INFLUENCE OF DESIGN AND PROCESS PARAMETERS OF THE INJECTION MOLDING TECHNOLOGY ON THE TIGHTNESS OF A SERVO DRIVE PLASTIC HOUSING

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The aim of the presented study is to analyze the causes of a leakage type failure occurring in a servo drive plastic housing and to identify the design and process factors that contribute to its formation. Based on a Design FMEA, which classified the housing leakage as a critical failure mode with a high Risk Priority Number (RPN = 196), a numerical simulation of the injection molding process was performed using the NX EasyFill Analysis environment. The simulation included filling, packing, and cooling analyses, while key parameters such as temperature fields, pressure distribution, weld line formation, air traps, Frozen Layer Ratio, and volumetric shrinkage were evaluated. The results showed that the leakage is caused by a synergistic combination of several phenomena, particularly cold weld lines near functional surfaces, non-uniform solidification of the material, significant thermal inhomogeneity, locally increased shrinkage, and insufficient pressure coverage in remote areas of the cavity. Based on these findings, specific design and process measures were proposed, focusing on optimizing wall thickness, rib geometry, gate location, venting, mold cooling, and adjusting injection molding parameters. The results confirm that numerical simulation combined with the FMEA methodology represents an effective tool for reducing the risk of failures already in the design phase and significantly contributes to improving the reliability and service life of servo drives.

KEYWORDS

plastic injection molding, numerical simulation, NX EasyFill Analysis, FMEA, housing leakage

1 INTRODUCTION

Ensuring the reliability and functional integrity of mechatronic systems represents one of the key prerequisites for their successful deployment in industrial practice. Modern servo drives, as integral components of automated production lines, robotic systems, and precision positioning mechanisms, are exposed to a combination of mechanical, thermal, and environmental influences. These factors can significantly affect their service life, operational stability, and ability to maintain the required performance parameters over long periods. For this reason, it is essential to implement systematic quality management methods that enable the identification of potential failures already in the design phase and minimize their impact on the final product [Asahi 2023].

One of the most widely used methodologies for preventive risk management in design and technological preparation of production is the FMEA (Failure Mode and Effects Analysis) method. This method makes it possible to systematically analyze potential failure modes, assess their severity, occurrence probability, and detectability, and subsequently quantify the risk using the Risk Priority Number (RPN). Within the design FMEA performed for the analyzed servo drive by our partner – Regada, s.r.o. Presov – a critical failure related to leakage of the servo drive housing was identified. The calculated risk number reached a value of 196. Such a high RPN clearly indicates a failure mode with potentially serious consequences for the device's functionality, operational safety, and long-term reliability.

Leakage of the servo drive housing represents a significant risk, particularly in terms of moisture, dust, or chemical substances penetrating into the internal parts of the drive. These contaminants may cause corrosion, reduced insulation properties, lubricant degradation, malfunction of electronic components, or complete drive failure. In environments with high dust concentration or increased humidity, such a failure can become critical even after a short period of operation. At the same time, this type of defect is often difficult to detect during production, as leakage may manifest only during long-term operation or when the device is exposed to dynamic pressure and temperature changes.

Given the identified risk, it is necessary to analyze the causes of leakage formation, evaluate the design of the housing and its interaction with sealing elements, and propose measures that reduce the probability of failure occurrence or increase its detectability [RJC 2023]. A scientific approach to solving this issue requires a combination of design analysis, material evaluation, simulation methods, and experimental verification. The aim of this article is therefore to examine the identified failure in detail, analyze its causes, and propose effective measures to reduce the associated risk in accordance with quality management principles and the FMEA methodology.

The injection molding of thermoplastics ranks among the most important technologies for the mass production of precise plastic components, with the quality of the molded part being highly sensitive to a wide range of interrelated factors. As noted by [Rafli 2025], even small imbalances in pressure and temperature may lead to melt leakage or the formation of seal failures in critical regions of the mold. Similarly, [Kovari 2015] emphasizes that medium leakage—although in his case analyzed within electrohydraulic servo systems—significantly affects system dynamics, a perspective that can also be applied to evaluating polymer leakage during cavity filling.

A key tool for defect prediction and process optimization is computational CAE simulation. According to the technical documentation [Siemens 2021], NX Mold Flow Analysis solutions (EasyFill, EasyFill Advanced) can identify potential issues such as air traps, short shots, weld lines, or local material overpacking. The integration of Moldex3D and NX into design workflows enables detailed monitoring of temperature, pressure, flow velocity, and volumetric shrinkage distributions, which plays a crucial role for components sensitive to sealing performance.

Weld lines belong to the most common and most critical defects, especially in thin-walled or functional parts. Industrial and technical analyses [TK Precision Plastics 2023, Li 2024], and [PremiumParts 2025] report that weld lines form where flow fronts meet under low temperature or insufficient pressure, causing significant material weakening. A more advanced scientific perspective is provided by [Bao 2025], who—using a combination of Moldex3D, Digimat, and Abaqus—demonstrated how variations in temperature, pressure, and glass fiber content strongly influence the strength in the weld region. This is highly relevant for ensuring the tightness of technical components, where even minor weakening may lead to local permeability.

Experimental validation of simulation models is essential for their practical applicability. [Loaldi 2020] showed that CAE analyses of micro-feature geometries can accurately predict critical phenomena such as flash formation or insufficient cavity venting. This approach confirms the importance of combining simulation with real processing when tuning technological parameters.

A crucial aspect of injection molding is systematic risk analysis. [Neamtu 2015] demonstrate that FMEA is an effective tool for identifying potential mold failures such as insufficient venting, improperly dimensioned cooling systems, or risks of incomplete filling. Similarly, [Shivakumar 2015] combines FMEA with DOE to identify key parameters—barrel temperature, injection speed, and screw rotation speed—that most significantly influence the occurrence of defects (e.g., black spots, bubbles, material degradation). [Randelovic 2015] links FMEA with FEM simulation results (Moldex3D) in the production of molded parts and show that modifying gate location or optimizing geometry can significantly reduce RPN values and eliminate crack formation.

Another dimension is added by integrating process simulation results into structural analyses. [Bernard 2022] states that the SIGMALINK® tool enables the transfer of weld line data, stress gradients, or local fiber orientation directly into FEA analysis, allowing precise evaluation of part strength under operational conditions. This approach is particularly important in the production of plastic housings and components where functional or sealing surfaces are exposed to vibration, pressure, or chemical stress.

In summary, modern publications consistently highlight the need to integrate CAE simulations, process design, FMEA, and experimental validation. Authors such as [Neamtu 2015, Arif 2024, Bao 2025, Shivakumar 2015, Randelovic 2015], and [Loaldi 2020] emphasize that a multidisciplinary approach is essential for minimizing defects, improving sealing performance, and achieving high manufacturing quality. For components with stringent reliability requirements, not only the optimization of injection molding parameters but also thorough risk analysis and the integration of simulation, design, and experimental methods are decisive.

2 METHODOLOGY AND CONDITIONS OF THE INJECTION MOLDING SIMULATION

The methodology of the numerical analysis was designed to enable a comprehensive assessment of polymer melt behavior during injection molding and to identify potential design deficiencies that may lead to failures such as leakage of the servo drive housing. The procedure consisted of several consecutive steps, including preparation of the geometric model, creation of the computational mesh, definition of material properties, setting of processing conditions, and subsequent simulation of the individual phases of the injection cycle. The entire process was carried out in the NX EasyFill Analysis environment, which enables detailed evaluation of flow behavior, temperature fields, pressure loading, and shrinkage in a 3D domain.

The geometric model of the servo drive housing was imported into the simulation environment without major modifications to preserve its design integrity. A coarse 3D computational mesh was then generated as a compromise between computational cost and sufficient accuracy for identifying realistic flow and thermal conditions. The mesh contained approximately 162,000 elements, which allowed the capture of fundamental flow and temperature characteristics, while acknowledging that local defects may require a finer mesh in subsequent iterations.

The material properties of ABS Terluran 877 M were taken from the NX EasyFill Analysis database, including viscosity, thermal, and PVT characteristics. These data are essential for accurate modeling of melt behavior, as the viscosity of ABS is strongly dependent on temperature and shear rate. The model therefore enables simulation of real processing conditions under which cold welds, air traps, or uneven solidification may occur.

The processing conditions were defined according to the actual technological settings of the injection molding process. The melt temperature was set to 225 °C and the mold temperature to 60 °C. The filling time was specified as 3.07 s, and the transition from filling to packing was defined at 98 % of the cavity volume. These parameters made it possible to simulate the dynamics of polymer flow within the cavity and to identify regions with high flow resistance or premature solidification. The packing phase was modeled with a duration of 12.4 s, enabling analysis of shrinkage compensation efficiency and pressure distribution within the cavity.

The simulation was divided into three main phases: filling, packing, and cooling. During filling, the flow front progression, temperature fields, shear rate, and the formation of potential defects such as air traps and cold welds were evaluated. In the packing phase, pressure distribution, the effectiveness of pressure transmission into remote areas of the cavity, and the evolution of the Frozen Layer Ratio were assessed. The cooling phase enabled evaluation of the part's thermal homogeneity, the time required to reach ejection temperature, and potential risk areas in terms of deformation.

The simulation results were subsequently compared with the outputs of the design FMEA, in which the critical failure mode "servo drive housing leakage" with an RPN value of 196 had been identified. The aim of the methodology was therefore not only to describe melt behavior but also to identify design or technological factors that may contribute to the occurrence of this failure. The numerical analysis thus served as a tool for verifying FMEA hypotheses and for proposing preventive measures aimed at reducing the risk of failure.

3 NUMERICAL SIMULATION RESULTS

The numerical simulation of the injection molding process for the ABS Terluran 877 M component provided a detailed insight into the filling, packing, and cooling phases, enabling the identification of several phenomena directly related to the failure mode "servo drive housing leakage" identified in the design FMEA. The results indicate a combination of thermal, flow, and design factors that may lead to local weakening in the areas of sealing surfaces or fastening features of the housing.

The filling simulation of the ABS part showed that, despite complete cavity filling without a short shot, several defects appeared in critical regions that may directly affect the sealing performance of the housing. The visualization of weld lines in Siemens NX confirms that flow fronts meet in areas with low melt temperature, resulting in the formation of cold welds. These welds are particularly critical when located near sealing surfaces or connection zones of the housing, where high mechanical integrity is required.

Figure 1 provides a visualization of the weld joints formed by the meeting of flow fronts in the area of the reinforcing ribs and sealing surfaces. The red lines indicate locations that may be weakened in terms of mechanical strength and sealing performance.

In addition to cold welds, the presence of air traps was identified in several regions of the cavity. These traps formed primarily in areas where the part geometry creates enclosed spaces or sharp transitions that hinder proper venting.

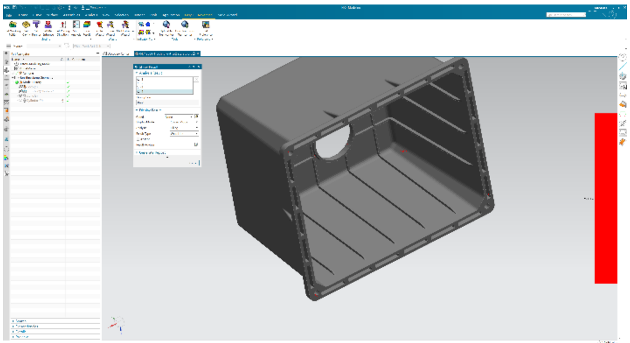

Figure 1. Weld Line Visualization on the Servo Drive Housing

Air traps can lead to local incomplete fusion of the material, surface defects, or even microcracks that may propagate during long-term operation. In the case of the servo drive housing, the presence of air inclusions may disrupt the sealing plane or cause leakage under dynamic loading.

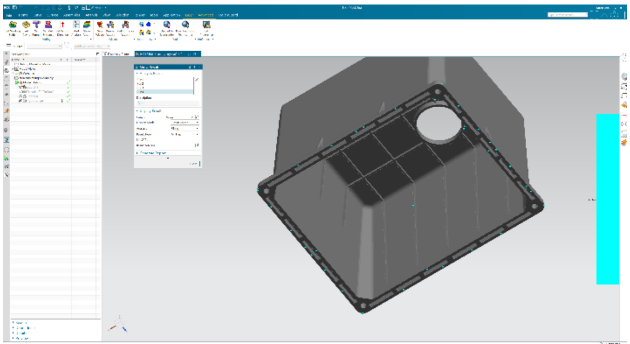

Figure 2. Air Trap Localization During the Filling Phase

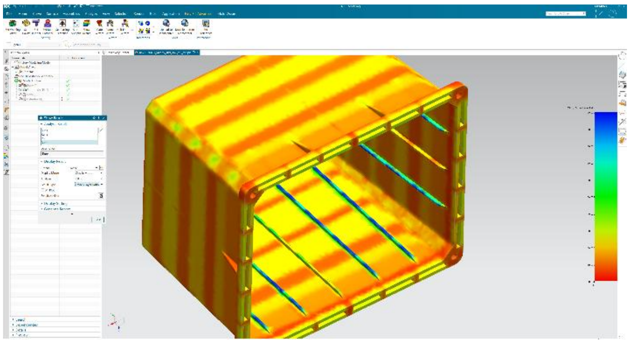

Figure 3. Frozen Layer Ratio at the End of Filling

An important factor influencing the quality of the part was the rapid increase in the Frozen Layer Ratio (Fig. 3) already in the early stages of filling. This phenomenon confirms the intensive solidification of the material along the cavity walls, which increases flow resistance and may lead to uneven filling. In regions with a high Frozen Layer Ratio, the effectiveness of the packing phase decreases, which can result in insufficient shrinkage compensation and the formation of micro-deformations. For servo drive housings, where sealing performance depends on the flatness and geometric stability of the mating surfaces, this effect may be critical.

The pressure conditions during packing were generally favorable, with the maximum pressure reaching only 14.9 MPa (Fig. 4). This indicates that the cavity was well accessible for pressure transmission; however, it also suggests that in areas with premature solidification, the packing pressure may not be sufficiently effective. Uneven penetration of packing pressure can lead to local voids or reduced material density, which may negatively affect the sealing properties of the part.

The cooling results revealed a pronounced non uniformity of the temperature field within the part. ABS, as a material with low thermal conductivity, naturally forms local hot spots that extend the time required to reach the ejection temperature. These regions may be prone to deformation after removal from the mold, which can lead to deviations in the geometry of the sealing surfaces. In combination with low strength weld joints, a synergistic effect may occur, significantly increasing the likelihood of leakage (Fig. 5).

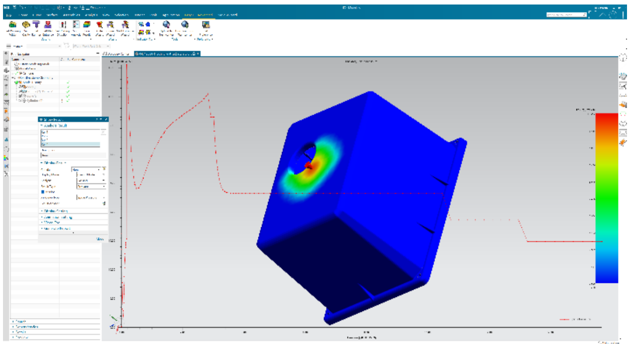

Figure 4. Pressure Distribution Profile During the Packing Phas

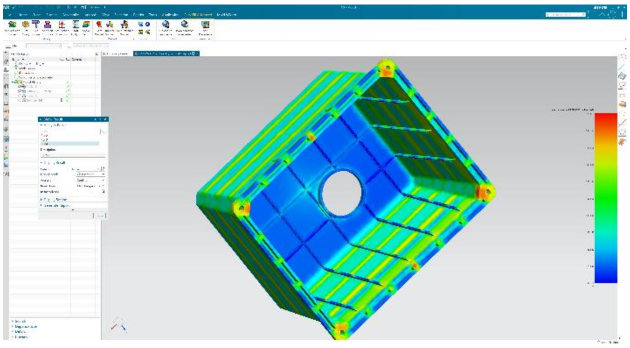

Figure 5. Temperature Distribution in the Part During Cooling

In the present case, the temperature range spans from approximately 62 °C to 179 °C, indicating a pronounced thermal non-uniformity. Hot spots (red regions) may be particularly critical in the vicinity of:

- the housing's mating surfaces,
- weld joints,
- or functional areas where geometric stability is required.

Cold regions, which appear as blue to green shades on the temperature map, reach temperatures below 100 °C and indicate faster cooling of the material. They typically occur near thin walls, close to cooling channels, and along the outer edges of the part where contact with the mold is most intense. In these areas, uneven solidification may lead to internal stresses; combined with adjacent hot zones, significant thermal gradients arise that promote structural distortion of the part.

Transition zones, usually shown in yellow to green colors, represent an intermediate state between cold and hot regions and often exhibit local shrinkage, stress concentrations, and unstable geometric behavior. If these transition zones are located in the area of the housing's mating surfaces, they may substantially contribute to leakage formation. Such analysis is crucial when evaluating housing tightness, as deformations caused by uneven cooling may disrupt the flatness or shape of the sealing surfaces.

The analysis shows that the part exhibits a markedly non-uniform temperature field after the packing phase. Hot spots in the central region and around the ribs pose a deformation risk, while cold edges may cause premature solidification and limit packing effectiveness. This combination promotes the formation of micro-deformations, flatness deviations, and sealing failures, correlating with the failure identified in the FMEA—servo drive housing leakage.

One of the key outputs of the numerical injection-molding simulation is the volumetric shrinkage analysis, which provides information on the material's volume change due to pressure and temperature drop during cooling. This analysis is particularly important for assessing the geometric stability of the part, as asymmetric shrinkage may lead to local warpage, deformation, and flatness deviations that directly affect the functionality of the servo drive housing's sealing surfaces.

Figure 6 shows the shrinkage distribution within the part, with a color scale ranging from blue (0.298 %) to red (9.667 %), illustrating the extent of volumetric changes. The analysis indicates that the highest shrinkage values are concentrated in areas with thicker walls, around the ribbing, and near the central opening, where heat accumulates and pressure compensation is limited. These regions are also exposed to an increased risk of micro-deformations that may disrupt the flatness of the mating surfaces or cause misalignment of sealing elements.

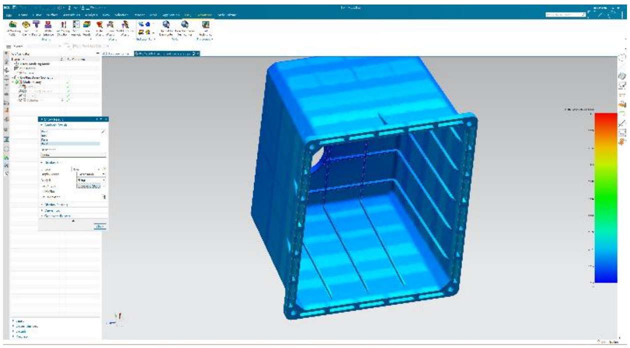

Figure 6. Analysis of the Volumetric Shrinkage of the Examined Plastic Housing

Conversely, the blue regions with low shrinkage are located predominantly along thin walls and at the edges of the part, where cooling is more intensive. This creates a thermal and volumetric gradient that promotes part warpage and asymmetric deformation. In combination with the identified weld lines and air traps, volumetric shrinkage becomes a significant factor influencing the overall sealing performance of the housing.

From a design perspective, it is therefore essential to optimize wall thickness, rib distribution, and gate location to minimize areas with excessive shrinkage. At the same time, it is advisable to reconsider mold cooling in critical regions and evaluate the use of conformal cooling or additional cooling circuits. The volumetric shrinkage analysis thus provides valuable input for both part and mold design, with the goal of reducing leakage risk and ensuring long-term functionality of the servo drive.

One of the important outputs of the injection-molding simulation is the analysis of pressure distribution during filling, which provides insight into how pressure propagates through the mold cavity from the gate to the end-of-flow regions. Figure 7 shows a color map of the filling pressure, where red areas (up to 36.6 MPa) indicate high pressure near the gate, while blue and green areas (close to 0 MPa) appear at the outer edges of the part, where the pressure is significantly lower.

This pressure gradient indicates that the material reaches distant regions with substantially lower pressure, which may lead to short shots, cold weld formation, or air traps. For the servo drive housing, this is particularly critical if such regions are located near sealing surfaces or functional joints where high mechanical integrity is required.

The analysis also includes the Sprue Pressure graph (Fig. 7), which shows the pressure evolution over time. The curve indicates that the pressure reaches a maximum of approximately 45 MPa at the beginning of filling and gradually decreases until the end of the cycle (~3.01 s). This behavior is typical for ABS injection molding; however, sharp drops or instability in the curve may indicate flow issues or unstable filling, which could lead to defects in end-of-flow regions.

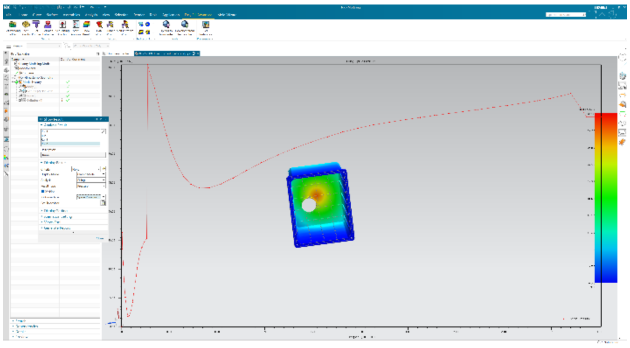

Figure 7. Graphical Representation of Pressure Evolution Over Time

From a design perspective, it is important to ensure that the pressure is evenly distributed throughout the entire cavity. This can be achieved by optimizing gate location, the number of gates, or modifying the part geometry to reduce flow resistance in critical areas. The pressure analysis therefore provides important evidence that the housing leakage may be caused by insufficient pressure coverage of the sealing regions during filling.

Overall, the simulation results show that the identified failure mode "servo drive housing leakage" may be caused by a combination of several factors: low melt-front temperature in critical regions, formation of cold welds, presence of air traps, uneven solidification of the material, and local deformations resulting from non-uniform cooling. These phenomena represent potential weak points that may lead to loss of sealing integrity under operational loading.

4 DISCUSSION AND INTERPRETATION OF RESULTS

The results of the numerical simulation clearly show that the identified failure mode, "servo drive housing leakage," has a multifactorial nature, with a decisive influence arising from the combination of design-related, material, and processing factors. A key finding is that several critical phenomena—cold welds, air traps, uneven solidification, pressure shadows, and volumetric shrinkage—occur in regions directly associated with the functional and sealing surfaces of the housing. This means that even small local geometric deviations or micro-defects may lead to loss of sealing integrity during servo drive operation.

The weld lines identified in the area of the reinforcing ribs and near the sealing surfaces represent a significant material weakness. Due to the low melt-front temperature in these regions, it is likely that the strength of the weld lines is lower than that of the homogeneous material. Under long-term mechanical or vibrational loading, these welds may gradually degrade, potentially leading to microcracks and subsequent leakage. This phenomenon is particularly critical for ABS, which is sensitive to local stress concentrations and thermal cycling.

Air traps identified in enclosed geometries and around ribbing represent another important factor affecting part quality. Their presence may lead to surface defects, incomplete fusion, or void formation, all of which reduce local strength and may compromise the flatness of sealing surfaces. Combined with uneven cooling, a synergistic effect may occur, where deformations and material weakening reinforce one another.

The Frozen Layer Ratio analysis confirmed that the material solidifies very rapidly along the cavity walls, increasing flow resistance and reducing the effectiveness of the packing phase. This effect is especially problematic in areas with complex geometry, where pressure cannot be transmitted uniformly. Insufficient shrinkage compensation subsequently leads to local warpage and flatness deviations, which can directly impair sealing performance.

The pronounced thermal non-uniformity observed during cooling is another critical factor. Hot spots in the central region of the part and around the ribs are prone to greater shrinkage, while the colder edges solidify more quickly. This difference creates thermal and volumetric gradients that promote part warpage and asymmetric deformation. In the case of the servo drive housing, even a small deviation in the flatness of the sealing surface may lead to leakage, especially when the housing is exposed to pressure fluctuations or vibrations.

The pressure analysis during filling showed a significant pressure gradient between the gate and the end-of-flow regions. This means that distant areas are filled under lower pressure, increasing the risk of cold weld formation and short shots. This issue can be partially mitigated by optimizing gate location or modifying part geometry to reduce flow resistance in critical regions.

Volumetric shrinkage represents the final, but highly significant, factor influencing housing tightness. Areas with high shrinkage overlap with regions where hot spots and weld lines were identified. This indicates that deformations arising during cooling may further degrade weld quality and disrupt the flatness of sealing surfaces. From a design standpoint, it is therefore essential to optimize wall thickness and ribbing to minimize regions with excessive shrinkage.

In conclusion, the numerical simulation provided a comprehensive view of part behavior during injection molding and enabled the identification of specific design and processing factors that may lead to servo drive housing leakage. The results confirm that the leakage issue is not caused by a single factor but by a combination of interacting phenomena. Therefore, both part and mold optimization must be approached holistically, with emphasis on uniform filling, effective venting, optimized cooling, and minimization of volumetric shrinkage.

Measures Resulting from the Numerical Analysis

The simulation results highlight several areas in which the risk of servo drive housing leakage can be reduced through design or process related modifications. Based on the identified defects, the following measures can be recommended:

1. Optimization of Wall Thickness and Ribbing:

The analysis of volumetric shrinkage and the temperature field showed that thick walls and massive nodes around the ribs create hot spots with high shrinkage. This leads to deformation of the sealing surfaces.

Recommended measures:

- unify the wall thickness in critical areas,
- reduce rib thickness to 0.5–0.7 times the thickness of the base wall,
- add transition radii and relief features at rib junctions.

2. Adjustment of Gate Location and Gate Type:

The pressure analysis and the distribution of weld lines showed that the current gate location leads to a pronounced pressure gradient and the formation of cold welds near the functional surfaces.

Recommended measures:

- move the gate closer to the regions with high flow resistance,
- consider using multiple gates to achieve more uniform filling,
- use a tunnel gate or valve gate for improved flow control.

3. Improvement of Mold Venting:

Air traps identified in the rib areas and enclosed geometries pose a risk of incomplete fusion and microcracks.

Recommended measures:

- add venting channels at the locations where air traps were identified,
- increase the size of existing venting gaps,
- modify the geometry to eliminate enclosed spaces.

4. Optimization of Mold Cooling:

The thermal analysis revealed significant cooling non-uniformity, causing deformation and uneven shrinkage.

Recommended measures:

- bring cooling channels closer to hot spots (while maintaining mold strength),
- add additional cooling circuits in the rib areas,
- consider the use of conformal cooling for complex shapes.

5. Improvement of Sealing Surface Flatness:

Warpage (as indicated by thermal and shrinkage analyses) may impair sealing performance.

Recommended measures:

- add peripheral reinforcement around the sealing plane,
- reduce local shrinkage by adjusting wall thickness,
- ensure uniform cooling in the area of the mating surface.

6. Minimization of Cold Weld Formation:

Weld lines near functional areas pose a risk of material weakening.

Recommended measures:

- modify the flow path by changing the gate location,
- increase mold temperature in critical regions,
- extend the filling time to achieve a more stable melt flow.

7. Process-Related Technological Adjustments:

Some issues can be mitigated without modifying the housing design.

Recommended measures:

- increase melt temperature by 5–10 °C to improve weld line quality,
- increase mold temperature to reduce the Frozen Layer Ratio,
- optimize the injection speed profile for more uniform filling.

5 CONCLUSIONS

The numerical simulation of the injection-molded servo drive housing made it possible to identify and analyze in detail the key factors that may lead to leakage-type failures. The results clearly confirmed that the problem is multifactorial, arising from a combination of design-related, material, and processing influences. The most significant identified phenomena include cold welds near functional surfaces, the presence of air traps, uneven material solidification, pronounced thermal non-uniformity during cooling, locally increased volumetric shrinkage, and uneven pressure conditions during filling.

These phenomena interact with one another and create a synergistic effect in critical regions, potentially leading to micro-deformations, flatness deviations of sealing surfaces, and material weakening at weld lines. The simulation results therefore directly support the conclusions of the design FMEA, which identified housing leakage as a failure mode with a high risk priority number, RPN = 196.

Based on the analyses performed, specific design and process-related measures were proposed that can significantly reduce the risk of failure. The most important recommendations include optimizing wall thickness and ribbing, adjusting gate location and gate type, improving mold venting, optimizing cooling, and modifying key processing parameters. Implementing these measures can lead to more uniform cavity filling, reduced thermal and volumetric gradients, fewer cold welds, and improved geometric stability of the part.

Overall, it can be concluded that numerical simulation is an effective tool for identifying the root causes of defects and supporting both design and process decision-making. When combined with the FMEA methodology, it enables systematic reduction of failure risks already in the design phase and contributes to increased reliability and service life of the final product. For further research, experimental verification of the proposed measures is recommended, along with potential mold or process optimization based on an iterative CAE approach.

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