FLOW ANALYSIS FOCUSED ON DESIGN OPTIMIZATION IN PLASTIC PART MANUFACTURING

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Abstract: In this study, the flow behavior of 780 grade ABS polymer material within the injection mold cavity was analyzed comprehensively using Autodesk Moldflow Adviser, and part production was carried out based on the simulation results. The effects of injection parameters (injection speed, melt temperature, mold temperature, holding pressure) and mold geometry on material flow and final part quality were examined. Critical quality factors such as filling time, pressure distribution, weld lines, burr formation, number and location of air traps, and shrinkage were evaluated through simulation to reduce the need for trial-and-error experiments. The actual molding process was then carried out under real production conditions with brand new, fifty percent recycled and a hundred percent recycled material, utilizing the optimum process parameters derived from the Moldflow analysis in order to observe the real-life performance of the material. The manufactured parts have been found to be satisfactory in terms of both strength and aesthetic appearance. The consistency between simulation and production results demonstrated the effectiveness of numerical analysis in mold design and process optimization. Furthermore, this study emphasizes the significance of material-specific flow analysis in enhancing product quality and manufacturing reliability in plastic injection molding, particularly when recycled polymers are incorporated into production.

Keywords: 780 ABS, Plastic Injection Molding, Flow Analysis, Process Optimization

INTRODUCTION

Today, plastic materials have become indispensable in many sectors such as automotive, electronics, packaging and medical, thanks to their lightness, durability, processability, and cost advantages (Rosato et al., 2004). At the heart of this wide range of applications lies the diversity offered by different types of plastics each allow for various applications with their unique mechanical and thermal properties (Ashby & Johnson, 2013). This material diversity provides flexibility in product design while also making it necessary to determine the correct manufacturing parameters (Strong, 2006).

Plastics are synthetic or semi-synthetic materials which typically possessing an organic polymer structure that can be shaped under the influence of heat or pressure. Through the use of various additives and formulations, the mechanical, thermal, and optical properties of plastics can be tailored to specific applications (Jr & Rethwisch, 2020). Based on their thermal behavior, plastics are classified into two main groups: thermoplastics which soften and become moldable when heated, then solidify again upon cooling (ABS, PE, PP) and thermosets which undergo chemical hardening during the initial molding process and do not melt upon subsequent heating (epoxy and phenol-formaldehyde resins) (Fried, 2014). The performance parameters of plastics can be enhanced through additives used during production, thereby further expanding their scope of application (Rosato).

The widespread use of plastics leads to serious environmental problems. Since plastic waste persists in nature without decomposing for long periods, it causes lasting pollution in terrestrial and marine ecosystems (Geyer et al., 2017). Plastic recycling technologies and sustainable material policies, developed to address these issues, aim to mitigate the environmental impact of plastics. Through mechanical and chemical recycling methods, plastic waste can be reintroduced

into the production process. Additionally, biodegradable plastics (bioplastics) and eco-friendly production methods form the foundation of sustainability-oriented transformations within the plastics industry (Hopewell et al., 2009).

Injection molding, a method frequently preferred in the production of plastic parts with complex geometries, offers high precision and fast production capabilities. However, for this method to work efficiently, mold design and process conditions must be planned correctly (Rosato & Rosato, 2012). Flow analysis is used for simulating how the molten plastic moves inside the mold and making it possible to predict potential errors before production (Osswald & Hernández-Ortiz, 2006). Flow analysis allows for the early detection of defects that may be encountered during production, such as air entrapments, weld lines, and underfilling (Menges et al., 2001).

Acrylonitrile Butadiene Styrene (ABS) stands out as an engineering plastic noted for its mechanical strength, excellent electrical insulation properties, chemical and UV resistance and surface quality, making it eligible for both functional and aesthetical products. ABS is an amorphous thermoplastic produced by combining acrylonitrile which provides chemical and heat resistance; butadiene which enhances impact strength, and styrene monomers which enhance processability and surface gloss (Jr & Rethwisch, 2020). Due to its thermoplastic nature, ABS is highly suitable for injection molding. Its average processing temperature ranges from 210°C to 250°C, while its service temperature varies between 85°C and 105°C (Brydson, 1999).

Various technical challenges can arise during the injection molding process of ABS with foremost among these issues being shrinkage and contraction. ABS tends to shrink by an average of 0.4% to 0.7% during molding (Strong, 2006). Imbalances during the cooling stage can cause ABS parts to warp or twist. To prevent such defects, processing temperatures must be controlled in accordance with manufacturer recommendations (Goodship, 2007). Furthermore, if mold temperature, injection pressure, and cooling time are not correctly set, undesirable surface defects such as surface waviness, loss of gloss, and burn marks occur. Inadequate venting can lead to gas entrapment, resulting in both aesthetic and mechanical defects (Osswald & Hernández-Ortiz, 2006). Ejecting ABS parts from the mold also requires careful attention to obtain a glossy finish as the material may adhere to the mold as the contact area increases. Therefore, design measures such as adequate draft angles and proper ejector pin placement must be implemented (Osswald et al., 2019).

The objective of this study is to measure the correlation between simulated values and real-world performance for plastic products currently in production, and to determine the optimal parameters based on these findings. Specifically, the study focuses on identifying the most efficient way to establish optimal processing parameters for plastic products intended for mass production. The mold selected for this study is currently used for mass production but has exhibited issues such as excessive flash formation or incomplete filling during the molding process. The product features a thin-walled design, which complicates the filling process because the molten raw material struggles to flow freely and solidifies rapidly upon contact with the cooler mold environment. Given that the mold temperature is not externally raised (relying instead on the heat from the injected raw material) initial temperature settings must be established for the molding process. As the mold naturally heats up during operation, it creates a more favorable environment for the flow of the molten plastic, thereby facilitating the filling process. However, increase in temperature can lead to flash formation; therefore, the aim is to find a balanced working temperature in order to extend the mold's service life and minimize flash while making sure the entire mold is filled. Consequently, flow analyses were conducted to calculate the optimal injection pressure and speed. These calculations were subsequently evaluated against actual molding results and mold temperature conditions. Additionally, test prints were produced using mechanically recycled raw materials; their physical properties were compared, and the usability of the recycled raw materials was evaluated.

EXPERIMENTAL METHOD

This study focuses on resolving issues encountered during the molding of a product which is currently in mass-production. Given the product's commercial nature, its visual appearance is of critical importance; the surface must be free from any staining, sink marks, or waviness. The material used in the study is ABS 780. The recycled material was obtained via physical methods and may contain various impurities inherent to the recycling process.

Initially, the virgin raw material was oven-dried for two hours to remove moisture; subsequently, moldings were produced and photographed. Next, a blend consisting of 50% virgin material and 50% recycled material was prepared and molded. Finally, the same procedure was repeated using 100% recycled material. As the objective was to observe surface defects and sink marks, the processing parameters were kept unchanged from the initial settings. The technical specifications of the ABS material are as given in Table 1.

Table 1. Technical Properties of ABS 780

Property	Value	Unit	Test Method
Density	1.04	g/cm^3	ASTM D792, ISO 1183
MFR (200°C / 21.6 kg)	75	g/10min	ASTM D1238
MFR (220°C / 10.0 kg)	55	g/10min	ASTM D1238, ISO 1133
Molding Shrinkage - Flow Direction	0.50 – 0.80	%	ASTM D955, ISO 294-4
Yield and Tensile Strength	44.9	MPa	ASTM D638
Yield Stress	44.0	MPa	ISO 527-2
Yield Elongation	20	%	ASTM D638
Elongation at Break	24	%	ISO 527-2
Flexural Modulus	2100 / 2250	MPa	ASTM D790 / ISO 178
Flexural Strength	60.8	MPa	ASTM D790
Bending Stress	65.0	MPa	ISO 178
Notched Charpy Impact Strength (23°C)	24	kJ/m^2	ISO 179/1eA
Notched Izod Impact Strength (23°C)	23	kJ/m^2	ISO 180/1A
Rockwell Hardness	108	R scale	ASTM D785, ISO 2039-2
Heat Deflection Temperature (0.45 MPa)	91.0	°C	ISO 75-2/B
Heat Deflection Temperature (1.8 MPa)	85.0	°C	ASTM D648
Heat Deflection Temperature (1.8 MPa)	80.0	°C	ISO 75-2/A
Vicat Softening Temperature	95.0	°C	ASTM D1525, ISO 306/B50
Flame Resistance (1.6 mm)	HB	-	UL 94

For plastic injection molds featuring two cavities of unequal volume, runner diameters must be determined by considering both runner length and cavity volume. In this context, the fundamental approach is to equalize flow resistances to ensure that both cavities fill simultaneously. Under the assumption of laminar flow, pressure drop is approximately expressed as $\Delta P \propto L/D^4$. However, this is insufficient when cavity volumes differ; the difference in filling time associated with volume must also be taken into account. Consequently, the formula developed is:

$$D2 = D1 * \left[\frac{L2 + \alpha * V2}{L1 + \alpha * V1}\right]^{\frac{1}{4}}$$

Here, D1 and D2 represent runner diameters, L1 and L2 represent runner lengths, and V1 and V2 represent part volumes. α is an empirical coefficient dependent on flow characteristics and material type. This formula enables the optimization of runner diameters in molds with asymmetric cavity volumes, thereby facilitating more balanced filling and higher product quality (Osswald & Hernández-Ortiz, 2006; Goodship, 2007; Rosato & Rosato, 2012). Upon performing

the necessary calculations and incorporating them into the design, a value of 0.75 mm was selected as the optimal diameter, and the runner was designed accordingly.

RESULTS AND DISCUSSION

Since the cavities have different volumes, the diameters of the runners leading to the cavities were determined based on the cavity volumes. The analysis results were compared with the actual molded part, and the accuracy of the analysis was evaluated.

Temperature Variance

As shown in Figure 1, the temperature decreases and filling the mold becomes more difficult as the distance from the runner increases. To prevent the prematurely solidifying material from clogging the mold, the mold temperature must be maintained between 50 and 80 °C. The difference between the hottest and coldest points is 7.221 °C. This narrow temperature distribution reduces the risk of warping and residual stress formation.

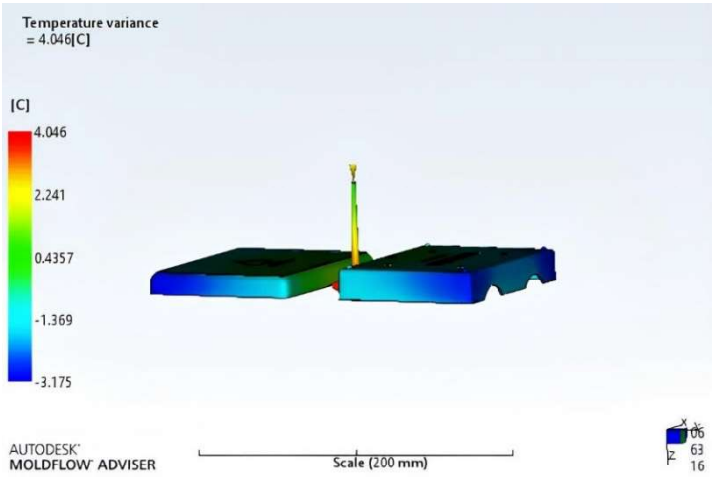

Figure 1. Temperature Variance Analysis

Quality Prediction

An examination of Figure 2 reveals a drop in quality in narrow areas. This is a common occurrence in plastic molding. As the semi-fluid molten plastic moves within the mold, it tends to spread into wider areas first, making it more difficult to fill narrow spaces. Incomplete filling can result from the material failing to fully reach the corners of the mold.

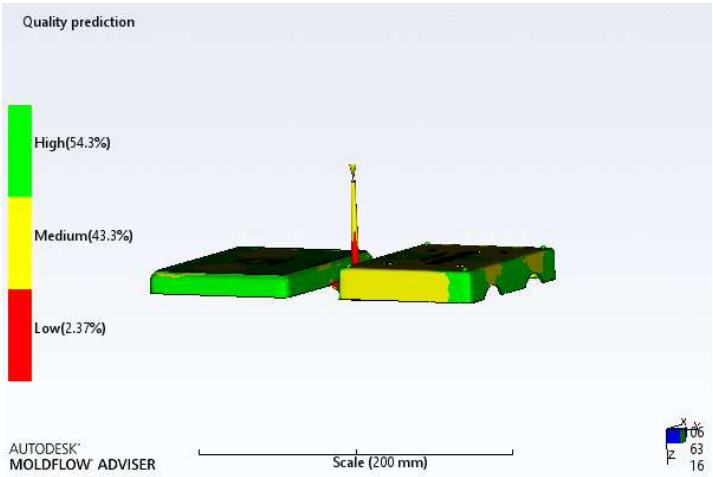

Figure 2. Quality Prediction Analysis

Cooling Quality

No cooling system was employed in the mold; consequently, the flow analysis was conducted without incorporating features such as cooling channels. Figure 3 reveals that while cooling quality is relatively lower in areas containing edge channels and bosses, it is high for flat surfaces. The sprue exhibits the lowest cooling quality, as it remains hot due to the incoming material.

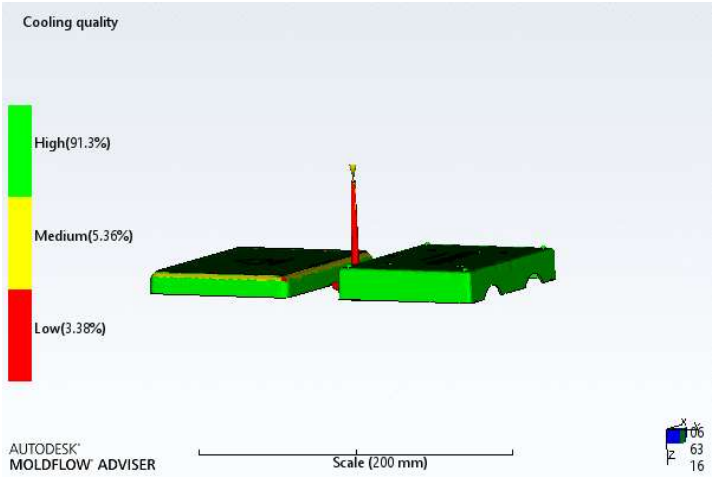

Figure 3. Cooling Quality Analysis

Fill Time

As seen in Figure 4, the corners are the last areas to fill. Since ABS material tends to solidify while in motion, incomplete filling was observed in these sections. The actual printing process took 9–10 seconds, and the result did not align with the analysis findings. This discrepancy is attributed to the fact that both the ambient temperature and the initial mold temperature during the actual print were lower than those used in the analysis.

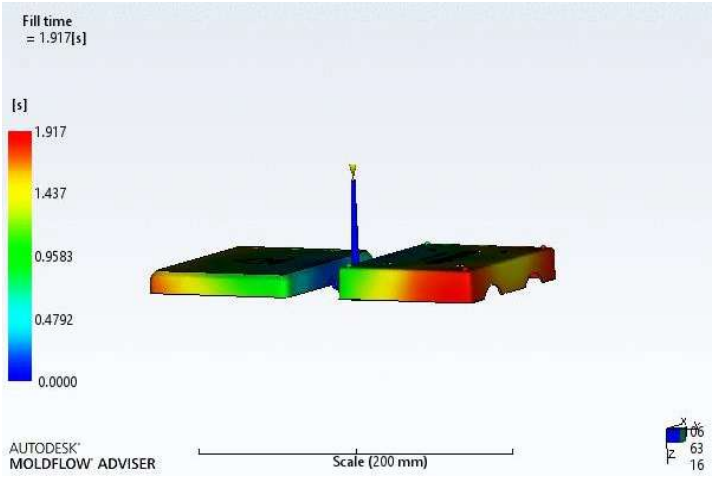

Figure 4. Fill Time Analysis

Pressure Drop

A pressure of 73.42 MPa is required to fill the most difficult-to-fill corner sections of the mold (Figure 5). However, performing the entire molding operation at such high pressure would increase flash formation. To reduce flash formation, the molding pressure was initially set at 75 bar and gradually reduced to 10 bar.

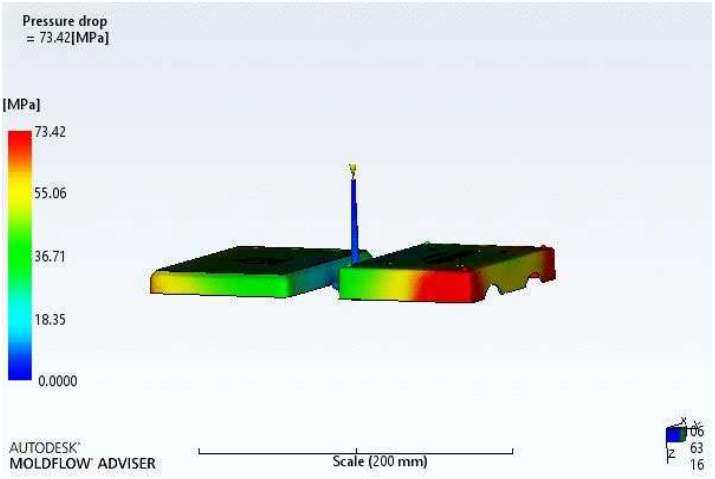

Figure 5. Pressure Drop Analysis

Flow Analysis

As shown in Figure 6, it is observed that the raw material advances parallel to the surface but undergoes a change in orientation upon reaching the curvature points. This change in orientation can affect the part's strength characteristics and its physical appearance; however, the physical properties of the part were not adversely affected, and no issues were encountered.

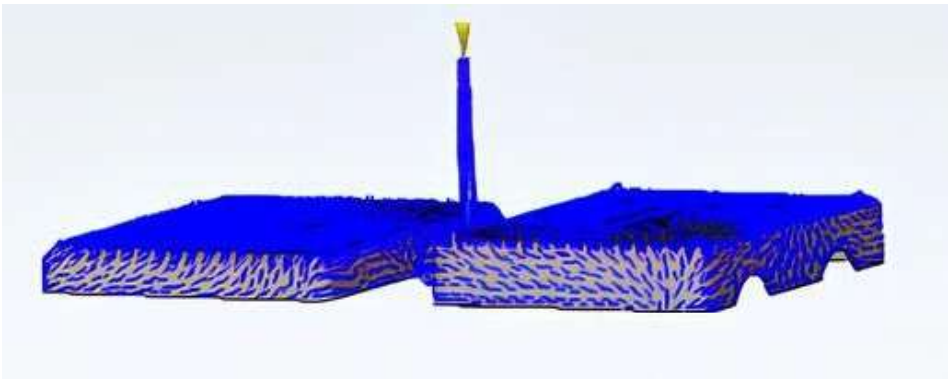

Figure 6. Flow Analysis

Entrapped Air Pocket Analysis

Air pockets generally result in incomplete molding of the object. Therefore, to eliminate these air pockets, air vents have been incorporated into the sections that are difficult to fill completely.

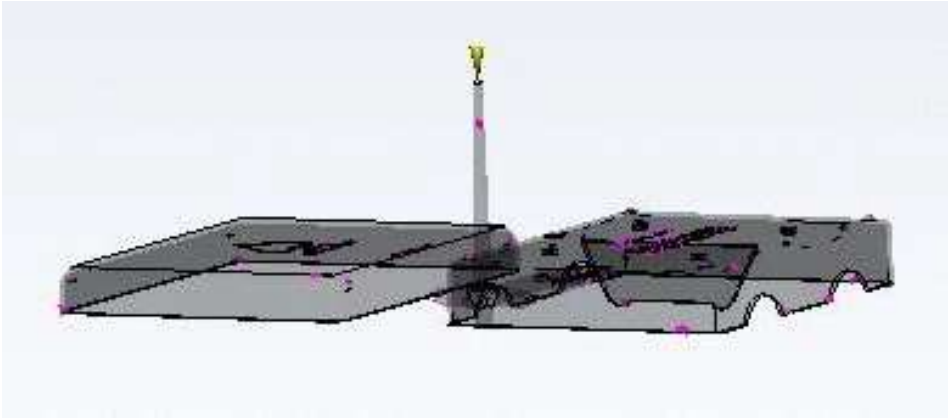

Figure 7. Entrapped Air Pocket Analysis

Weld Line Analysis

Figure 8 shows potential weld line formations. There is a possibility of poor material fusion in the regions indicated in blue and light blue. No visible lack of fusion was observed after manufacturing.

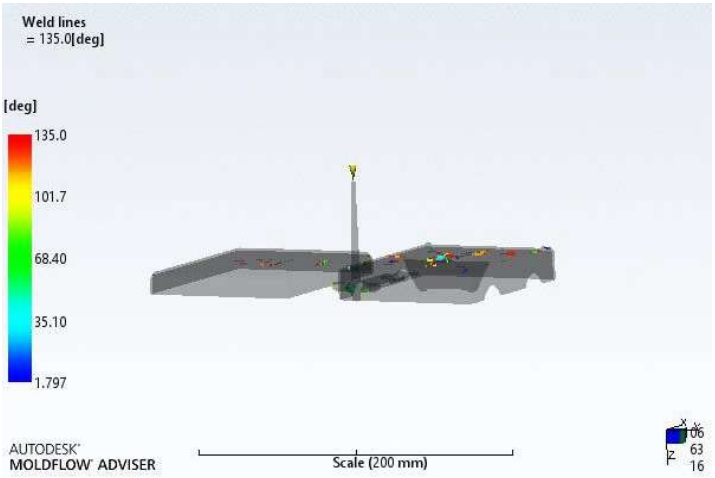

Figure 8. Weld Line Analysis

Comparison of Analysis Results and the Final Product

Following flow analysis and runner design, a trial production run was carried out, and the final product was visually inspected. No visual defects were detected on the matte surface. On the glossy surface, however, slight warping caused by thermal shrinkage occurred due to the internal channels. To rectify this issue, the final pressure level and the amount of ironing were increased, but this resulted in increased flash formation. Consequently, production was continued using the initial parameters.



Figure 9. The Final Product

CONCLUSION

Due to the uneven nature of the part's features, a specific runner design was implemented to optimize the runner channel entry. A comparison between the analysis and the physical product revealed that defects similar to those predicted in the analysis appeared in the physical part, demonstrating the general accuracy of the analysis. However, it was observed that external factors

affecting the mold (depending on the specific molding machine used) prevented the part from being molded perfectly using the initially recommended settings. Ejector pressure was initially reduced to 10 bar to minimize ejector marks, this failed to provide sufficient ejection force; thus, the pressure was raised back to 15 bar, accepting the resulting marks.

In the analysis, the cycle time, part weight, and fill time were estimated at 34.23 seconds, 58.385 grams, and 1.92 seconds, respectively; whereas in actual production, they were measured at 36.5 seconds, 59.4 grams, and 10 seconds. While the other two parameters were estimated quite close to the actual values, there is a significant deviation in the fill time. It is believed that this is due to differences between actual environmental conditions and those used in the analysis, as explained in the fill time analysis section. This factor should be taken into account in future analyses.

Despite ambient temperature fluctuations, the results obtained from the flow analysis closely matched reality, validating the adjustments made on the production line. The optimized production settings facilitated the manufacturing of defect-free parts. No issues were encountered regarding commercial production. No visual difference was detected between products manufactured from new and recycled materials.

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