the effects of different reinforcement ratios on the mold filling process using Moldflow simulation. By simulating various composite formulations, they compared the influence of fiber content on void formation and filling time, concluding that a fiber content of 10% provided the most balanced filling process [12]. In glass fiber-reinforced and unreinforced PA6 composites produced by injection molding, numerous studies have examined the formation of weld lines and their impact on mechanical properties. Li et al. reported that weld lines create microstructural weaknesses that reduce material strength and that various methods have been developed to minimize these defects [13]. Mokarizadehhighishirazi et al. demonstrated that short glass fibers cause orientation losses in the weld line region, thereby reducing mechanical strength [14]. Mrzljak et al., in their study based on the constant temperature approach, highlighted the effects of injection parameters on fatigue behavior [15]. Rochardjo and Budiyanoro investigated the role of material structure and processing parameters on the wear resistance of hybrid-reinforced PA6 composites [16]. Uyen et al. through ANN-based analyses, revealed that packing pressure and melt temperature play a critical role in determining tensile strength [17].

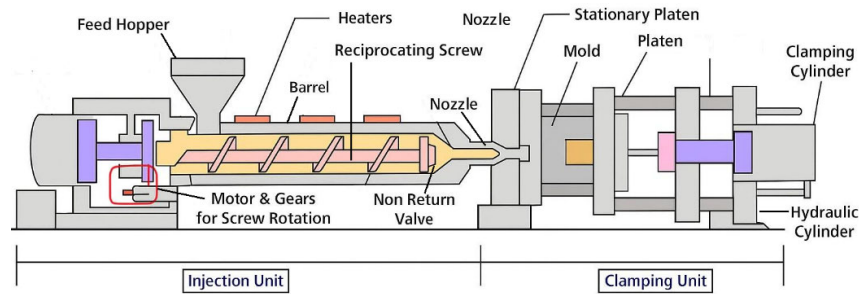


Figure 1. Injection molding machine units.

Nguyen et al. noted that life cycle inventory (LCI) data do not sufficiently reflect process variability, which creates uncertainty in energy consumption analyses [18]. Zhao et al. emphasized that measurement techniques developed for assessing machine condition, melt flow behavior, and product quality can provide a clearer understanding of the variabilities encountered during the molding process and enable optimization of the production process [19]. In the study by Dağlı et al., it was observed that with increasing glass fiber content, mold shrinkage decreased from 1.29% to 0.7%, while warpage was reduced to levels as low as 0.1 mm. In particular, polypropylene (PP) samples containing 20% glass fiber exhibited high performance in ring flexibility tests, withstanding up to 40% expansion of their inner diameter without fracture and offering the most suitable locking ring configuration [20]. In the work of Liu et al., it was found that the addition of PA6 strengthens the interfacial bonding between polymer and metal, thereby requiring higher stress to detach molecular chains from the surface, ultimately providing a more robust joint [21]. Veneziani stated in his study that the Injection Molding Technique (IMT) enables the use of fluid and heated composites in a multilayer approach, thereby improving both aesthetic and functional outcomes. This is analogous to optimizing of material properties in polymer composite applications through material distribution and layering [22]. Karthikeyan et al. reported that in composite materials reinforced with natural fibers and nano-SiC, the uniform dispersion of the reinforcement materials and their effective interaction with the matrix lead to significant improvements in mechanical properties, resulting in superior strength values [23]. Zhao et al. emphasized that quality control in the injection molding process plays a critical role in minimizing warpage and shrinkage deformations. They noted that reducing these deformations is a key factor in minimizing shape distortions in the final products [24]. Guerra et al. similarly demonstrated that post-molding conditions and process parameters in the injection molding process have a significant impact on shape deformations, particularly shrinkage and warpage. Their study emphasized the importance of optimizing these parameters for complex geometrical plastic parts [25].

Wilczyński et al. investigated polymer melting and flow as key factors in composite material processing, examining the influence of processing conditions (screw speed, plastication stroke, and back pressure) on the process [26]. Dekel et al. concluded that high injection speeds and high mold temperatures lead to deterioration in mechanical properties, whereas low injection speeds and low mold temperatures result in improved mechanical performance [27]. Baum et al. stressed the necessity of developing accurate simulation techniques by considering the interaction of geometric parameters that influence the dynamic evolution of fluids during the filling stage of the injection molding process [28]. Wang et al. stated that injection molding is a complex process used in the production of polymer composite products, and identified the optimal processing conditions for improving the mechanical properties of PP SPCs as a barrel temperature of 260 °C, an injection pressure of 127.6 MPa, an injection speed of 0.18 m/s, and a holding time of 60 seconds [29].

Kuo et al. evaluated the cooling performance of injection molds produced by direct tooling (DT) and indirect tooling (IDT) methods, identifying the most suitable method for each case based on total production cost, cooling time, and bending strength [30]. Fu et al. noted that injection molding is widely applied across numerous industries from consumer products to aerospace components, and

continues to evolve in response to new material processing challenges and technological advancements [31]. Li et al. stated that in the injection molding process of short fiber-reinforced composites, warpage, shrinkage, and residual stresses are critical quality criteria. They concluded that these parameters are significantly influenced by processing conditions and fiber properties. Moldflow simulations and optimization methods represent an effective approach to improving quality [32]. Amjadi et al. proposed a critical plane-based fatigue damage model for predicting the tension–tension or tension–compression fatigue life of short glass fiber-reinforced thermoplastics, taking into account the effects of fiber orientation [33].

Lee et al. investigated the influence of weld lines on the mechanical properties and fracture behavior of glass fiber-reinforced and unreinforced polyamide 6 (PA6) materials produced by injection molding [34]. Ucpinar et al. reported that short glass fiber-reinforced composites were produced using the melt blending method with a twin-screw extruder, followed by injection molding [35]. Artykbaeva et al. observed that increasing the glass fiber content in PA6/PA610 blends reduced the water absorption (WA) value of neat PA6, demonstrating the influence of glass fibers on the properties of PA6/PA610 composites [36]. Wu et al. examined the effect of different boundary conditions on the shear strength of carbon fiber (CF)-reinforced thermoplastic composite material (PA6/CF) produced by adding CF into polyamide (PA6). Under optimal conditions, the shear strength reached up to 85% of that of the neat PA6 matrix [37].

Besides all the studies mentioned above, the new research conducted by Tan et al. has significantly contributed to understanding the behavior of polymers in injection molding under various material and process conditions. To begin with, Tan and Birişik [38] achieved the optimum values of both material and process parameters for piezoresistive card-type pressure sensors with the help of the finite element method. While in their study, Tan and Alkan [39] have deeply studied the effect of cooling parameters on the behavior of the melt in the mold during microinjection molding of the piezoelectric pump. In another work, Tan [40] investigated the mechanical characteristics of PA66+PA6I/6T composites by employing the Response Surface Methodology (RSM) combined with Grey Wolf Optimization, thus, opening a new horizon of reinforcements-property interrelationships. Besides that, Tan and Alkan [41] performed a numerical study on the thermophysical and mechanical performance of the injection-molded femur implant, thus, indicating the possibility of using simulation-driven methods in various polymer-based components.

In contrast to previous studies that have mostly emphasized individual molding variables such as shrinkage, warpage or thermal response separately, the current research offers a thorough multi-parameter analysis of the incorporation of glass fiber into PA6. A majority of current research primarily emphasizes the impact of reinforcement on mechanical characteristics or single-phase flow processes, often disregarding the integrated effects on energy consumption, heat transfer and dimensional changes under similar boundary conditions. The present study aims to fill this gap by conducting a detailed numerical analysis of the injection molding behavior of a firearm grip component made of PA6 with four different glass fiber reinforcement levels (0%, 15%, 30%, 45%). Using Autodesk Moldflow Insight, key outputs including temperature distribution, pressure drop, shrinkage, warpage and energy input were comparatively analyzed. The findings offer valuable insight into the complex trade-offs between reinforcement level, process efficiency and dimensional stability, ultimately providing guidance for material and process optimization in high performance polymer applications.

2. Materials and Methods

2.1. Material

This study investigates the injection molding behavior of a polyamide-based firearm grip. An injection molding analysis was conducted on the buttstock of the AR15/M4 rifle produced by the injection molding method with different reinforcement ratios. The impact of various PA6 reinforcement levels was analyzed in order to determine their influence on the critical molding

production. DSM Engineering Materials supplied the following four grades for the test, namely: Novamid 1015 (Unfilled, 0 %), Novamid 1015G15 (15% Glass fiber), Novamid 1010C2 (30% glass fiber) and Novamid 1010G30 (45% Glass fibers). These materials are widely used in technical applications due to their high specific strength and also thermal resistance. Table 1 shows the mechanical properties of the Novamid 1015 materials.

Table 1. Properties of Materials .

DSM Plastics	Japan Engineering	Novamid 1015G	Novamid 1015G15	Novamid 1015G30	Novamid 1015G45
Glass Fiber Ratio (%)		0	15	30	45
Elasticity Modulus (MPa)		2910	5390.1	8802.75	12750.1
Poisson Ratio (ν)		0.386	0.4032	0.4057	0.4002
Shear Modulus (MPa)		1050	1554.91	2288.73	3189.61
Melt Density (g/cm3)		0.89912	1.0576	1.2035	1.3511
Thermal	Expansion	8.15e-005	4.524e-005	2.758e-005	1.885e-005
Coefficient (1/C)					

As the glass fiber content increases, there is a marked improvement in both stiffness- related and thermal parameters. Specifically, it has been indicated that the elastic and shear moduli increase as the degree of reinforcement is increasing, thus resulting in bigger construction rigidity. Simultaneously, the coefficient of thermal expansion (CTE) shows a major decline, indicating that reinforced grades can better withstand dimensional changes during thermal cycling. Also, the increase of melt density as another diversifying phenomenon which reflects the highly packed density of fiber filled materials that in turn affects the flow and cooling behavior during processing. In addition to mechanical trends, the thermodynamic response of each material was characterized through pressure-volume-temperature (PVT) analysis. The specific volume versus temperature curves under multiple pressure levels (0–200 MPa) are presented in Figure 2. As the reinforcement ratio increases, the curves shift downward and become more linear, indicating lower compressibility and more predictable shrinkage under pressure. For firearm grips where dimensional consistency and surface integrity are essential, this behavior is critical. While fiber filled materials offer better thermal stability and shrinkage control, they may accumulate internal stress if the packing phase is not carefully optimized.

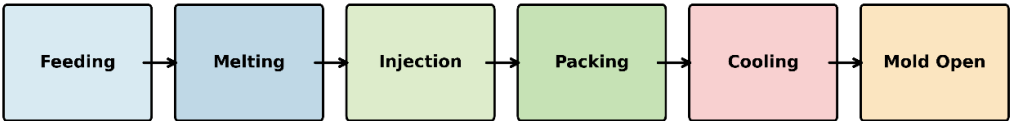
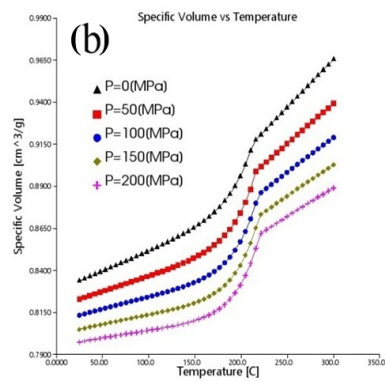
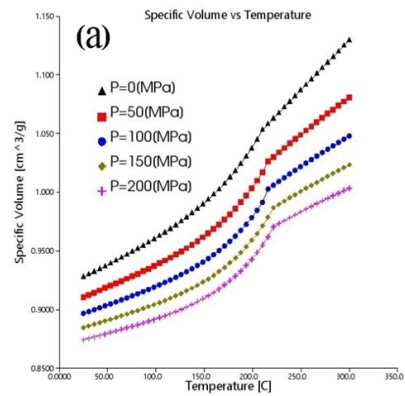


Figure 2. Injection molding process schematic.

Conversely, unfilled PA6 is more prone to volumetric contraction, increasing the risk of warpage in complex geometries. The PVT characteristics, therefore, provide valuable insights into the material dependent deformation tendencies during cooling. Overall, the trends observed in Table 1 and Figure 3 indicate that increasing fiber reinforcement enhances dimensional predictability and thermal stability, though it may also introduce internal stresses if the packing and cooling stages are not well calibrated. These material specific behaviors provide the foundational context for evaluating flow, shrinkage and deformation responses in the subsequent simulation results.



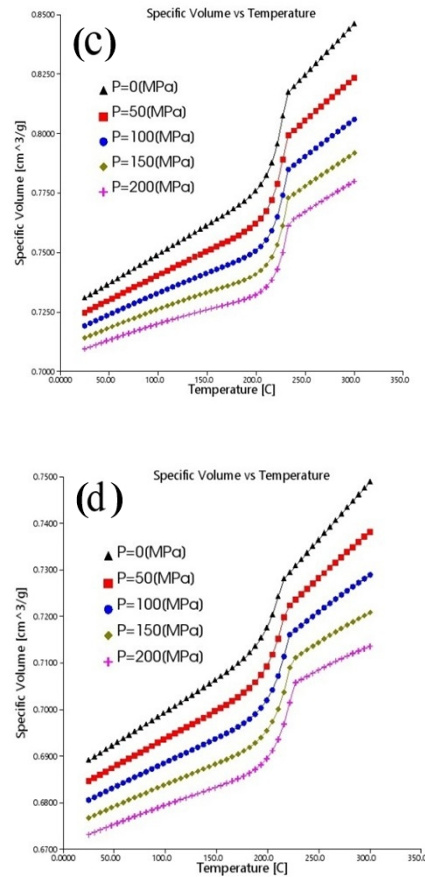


Figure 3. PVT diagram for a) 0% b) 15% c) 30% d) 45% .

2.2. Model and Mesh

The component analyzed in this study is the pistol grip of the AR15/M4 rifle, a critical interface element between the user and the weapon. As shown in Figure 3 (A–C), the part features a combination of ribbed textures for improved grip, curved ergonomic contours and a mounting structure designed to connect securely with the lower receiver. Its geometry includes thin-walled regions, sharp transitions and long unsupported surfaces, all of which make it highly susceptible to warpage and shrinkage during injection molding. Due to its direct contact with the user's hand and its mechanical role in firearm stability, achieving dimensional accuracy, surface quality and structural integrity in this component is essential, making it an ideal subject for reinforcement dependent process simulation. The visuals of the 3D model of the part are shown in Figure 4.

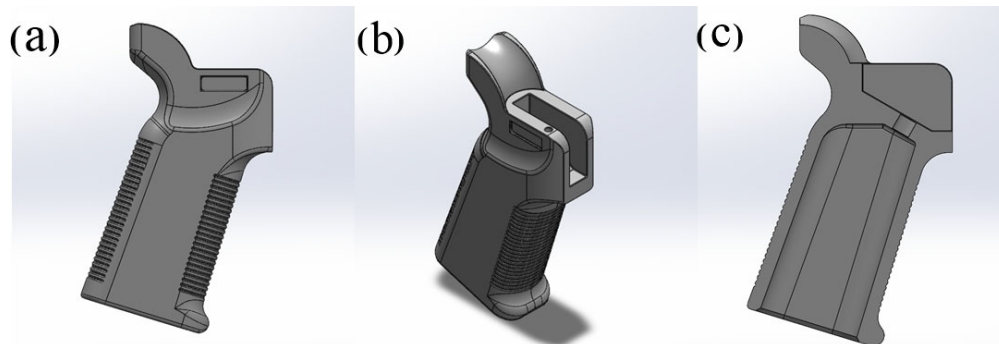


Figure 4. AR15/M4 Rifle Model a) Right b) Isometric c) Left view .

All models were applied with the three dimensional tetrahedral elements of the best quality as can be seen from Figure 5. The mesh consisted of about 657848 tetrahedral elements; 126579 nodes and this demonstrated the complexity of the AR15/M4 pistol grip that was especially ribbed and curved. The total mesh volume was 66.79 cm³, which was the cavity volume, cooling and mold inserts were excluded. Mesh quality metrics were carefully observed throughout the simulation to ensure that it remained stable and converged. The highest aspect ratio was 26.15, whereas the average and lowest were 2.25 and 1.04 respectively. These values indicate sufficient refinement and element uniformity across the domain. The maximum dihedral angle recorded was 171.5°, remaining within acceptable limits for accurate finite volume computation. A magnified section of the mesh (top right in Figure 5) highlights local refinement in thin walled regions where thermal gradients and shrinkage effects are expected to be most pronounced.

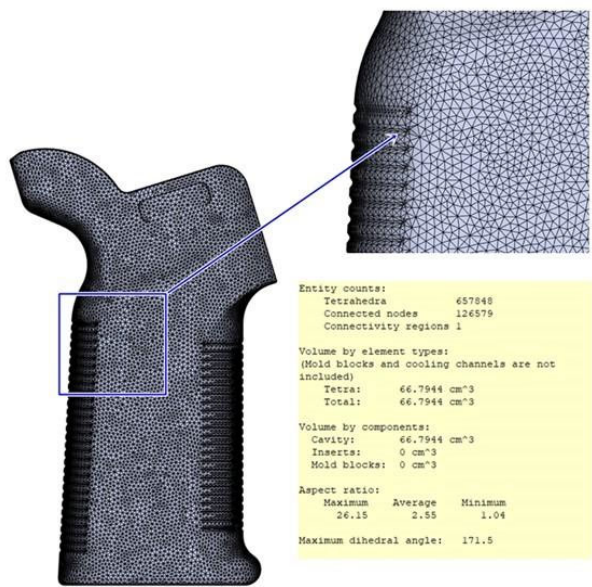


Figure 5. Mesh model and Mesh metric.

2.3. Process and Machine Setup

All simulations were performed using Autodesk Moldflow Insight, applying identical process conditions across all material configurations to ensure that the observed differences could be attributed solely to the variation in glass fiber content. The selected process parameters were based on industry relevant settings for high performance polyamide components with complex geometry. The melt temperature was fixed at 270 °C, while the mold surface temperature ranged between 81.82 °C (30% GF) and 83.33 °C (0% GF). A uniform cooling time of 20.0 seconds was used to ensure comparability of heat removal performance between reinforcement levels. The maximum injection pressure was set to 180 MPa and the screw intensification ratio was defined as 10.0, yielding realistic pressure amplification in the simulation. The clamp force was modeled with a capacity of 1.0194×10^{33} N, exceeding the theoretical requirements to prevent mold separation during the injection cycle.

The filling phase was configured to be flow rate controlled. Due to differences in viscosity and thermal conductivity, the fill time varied among materials: 0.62 seconds for 15% and 30% GF and 1.13 seconds for 0% and 45% GF. The velocity to pressure switch-over was activated at 100% volume in all cases; however, the switch-over pressures ranged from 30.92 MPa (30% GF) to 47.69 MPa (15% GF), indicating material dependent resistance to flow during cavity filling. Packing pressure was applied through a two stage profile with hold and decay steps and the total injection hold time was

maintained at approximately 30 seconds for each case. Cooling performance and flow resistance were further analyzed through frozen volume ratio, Reynolds number, pressure drop and pumping power outputs, extracted directly from the results. This standardized setup enabled a controlled comparison of how reinforcement ratio affects thermal distribution, shrinkage behavior and energy demand in the injection molding of geometrically demanding components such as firearm grips.

2.4. Gate Location Design

In the next step, the Gate Location analysis was conducted for the model. This analysis is the critical step for the model to be filled correctly. The right injection entry point chosen provides the balanced distribution of the fluid within the part and it prevents the flow problems. The optimized entry point seen in Figure 6 was specified, to be the model's balanced filling point thus, the efficiency in the production process has also been increased. This phase is very significant to increase the part quality and at the same time minimize the production faults.

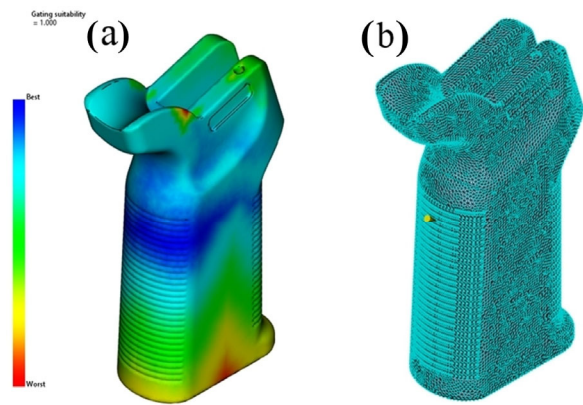


Figure 6. a) Gating Suitability b) Injection location .

2.5. Cooling Circuit and Runner System Design

Another crucial phase of the project is the research of cooling channels and the runner system. In the injection molding process, cooling ensures uniform solidification, thus increasing the production speed. The cooling process also enhancing dimensional stability of the part. The design of the cooling channels has been optimally done in a careful way determined by the analysis of how the part behaves which is Cool-Fill-Pack-Warp method. The efficiency of the cooling process allows the uniform and efficient distribution of the fluid within the mold. The design that is shown in Figure 7 includes that placement of the runner should be such that its structure parts can be also reached accordingly.

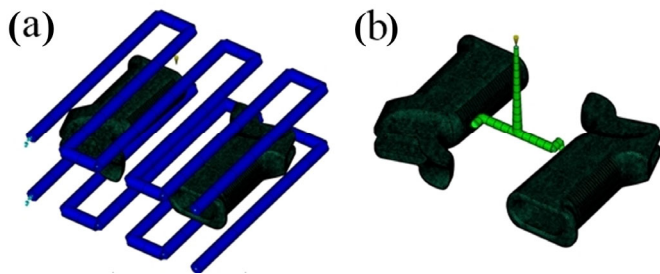


Figure 7. a) Cooling System b) Runner system.

The injection mold was made in such a way that it has a three channel cooling system with a diameter of every 10 mm and a distance of overlaying as high as 30 mm with a distance of 80 mm on

the surface so that the cooling is uniform across the grip geometry. The runner system was designed to have a circular runner with a diameter of 6 mm, the entry point of which was a 3 mm sprue hole with a 110 mm length and the output holes were 3 mm in diameter with the ones on the side being 8.49 mm long. The parting plane was at $Z = -6.56$ mm, with the position of the entry prong being placed off-center, which could be likely to have an impact on the filling process. The layout of this mold was such that the cooling would be fast and effective, as well as the pressure loss in the important areas of the grip would be minimum in the design of the firearm. This was accomplished by taking the right design path.

Table 2. Cooling and Runner system dimensions .

Cooling System Dimensions (mm)		Runner System Dimensions (mm)	
Part dimension (X)	167.11	Specify the sprue position (X)	-58.42
Part dimension (Y)	109.05	Specify the sprue position (Y)	-40.64
Part dimension (Z)	28.03	Parting plane (Z)	-6.56
Channel diameter	10	Sprue Orifice diameter	3
Alignment shape of the circuit	25	Runners diameter	6
Number of channels per part	3	Sprue Lenght	110
Distance between channel centers	30	Side Gates orifice diameter	3
Distance from part edge	80	Side Gates Lenght	8.49
Top and bottom distance		Include angle	3

3. Results

3.1. Temperature Distribution

All four of the different glass fiber reinforcement ratios under the same process conditions were compared with regard to the temperature distribution and thus the heat removal performance. According to the simulation results, the higher the reinforcement ratio, the lower the part surface temperature and the average external temperature of the mold. The highest part surface temperature 188.93 °C was recorded in the unfilled PA6 and decreased till 186.72 °C at the 30% reinforcement level and the minimum values were similar. Such findings indicate that the fiber reinforced materials because of their higher thermal conductivity allow for a more efficient heat transfer during the cooling stage. The temperature distribution under identical process conditions is summarized in Figure 8.

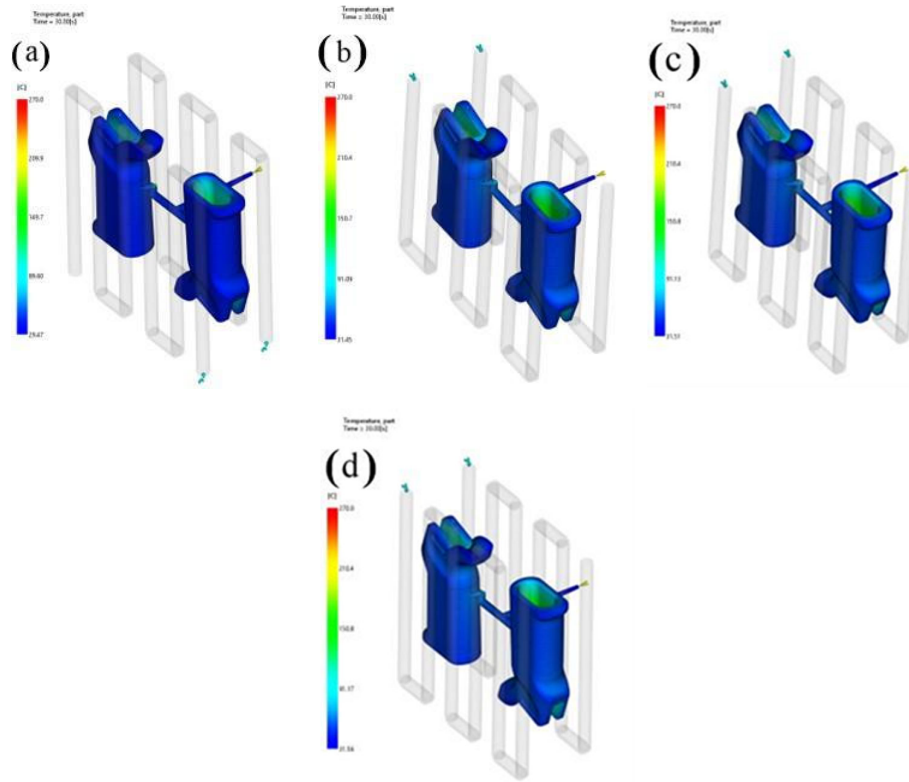


Figure 8. Temperature distribution for a) 0% b) 15% c) 30% d) 45%.

The same situation was noticed in the average molded outer surface temperature, that is that it dropped slightly just after the addition of fiber and reached to the lowest level at 30% addition. But, a slight rise in 45% means that a very high fiber part can reduce the uniformity of melt flow and thus, the non-uniform heat distribution will happen leading to the heat being retained in those areas only. Similarly, the extent of heat removal followed this tendency, with 15% and 30% GF grades removing heat more effectively than unfilled or 45% configurations. A combination of augmented thermal conductivity and thus lower melt viscosity is to be credited for the superior thermal behavior since this aids in the speedier solidification process. In fact, despite the better cooling performance, the increased reinforcement ratios do not appear to have an impact on warpage or shrinkage reduction, to be discussed in other sections. This, therefore, underlines the complicated interplay between a thermal response and mechanical deformation. In general, the findings validate that moderate reinforcement levels (15-30%) bring a superlative equilibrium between heat sinking and process steadiness, thus, they are more useful for the high precision molding of thin walled and ribbed structures in firearm components.

3.2. Flow Behavior and Pressure Characteristics

In this study, the influence of the different glass fiber content on the flow properties of PA6 was determined on the basis of some important parameters like the pressure drop, pumping power, fill time and velocity-to-pressure (V/P) switch-over pressure. When the ratio of reinforcement increased, there was a non linear trend in flow resistance. The lowest pressure drop was recorded for the 15% reinforced material (0.0061 MPa), followed by a slight increase at 30% and 45%. This points out that moderate reinforcement improves flowability, probably due to thermal conductivity enhancement and milling viscosity reduction during the initial filling process. However, in the case of high fiber contents, the melt stiffness is increasing, this leads to the resistance to flow and a little increase in the pressure loss.

The energy required to keep a flow rate steady was related to the pressure drop trend. The maximum flow efficiency was shown in the 15% GF configuration (0.000433 kW) tested which was the minimum pumping power required. The addition of the unfilled material along with the 45% GF ones did require a slightly higher energy input which in turn indicated the possibility of polymer fiber interaction resulting in either greater viscosity or shear stress. With respect to the filling dynamics of the various models, the time of filling for the 15% and 30% reinforced models amounted to 0.62 seconds, which was a noticeably shorter period than that of the unfilled and 45% models whose time was 1.13 seconds. This evidence demonstrated a good balance between the flow features and the mid range reinforcement levels where the melting remains sufficiently active without too much stiffness or under shearing happening. The variation in pressure at the velocity-to-pressure switch-over point for each reinforcement level is illustrated in Figure 9.

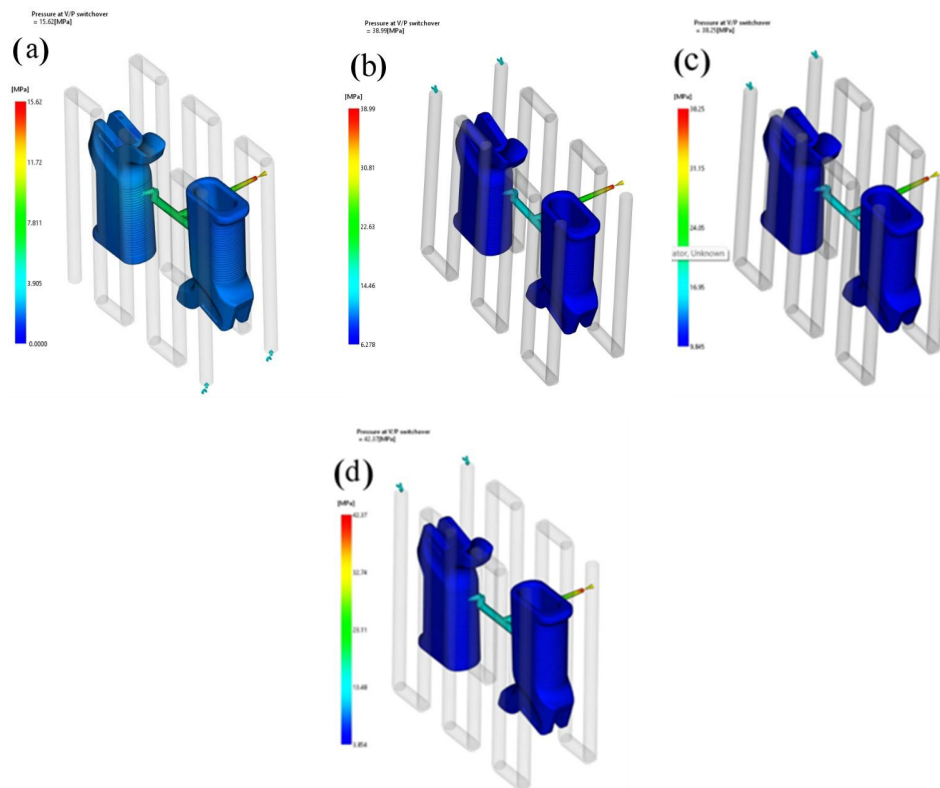


Figure 9. Pressure at V/P switch-over for a) 0% b) 15% c) 30% d) 45%.

Moreover, the observations of V/P switch-over pressures showed substantial differences. The 15% GF material demonstrated the greatest transition pressure (47.69 MPa), implying that the cavity was filled to the brim at the switching phase. On the other hand, the 30% GF material recorded the least pressure (30.92 MPa), which might reflect an earlier switch than intended or easier cavity saturation owing to a better heat transfer. The overall results revealed that 15% of glass fibers achieve the best balance between flow efficiency and energy consumption but excessive reinforcement may make the flow resistant which undermines thermal benefits in part. These results are of high importance for firearm components of long, thin or ribbed geometries where uniform filling and energy efficiency are the most important factors.

3.3. Volumetric Shrinkage

Injection molding volumetric shrinkage is a key aspect, particularly for components that demand structural integrity and have intricate geometries, like the AR15/M4 firearm grip. This study is comparing four percentages of reinforcement (0%, 15%, 30% and 45%) of the maximum, average and root mean square shrinkage values of the four groups as well as the dimensional stability of the system was done in the case of each material configuration repeat. It was found through simulation analysis that volumetric shrinkage increased in relation to the glass fiber content but it did not correlate in a linear way. The highest volume shrinkage of 17.76% was observed at the 30% GF configuration, while the unfilled PA6 had only a 13.57% maximum shrinkage which was the lowest. This can be attributed to the accumulation of internal stress and uneven packing efficiency in reinforced composite materials that are mid range. Average shrinkage was also highest at a fiber grade of 30% (12.18%), with the other configurations of 15% and 45% having nearly the same mean values around 10.5%. The corresponding volumetric shrinkage distributions for the four reinforcement levels are presented in Figure 10.

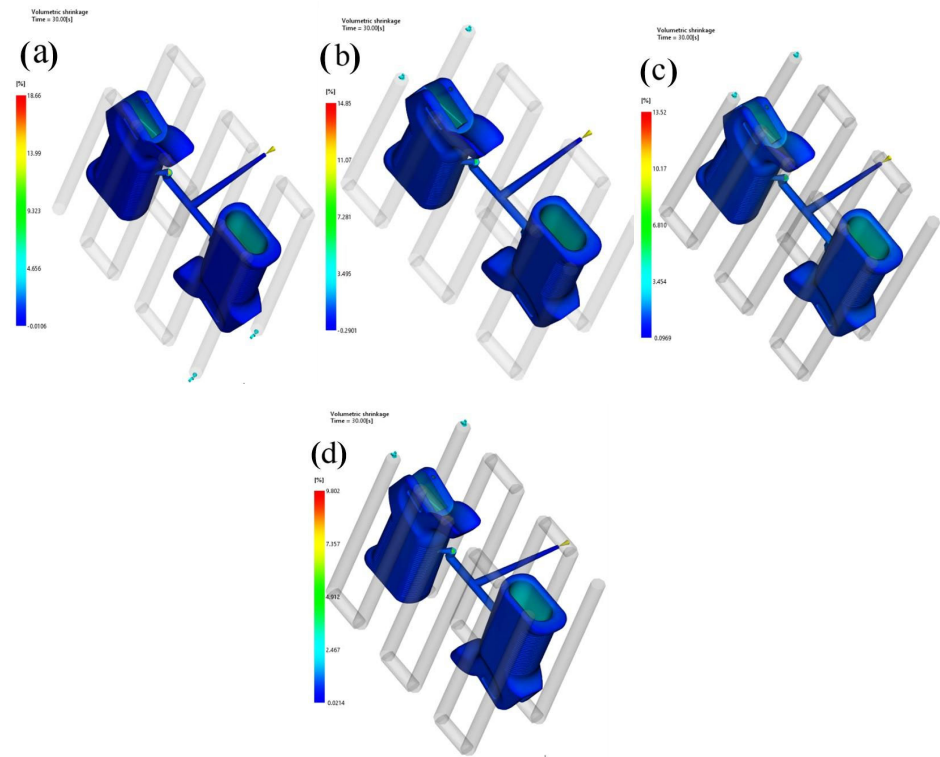


Figure 10. Volumetric shrinkage for a) 0% b) 15% c) 30% d) 45%.

It is demonstrated by these results that fiber reinforcement primarily enhances dimensional predictability, but intermediate levels (such as 30%) can also local shrinkage gradients that are not convenient. Therefore, both the type of material and the method used to fill the medium must be determined so that shrinkage related distortions in the firearm components are minimized. One report was given on a similar trend by Artykbaeva [36], who observed that at mid range reinforcement levels of PA6 composites, internal shrinkage increased due to uneven packing stress and rapid solidification.

3.4. Warpage

Warpage, which is characterized as the unwanted deviation of a molded part from its intended dimensions due to irregular shrinkage and residual stress, is a prominent problem in the field of firearm grip components, as they must hold ergonomical precision and structural integrity. This

study evaluated the warpage effects through the maximum displacement data in X, Y and Z directional dimensions of all four kinds of glass fiber reinforcement levels. The simulation results suggested that the assumption that the higher the reinforcement the lower the warpage is not accurate. This was seen in this project where it was shown in the 30% GF model which had the highest total deformation where the maximum of Y-direction displacement was 1.213 mm. This indicates that 30% GF while satisfying the requirements for thermal conductivity and cycle time reduction brings about the conditions for the higher rates of residual stresses by the fast cooling and the lack of molecular relaxation.

On the contrary, the configurations of 0% and 45% GF had less displacement values where the 45% model produced the warpage results which are even equal to or better than the unfilled PA6 which happened with the 45% GF configuration. This behavioral aspect shows the inconsistency of the fiber content and warpage, which is probably a result of a shift between the augmentation of stiffness and the blockage of flow induced orientation during the solidification phase. The simulated warpage patterns for different reinforcement ratios are shown in Figure 11.

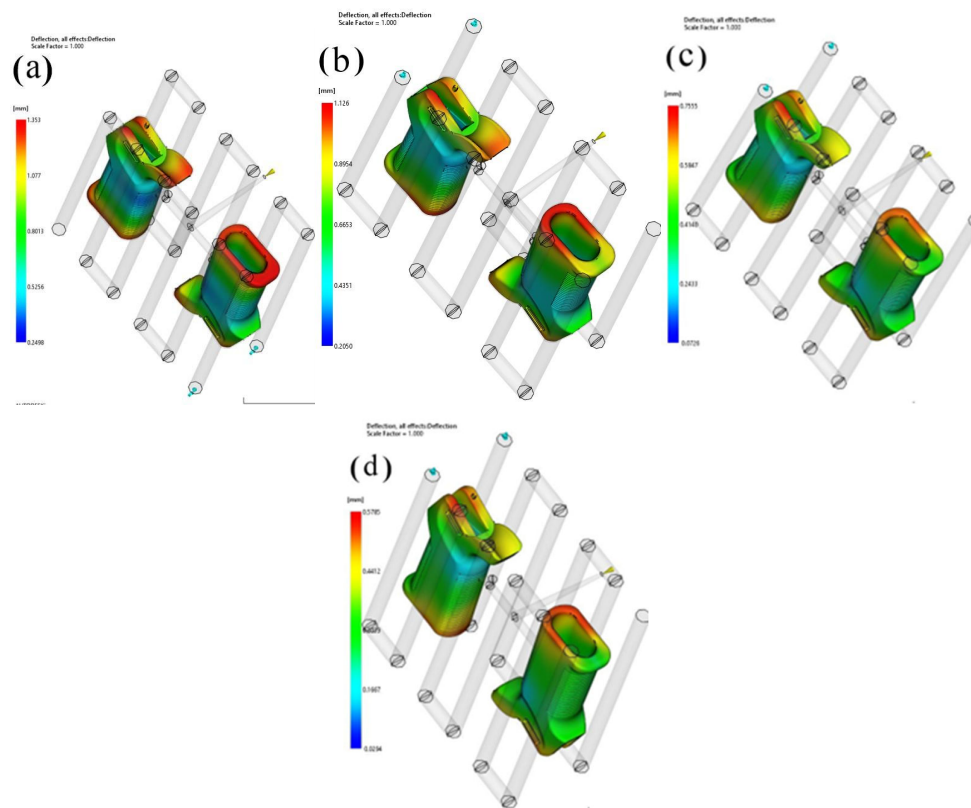


Figure 11. Warpage for a) 0% b) 15% c) 30% d) 45%.

In addition, the analysis of the directional data indicated that the displacement of the X and Z axes was relatively low and it was then inferred that the Y-direction, which is aligned with the long axis of the grip, is the most sensitive to the effect of the fiber. This is in line with the geometry of the part, where the long skin behavior and the uneven cooling are the main features of the deformation. The outcomes have been consistent with the research carried out by Lee [34], who pointed out that the deformation in the Y-direction generally dominates in longaxis polymer materials, particularly when there are uneven cooling conditions.

4. Conclusions

The result of the experiment suggests that the influence of glass fiber reinforcement on the process of injection molding in the case of PA6 has a nonlinear character and multi-dimensionality. Even though the thermal conductivity and stiffness are enhanced by the increase in fiber content, these enhancements do not automatically guarantee the superior dimensional stability or low energy consumption. From the various configurations assessed, the one with 15% GF always presented the best compromise of cooling efficiency, lower pressure loss, distortion and energy conservation.

The 30% GF composition was observed to have the greatest volumetric shrinkage and warpage in spite of its advantageous thermal properties. The performance of the 45% GF material, however, is on a level similar to PA6 without filler, but its energy expenditures are higher. The findings indicate that the best and most reasonable combination of mechanical performance with process efficiency can be obtained through mid range reinforcement (15%) and it is suitable for the precision molded parts such as firearm grips. The research posed in the present article is a thorough numerical analysis concerning the effects that changing the ratios of glass fiber reinforcement (0%, 15%, 30%, 45%) could have on the injection molding process of a very difficult to mold component of the PA6 firearm grip. The research attempted to find out the optimum degree of reinforcement based on an analysis of 61 simulation outcomes such as thermal, flow, shrink, warpage and energy parameters by means of which it could be ascertained that the levels of dimensional stability, process efficiency as well as structural performance could be achieved.

The results have found that the thermal and mechanical reactions of the materials were significantly altered by the glass fiber reinforcement. The 15% GF material showed the highest overall performance in a combination of the following properties: low pressure drop, electricity consumption for pumping, sufficient cooling and relatively low warpage and shrinkage. On the other hand, the 30% GF configuration displayed the highest deformation as a result of excessive internal stress despite the improved thermal conductivity. The 45% GF grade had a greater dimensional stability in comparison to 30% GF, however, more energy was consumed. According to these results, a moderate level of reinforcement (about 15%) is the most effective balance between flow quality, energy efficiency and the ultimate quality of the component.

In summary, it is necessary to select the reinforcement ratio cautiously based on the individual performance goals of the application. As seen in the case of the firearm grips, where both ergonomic precision and mechanical durability are important, the 15% GF configuration seems to provide an optimal balance. Further studies could include experimental confirmation of the findings and further optimization through shape and packing profile refinement. Despite this research offering a comprehensive numerical assessment of the influence of glass fiber strengthening on the injection molding behavior of pistol grip parts, additional studies are required to corroborate and amplify the results. Also, the analysis of fiber orientation regarding the gates and flow direction, in particular, may provide more information about the trends in stress distribution and deformation. An informed approach could be adopted in regulating dimensional stability by looking at the effect of gate design, packing pressure profiles and the use of multi-objective optimization techniques. Finally, doing fatigue and mechanical tests on molded parts would help one to have a more complete understanding of the structural effects of different levels of reinforcement in real work scenarios.

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Abbreviations

The following abbreviations are used in this manuscript:

GF	Glass Fiber
PVT	Pressure–Volume–Temperature
CF	Carbon Fiber
CTE	Coefficient of Thermal Expansion
IMT	Injection Molding Technique
IDT	Indirect Tooling
V/P	Velocity-to-Pressure (switchover)
RMS	Root Mean Square
LCI	Life Cycle Inventory

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