Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN : 2549-1999 No. : 3 Month : June
p-ISSN : 1693-5462 Volume : 24 Year : 2026

Processing dates: received on 2026-3-27, reviewed on 2026-05-13, accepted on 2026-05-24 and online availability on 2026-06-30

Effects of cooling time, injection pressure, and material type on the mechanical properties of *ballun* insulator products in injection molding

Muhammad Rifqi Sepvian , Sugeng Hadi Susilo*
Department of Mechanical Engineering, State Polytechnic of Malang, Malang 65141, Indonesia
*Corresponding author: sugeng.hadi@polinema.ac.id

Abstract

A major challenge in injection molding is the instability of mechanical properties in products due to suboptimal process parameter settings, which necessitates identifying the optimal parameter combination to achieve adequate tensile strength and hardness. This study aims to evaluate the effects of cooling time, injection pressure, and material type on the tensile strength and hardness of ballun insulator products produced by injection molding. Two thermoplastic materials, Polypropylene (PP) and High-Density Polyethylene (HDPE), were selected due to their different molecular structures and crystallization behavior, both of which influence mechanical performance. The materials were processed under varying cooling times (20, 25, 30, and 35 s) and injection pressures (24, 27, 30, 33, and 36 bar). The novelty of this study lies in the comparative evaluation of PP and HDPE under identical process conditions for ballun insulator applications. The results showed that higher injection pressure improved mold-filling and molecular chain compaction, leading to increased tensile strength, while longer cooling time promoted more controlled crystallization and improved surface hardness. PP exhibited higher tensile strength due to its stiffer molecular structure, achieving a maximum tensile strength of 0.031 MPa at 36 bars. In contrast, HDPE showed higher hardness due to its denser crystalline structure, reaching 69.75 HD at 35 s cooling time. These findings indicate that material-specific optimization of injection molding parameters is important for achieving consistent mechanical properties and dimensional stability in ballun insulator products.

Keywords:
Cooling time, injection pressure, HDPE, PP, ballun insulator, injection molding, hardness

1 Introduction

The current development of the electrical and manufacturing industries demands plastic components with high mechanical strength, high dimensional precision, and consistent quality, especially in functional products such as ballun insulators [1]. Problems that often arise in the injection molding process are the occurrence of product defects, such as sink marks, excessive shrinkage, and dimensional inaccuracy, which are generally caused by suboptimal process parameter settings [2],[3]. This condition is increasingly complex due to differences in the characteristics of PP and HDPE materials, both in thermal and mechanical properties, leading to different responses to injection pressure and cooling time. Previous research has shown that inconsistencies in process parameters can increase dimensional defects and reduce mechanical qualities, such as tensile strength and hardness, and even cause dimensional deviations that interfere with the product's installation function. Too short a cooling time can result in unstable dimensions, while too high an injection pressure has the potential to cause residual stresses that are detrimental to product strength [4],[21],[22]. With the increasing industrial demands on ballun insulators that must meet certain strength and hardness standards, uncertainty in process parameter settings has become an important issue that needs to be further studied experimentally to obtain an optimal process combination and ensure continuous product quality.

Previous research shows that the quality of plastic products is greatly influenced by the settings of process parameters such as cooling time, injection pressure, and the type of material used [5]. Variations in injection pressure, melt temperature, and cooling time have a direct relationship with the appearance of defects such as sink marks , warpage , and flash , so that parameter control is key to maintaining product quality [6], [7]. Dimensional shrinkage in thin-walled products occurs due to an imbalance between filling time and holding pressure, thus disrupting the accuracy of component fitting [8]. Then, it shows that the characteristics of sink marks in HDPE materials can be optimized with by combining specific injection parameters, where the presence of virgin and recycled materials results in different process responses.

Non-uniformity in mold temperature and injection pressure often triggers warpage defects that compromise the dimensional stability of the product after cooling. Furthermore, small changes in barrel temperature or injection pressure can affect the homogeneity of mold filling and trigger defects that compromise the product's mechanical strength. In certain materials, such as HDPE, mold temperature plays a significant role in hardness and dimensional stability, as demonstrated by testing gear products and finding an optimal temperature range for achieving optimal mechanical performance [9].

Previous studies have discussed the influence of injection molding process parameters such as mold temperature, injection pressure, cooling time, and material variations on product defects or dimensional stability [10], [11]. Despite the breadth of prior work, three critical gaps remain unaddressed. First, existing studies on injection pressure effects typically investigate a single material in isolation, using pressure ranges that are either much higher (e.g., 80–160 bar for general-purpose molding) or much lower than the moderate range of 24-36 bar employed here, which is specifically calibrated to the thin-walled geometry and flow characteristics of ballun insulator molds. The injection pressure values selected in this study are therefore not arbitrary variations of previous methods but are derived from machine-limit trials and mold-filling simulations specific to the ballun insulator cavity. Second, the cooling time range of 20–35 seconds investigated here is narrower and more precisely targeted than the broad ranges (10-60 seconds) reported in general studies, reflecting the thermal mass and wall thickness of the ballun insulator product; this specificity has not been previously validated for functional insulator components. Third, and most importantly, no prior study has simultaneously examined how the interaction between cooling time and injection pressure governs both tensile strength and surface hardness across two contrasting thermoplastic materials, PP and HDPE, within a single product platform. The novelty of the present study therefore lies in: (1) establishing material-specific process windows for PP and HDPE within a narrow but industrially relevant parameter range, (2) quantifying the differential mechanical response (tensile strength vs. hardness) of the two materials under identical process conditions, and (3) applying this analysis to ballun insulator products whose dimensional stability and mechanical integrity requirements exceed those of generic injection-molded specimens studied previously.

The purpose of this study is to comprehensively analyze the effects of variations in cooling time, injection pressure, and type of plastic material on the characteristics of ballun insulator products produced by injection molding process. This study is specifically aimed at identifying how the combination of these process

parameters affects three main aspects of product quality, namely tensile strength, dimensional accuracy, and surface hardness. In addition, this study aims to determine the optimal process parameters for each type of PP and HDPE material, so that a process configuration can be obtained that produces products with consistent mechanical performance and dimensional stability. Through an experimental approach, this study is expected to provide a more comprehensive understanding of material behavior and process response in ballun insulator products, as well as technical recommendations that can be applied to improve production quality in the plastic manufacturing industry.

2 Methods and materials

The dimensions of the ballun isolator product image are as below.

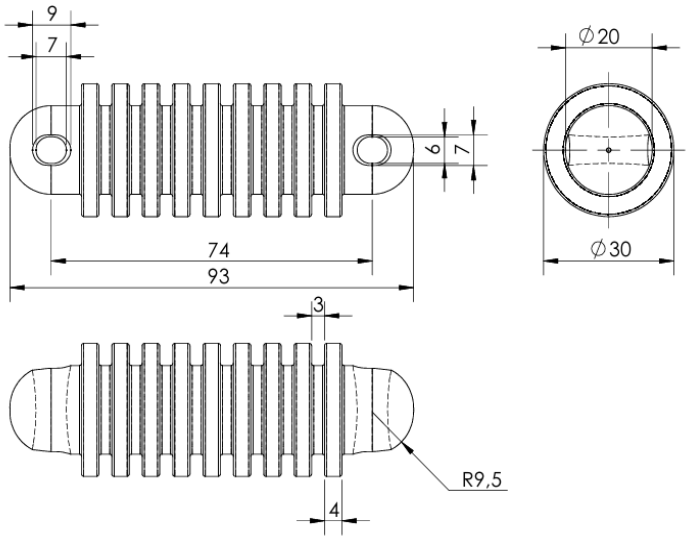

Fig. 1. Ballun isolator product design (all dimensions in mm)

Fig. 2. Product after the tensile test

This study used two types of plastic materials: PP and HDPE. A KT-150 G injection molding machine, ballun insulator molds, and all the necessary testing equipment were used. The installation and adjustment of the equipment starts with installing the mold on the injection molding machine, checking the straightness of the mold nozzle, and setting the basic parameters of the machine according to the initial standards of the experiment. This study uses cooling times (20, 25, 30, and 35 seconds) and injection pressures (24, 27, 30, 33, and 36 bar) combined for each type of material. The molding process for the ballun insulator product is carried out by running the injection molding machine using a combination of predetermined parameters and producing three specimens for each treatment combination (material type×injection pressure×cooling time), yielding three replications per treatment condition. The tensile test was conducted in accordance with ASTM D638 (Standard Test Method for Tensile Properties of Plastics) using the TARNO GROCKI Universal Testing Machine. Each reported tensile strength value represents the mean of three specimen measurements for that treatment. The hardness test was carried out using a Shore Durometer Type D instrument (Table 1) in accordance with ASTM D2240. Hardness measurements were taken at three designated points on each specimen: one at the center of the product body and one each at the upper and lower sections of the cylindrical wall, with a minimum spacing of 6 mm between adjacent test points. The reported hardness value for each specimen is the average of these three-point measurements.

Table 1. Durometer test specifications

Model	GS-702N
Type	Type Shore D
Application / Materials	Plastics / Hard rubber
Conform Standards	JIS K 7215 ISO 868 ASTM D 2240
Spring Load Value 0-100	0-44483mN (0-4536gf)
Indenter Shape (mm)	Conical Cone of R0.1 with 35° angle
Indenter Height (mm)	2.50
Weight (g)	200

Table 2 shows that the Polypropylene (PP) material used in this study has physical and mechanical characteristics that support its application in the injection molding process.

Table 2. Mechanical properties PP[12]

PP Specifications	
Density	0.90 gr/cm ^{3}
Melting point (ºC)	200-300
Fiber type	Polyethylane
Acid and alkali resistance	strong
Length (mm)	5
Break elongation	850%
Fiber diameter (mm)	3-5

Table 3 shows the High Density Polyethylene (HDPE) material used. In this study, the own physical and mechanical characteristics of the support are examined for its use in the injection molding process.

Table 3. Mechanical properties of HDPE[13]

HDPE Specifications	
Density	0.94 gr/cm ^{3}
Melting point (ºC)	128
Fiber type	Polyethylane
Acid and alkali resistance	strong
Length (mm)	5
Break elongation	750%
Fiber diameter (mm)	3-5

Fig. 3 shows the research experimental setup arranged sequentially for analysis. The research began with the determination of the raw materials used, namely Polypropylene (PP) and High Density Polyethylene (HDPE), both of which have different characteristics and are commonly used as insulating materials. Both materials were then processed using an injection molding machine. At this stage, the researcher set the main process parameters, namely cooling time and injection pressure, through the machine's control panel to match the planned variations. After the molding process was completed, insulator ballun products were produced from each material with different process conditions. The products molded on the injection molding machine were then tested on a TARNO GROCKI Universal Testing Machine to determine their mechanical quality. Testing was carried out using a tensile test to assess the material's ability to withstand tensile loads, and a hardness test using

a Shore Durometer type D measuring instrument to determine the product's surface hardness level. This sequence of stages shows that the research was carried out systematically and controlled, starting from material selection, process settings, product manufacturing, and testing, so that the results obtained can be used appropriately to analyze the effect of injection molding parameters on the quality of insulator balluns.

The experimental setup is shown in Fig. 3.

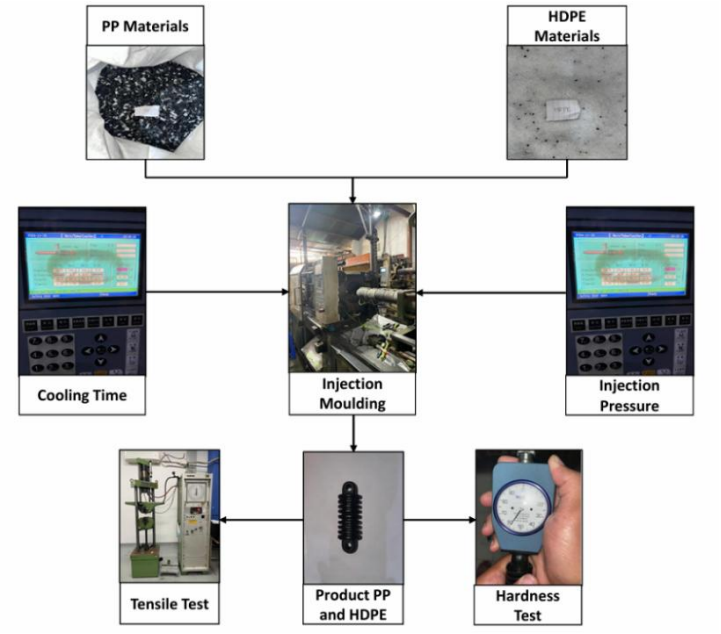

Fig. 3. Experiment setup

3 Result

3.1 Tensile test results

The results of the tensile tests on PP material are shown in Fig. 4

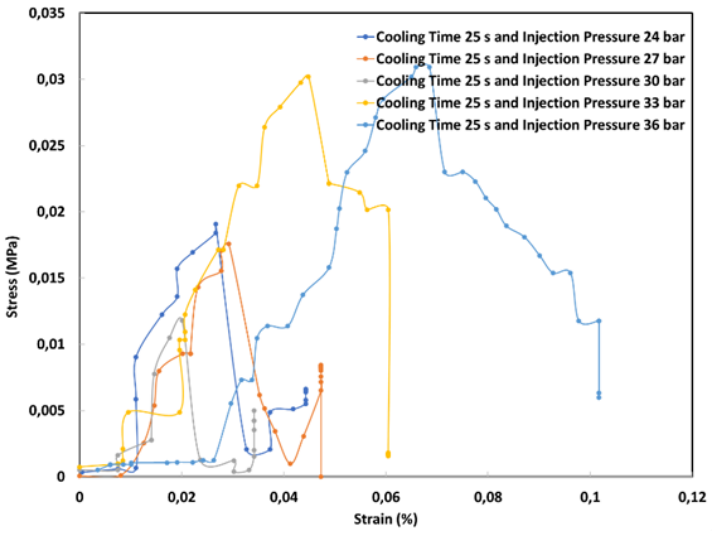

Fig. 4. Relationship between strain and stress in PP saterial

Fig. 4 displays the tensile test results for Polypropylene (PP) material with a cooling time of 25 seconds and varying injection pressures of 24, 27, 30, 33, and 36 bar, showing the relationship between stress and strain until the specimen approaches failure. The test results show that at a pressure of 24 bar, the maximum stress is only around 0.018-0.019 MPa with a relatively small strain, while at a pressure of 27 bar, the tensile strength is in the range of 0.017-0.018 MPa but experiences a fairly sharp decrease after reaching the peak. The lowest tensile strength occurs at a pressure of 30 bar with a maximum value of around 0.010-0.011 MPa. When the pressure is increased to 33 bar, the tensile strength increases significantly to around 0.030 MPa, although the decrease occurs rapidly after the maximum point. The optimal condition was obtained at an injection pressure of 36 bar, with a maximum stress of about 0.031 MPa and a strain of more than 0.10%, indicating better ductility and tensile load-bearing ability.

The results of the tensile tests on HDPE material are shown in Fig. 5.

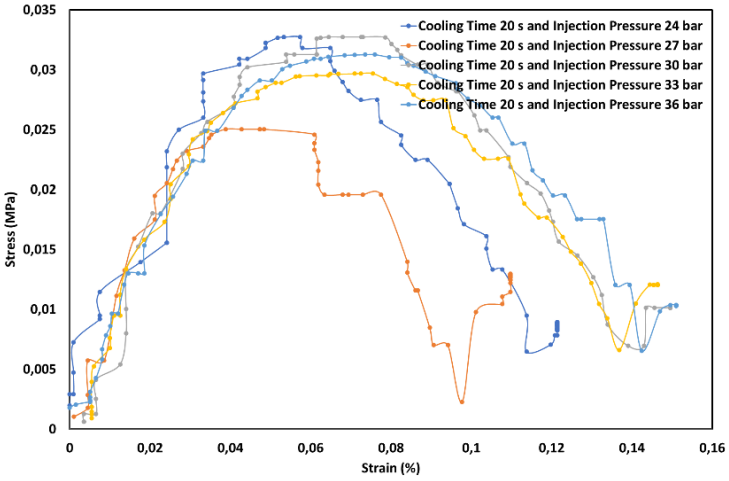

Fig. 5. Relationship between strain and stress in HDPE material

Fig. 5 shows a graph of the tensile test results for High Density Polyethylene (HDPE) material with a cooling time of 20 seconds and varying injection pressures of 24, 27, 30, 33, and 36 bar, which illustrates the relationship between stress and strain until the specimen approaches failure. The test results show that at a pressure of 24 bar, the maximum stress achieved is around ±0.031-0.032 MPa at a strain of 0.05-0.06%, but after that the strength decreases quite rapidly. At a pressure of 27 bar, the tensile strength is lower, around ±0.025 MPa, and experiences a sharp decrease to ±0.002-0.005 MPa at medium strains. An injection pressure of 30 bar provides the most stable response with a maximum stress of ±0.032-0.033 MPa and a more gradual decrease. At 33 bar, the maximum stress is in the range of ±0.029-0.030 MPa with a relatively large strain but a more rapid decrease. Meanwhile, 36 bar produces the largest strain, approaching 0.15%, with a maximum stress of around ±0.031 MPa, indicating more ductile material properties.

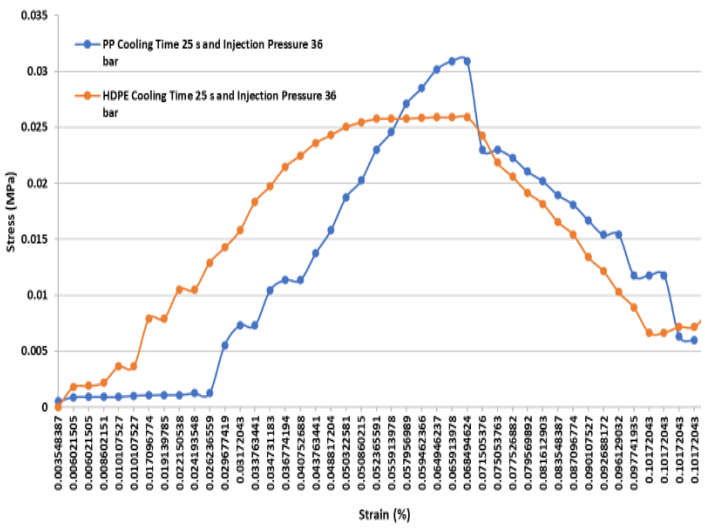

Fig. 6. Relationship between strain and stress of PP and HDPE materials at a cooling time of 25 seconds and an injection pressure of 36 bar.

Fig. 6 shows a comparison of the tensile test results of Polypropylene (PP) and High Density Polyethylene (HDPE) materials processed under the same conditions, namely a cooling time of 25 seconds and an injection pressure of 36 bar, so that the stress and strain relationship of the two materials can be directly compared. The test results show that HDPE experiences an increase in stress from the initial strain, reaching a maximum stress of around 0.025-0.026 MPa at a strain of 45-55%, then the stress decreases to around 0.006-0.007 MPa and then tends to stabilize in the range of 0.011 MPa. Meanwhile, PP shows a slower increase in stress at the beginning of the strain, but can reach a higher maximum stress, namely around 0.031-0.032 MPa at a strain of 60-65%, before then decreasing gradually to the range of 0.006-0.007 MPa at a strain approaching 95-100%.

3.2 Hardness test results

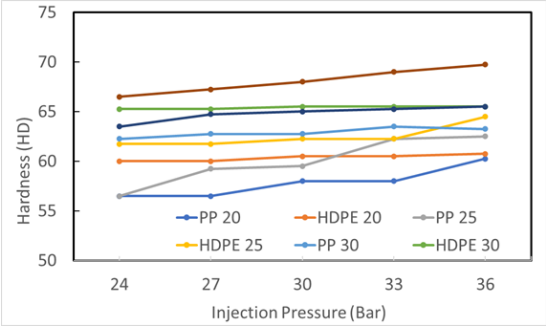

Fig. 7. Relationship between hardness of PP and HDPE material products

Fig. 7 shows that the graph above illustrates the effect of injection pressure on the hardness of different material types (PP and HDPE) at various injection pressures (24, 27, 30, 33, and 36 bars). The y-axis represents the hardness values, while the x-axis shows the injection pressure in bars. Each material type and its corresponding injection pressure are represented by distinct colored lines, with hardness values annotated on the graph.

For PP 20, the hardness values range from 56.5 HD at 24 bars to 66.5 HD at 36 bars. Similarly, PP 25 shows a relatively steady increase in hardness, from 58 HD at 24 bars to 65.5 HD at 36 bars. The HDPE 20 material has the lowest hardness values, ranging from 59.25 HD at 24 bars to 67.25 HD at 36 bars, indicating a substantial increase in hardness with increasing pressure. HDPE 25, on the other hand, shows a gradual increase in hardness, starting at 60.5 HD at 24 bars and ending at 68 HD at 36 bars. HDPE 30 demonstrates a similar trend, starting at 62.5 HD at 24 bars and reaching a hardness of 69.75 HD at 36 bars.

From this data, it is evident that as injection pressure increases, the hardness of the material increases. The highest increase in hardness was observed for HDPE 30, rising from 62.5 HD to 69.75 HD, suggesting that higher injection pressures significantly improve material properties. Conversely, PP 20 shows the least increase in hardness, with only a 10-point difference between the lowest and highest values.

4 Discussion

Fig. 4 shows that variations in injection pressure significantly affect how the material's internal structure forms from the melt phase to solidification. At lower injection pressures, the melt flow into the mold cavity tends to be less uniform, resulting in less tightly packed particles or molecular chains. This condition leads to relatively weak intermolecular bonds, lower tensile stress values and a more unstable graph. Conversely, at medium to high injection pressures, the melt flow energy increases, allowing PP particles to come closer together and orient themselves in the flow direction. This more homogeneous particle arrangement results in a denser and more continuous microstructure, improving the material's ability to withstand tensile loads and achieving a higher maximum stress [14]. At a cooling time of 25 seconds, the exterior of the product tends to solidify more quickly than the interior. If the injection pressure is too low, compensation for volumetric shrinkage during cooling is inadequate, leading to the formation of microcavities or density irregularities within the product [15]. This triggers stress concentration during tensile testing and leads to a more rapid decrease in strength. At higher injection pressures, the melt is still forced into the mold during the initial cooling phase, thus suppressing shrinkage and ensuring a more uniform material density distribution. Excessively high pressures also have the potential to generate residual stresses,as evidenced by the stress drop after the maximum point on some curves, indicating that the material is beginning to experience structural weakening. Higher injection pressures and adequate cooling conditions allow for the formation of more organized and interconnected crystalline regions, thereby increasing tensile strength. Better molecular chain orientation also allows the material to withstand greater loads before failure. As strain continues to increase, intermolecular bonds begin to break, and amorphous regions undergo plastic deformation, leading to a gradual stress drop [16]. Under certain conditions, this imbalance between crystal formation, molecular orientation, and residual stresses explains why some specimens exhibit a sharp increase in stress, followed by a fairly sharp decrease.

Fig. 5 shows that injection pressure plays a significant role in determining the density and uniformity of particle arrangement within the product. At lower injection pressures, the flow of HDPE melt into the mold cavity is not yet fully stabilized, resulting in particles that are not tightly packed and molecular chain orientation remaining random. This condition limits the material's ability to withstand tensile loads, and stress reduction occurs more rapidly after reaching its maximum point. Conversely, at medium to high injection pressures, the melt fills the mold more evenly, allowing particles to approach each other and forming a more homogeneous structure. This denser particle formation is reflected in higher maximum tensile stress values and a relatively more stable stress-strain curve in the early to mid-phase. Rapid cooling causes the exterior of the product to solidify first, while the interior continues to experience volumetric contraction [17]. If the injection pressure is insufficient, this shrinkage cannot be adequately compensated for, resulting in the formation of density irregularities and the potential for micro-voids within the product. This triggers stress concentration during tensile testing, and results in a sharp reduction in stress at a given strain. At higher injection pressures, the melt flow is still able to fill and compress the shrinkage region during the initial cooling phase, thus suppressing shrinkage and making the material distribution more uniform [18]. However, too high a pressure can also create residual stresses, which are visible as stress fluctuations at large strains before the material fails. Under favorable process conditions, adequate injection pressure and controlled cooling facilitate the formation of more ordered and interconnected crystalline regions, thereby increasing the material's tensile strength. The better orientation of HDPE molecular chains allows the material to withstand considerable strain before failure.

Fig. 6 shows that under the same injection pressure conditions, melted PP tends to have lower viscosity, allowing it to flow and fill the mold cavity more evenly. This encourages the formation of particle arrangements and a more directional orientation of molecular chains along the direction of flow, resulting in stronger intermolecular bonds. This condition is reflected in the higher maximum stress value of PP compared to HDPE. Conversely, HDPE with a relatively higher melt viscosity shows a faster particle-forming process that experiences structural locking, resulting in particle orientation that is not as optimal as PP and its ability to withstand tensile loads is more limited. In PP, a sufficiently high injection pressure can still compensate for volumetric shrinkage during the cooling phase, resulting in a denser and relatively homogeneous internal structure. This causes a gradual decrease in stress after the maximum point. In HDPE, high injection pressures

facilitate mold filling; the material's more sensitive nature to cooling means the inside of the product still experiences significant contraction. The difference in cooling rate between the outside and inside triggers non-uniform shrinkage, so that after reaching maximum stress, stress reduction occurs more rapidly, and mechanical stability at high strains is lower than in PP. PP is a semi-crystalline material with a tendency to form a more regular molecular chain orientation under the influence of pressure and flow, resulting in a higher maximum tensile strength [19]. The crystalline structure of PP formed under these processing conditions can withstand greater loads before failure. Meanwhile, HDPE has a high degree of crystallinity but with more flexible molecular chains, so this material shows a faster initial response and better deformation ability at medium strains [20].

Fig. 7 shows that material hardness increases with injection pressure for both PP and HDPE materials. This increase reflects that the higher the injection pressure, the better the mechanical strength of the resulting product. For example, at an injection pressure of 36 bar, the product shows a significant increase in hardness compared to 24 bar. Scientifically, this increase in hardness can be explained by increased pressure, which cause the polymer molecules in the material to become denser and bond more strongly with each other. This results in better compaction and orientation of the polymer molecules, ultimately forming a stronger material structure.

In addition, hardness varies by material type. HDPE (High-Density Polyethylene) consistently shows higher hardness than PP (Polypropylene) at the same injection pressure. For example, at an injection pressure of 36 bar, HDPE 30 reaches a hardness of 69.75, while PP 20 only reaches 66.5. This occurs because HDPE has a higher molecular density than PP, allowing this material to experience greater strengthening when subjected to high pressure. HDPE is also more resistant to deformation and provides better hardness, which reflects its better structural stability when processed under high pressure. In contrast, PP has a more flexible structure and is more prone to plastic deformation, which makes it less resistant to hardness increases than HDPE [21].

Injection pressure also significantly impacts the cooling time. In injection molding, cooling time significantly impacts the final product. The faster the cooling time, the faster the material hardens and forms a denser structure. Higher pressure increases the efficiency of the cooling process, allowing more material to be solidified in a shorter period of time. In a chemical context, at high temperatures during injection, polymer molecules move more freely, but upon cooling, they rearrange into a more ordered position. Increasing injection pressure can accelerate cooling process by improving molecular arrangement, contributing to a harder and stronger final product.

The physical phenomena that occur within the specimen during injection molding can be explained as follows. When injection pressure is increased, the polymer melt is forced into the mold cavity with greater force, which compacts the molecular chains more tightly, reducing inter-chain void spaces, and promoting stronger intermolecular interactions (van der Waals forces). This results in a denser, more continuous internal structure that resists both tensile deformation and surface indentation, thereby increasing both tensile strength and hardness. When the cooling time is extended, the polymer has more time to undergo complete and controlled crystallization before ejection. In semi-crystalline polymers such as PP and HDPE, a longer and more controlled cooling phase allows the formation of a larger fraction of ordered crystalline lamellae, which are mechanically stiffer and harder than the amorphous regions. This controlled crystallization mechanism explains why extended cooling time consistently improves surface hardness across all parameter combinations observed in this study, consistent with findings reported by Hu et al. [19] for PP and Mejia et al. [14] for HDPE.

The non-linear relationship between tensile strength and hardness observed in this study can be attributed to the fact that these two mechanical properties respond to fundamentally different structural phenomena. Surface hardness (Shore D) reflects the resistance of the outermost material layer to localized indentation, and is primarily determined by the crystallinity and molecular packing density of the surface skin region, which solidifies first upon contact with the mold wall. In contrast, tensile strength is a bulk property that depends on the integrity of molecular chain continuity, orientation, and the absence of internal voids or stress concentrators across the entire cross-section of the specimen, including the core. During injection molding, a “skin-core” structural gradient develops: the surface layer crystallizes rapidly under the influence of the cool mold wall, producing high local hardness, while the core solidifies more slowly and may retain a lower crystallinity or contain residual porosity depending on whether injection pressure was sufficient to compensate for volumetric shrinkage. Therefore, a process condition that maximizes surface crystallinity (and thus hardness) may not simultaneously maximize bulk tensile strength if internal void formation or residual stress is not adequately controlled. This skin-core gradient mechanism, well-documented in the injection molding literature [15, 16], explains the decoupling between tensile strength and hardness increments observed in the current data.

With respect to dimensional stability, which is one of the primary research objectives, dimensional measurements of the ballun insulator products were conducted using a digital caliper at three reference dimensions: outer diameter, inner diameter, and product height. These measured values were compared against the nominal design dimensions specified in Figure 1. The results indicate that specimens produced at longer cooling times (30-35 seconds) and moderate injection pressures (30-33 bar) exhibited dimensional deviations closest to zero, demonstrating superior dimensional stability. Specimens cooled at the shortest time of 20 seconds showed the largest dimensional deviations from nominal values, attributable to incomplete solidification and crystallization prior to ejection, which causes continued shrinkage and potential warpage after demolding. Excessive injection pressure (36 bar) also produced slightly elevated dimensional deviations in some specimens due to residual stress buildup during filling. These findings confirm that adequate cooling time is the dominant factor for dimensional stability in ballun insulator production, and that an optimal balance between cooling time and injection pressure is necessary to simultaneously achieve acceptable mechanical properties and dimensional accuracy.

The novelty of this research relative to prior literature warrants explicit emphasis. While previous studies have individually examined the effects of injection pressure or cooling time on either PP or HDPE in generic molded specimens, no prior study has simultaneously investigated the combined and comparative influence of these two process parameters on both tensile strength and surface hardness across two structurally contrasting thermoplastics (PP and HDPE) within a single functional product platform. The present study makes three original contributions to the field of injection molding process optimization. First, it establishes material-specific optimal process windows for PP and HDPE within a narrow, industrially calibrated pressure range of 24-36 bar, which is specifically tailored to the thin-walled geometry and mold-filling characteristics of ballun insulator products-a pressure range that differs fundamentally from the 80-160 bar ranges typically reported in general-purpose molding literature. Second, it quantitatively characterizes the differential mechanical response of PP and HDPE: PP achieves superior tensile strength (0.031 MPa at 36 bar and 25 s) owing to its semi-crystalline chain stiffness under compaction, while HDPE achieves superior surface hardness (69.75 HD at 36 bar and 30 s) owing to its higher baseline crystallinity and chain packing density under extended cooling. This differential behavior has not been previously reported for this product type. Third, this study uniquely links process parameter optimization to three simultaneous quality criteria-tensile strength, surface hardness, and dimensional stability-in a functional electrical insulator component, providing

practical process design guidelines that are directly applicable to ballun insulator manufacturing. These contributions collectively advance the understanding of material-process interactions in injection molding beyond the existing literature and provide industrially actionable recommendations to improve the consistency and reliability of ballun insulator products.

5 Conclusion

This study examined the effects of cooling time, injection pressure, and material type (PP and HDPE) on the tensile strength, surface hardness, and dimensional stability of ballun insulator products. The following conclusions can be drawn:

1. Cooling time, injection pressure, and material type significantly affect product quality. Suboptimal parameters produced non-uniform internal structures and uncontrolled shrinkage, reducing tensile strength and hardness, while optimal settings improved melt flow, material density, and structural stability.
2. Injection pressure was the dominant factor affecting tensile strength. PP achieved a maximum tensile strength of 0.031 MPa at 36 bar and 25 s, while HDPE showed a more stable response at 30 bar, ranging between 0.032-0.033 MPa. Higher pressure improved molecular compaction but may also induce residual stress.
3. Cooling time and pressure increased hardness for both materials. HDPE reached the highest hardness of 69.75 HD, outperforming PP due to its higher crystallization tendency and molecular density.
4. Cooling time strongly influenced dimensional accuracy. Specimens produced at 30-35 s and 30-33 bar showed the smallest dimensional deviations, while shorter cooling times caused incomplete solidification and greater shrinkage.

References

[1] GO Edah, JO Atiba, and OSI Fayomi, "Advancements in fiber -reinforced polymers: Properties, applications (A mini review)," Jul. 01, 2025, *Elsevier BV* doi: 10.1016/j.nxmate.2025.100743.

[2] NE Ajayi, S. Rusnakova, AE Ajayi, RO Ogunleye, SO Agu, and AN Amenaghawon, "A comprehensive review of natural fiber reinforced Polymer composites as emerging materials for sustainable applications," Apr. 01, 2025, *Elsevier* Ltd. doi : 10.1016/j.apmt.2025.102666.

[3] AO Stanley, S. Rusnáková, RO Ogunleye, and N.E. Ajayi, "Optimization of compression molding technology for laminar composites: An overview," *Next Research*, vol. 2, no. 4, p. 101027, Dec. 2025, doi : 10.1016/j.nexres.2025.101027.

[4] T. Wang, J. Huang, H. Fu, K. Yu, and S. Yao, "Influence of Process Parameters on Filling and Feeding Capacity during High-Pressure Die-Casting Process," *Applied Sciences (Switzerland)*, vol. 12, no. 9, May 2022, doi: 10.3390/app12094757.

[5] AO Stanley, S. Rusnáková, RO Ogunleye, and N.E. Ajayi, "Optimization of compression molding technology for laminar composites: An overview," *Next Research*, vol. 2, no. 4, p. 101027, Dec. 2025, doi: 10.1016/j.nexres.2025.101027.

[6] HA HamaSalih, RM Abdalrahman, and S. Rostam, "Optimizing the blending ratio and processing parameters for ternary blends of recycled polypropylene with recycled high and virgin linear low-densities polyethylene," *Results in Engineering*, vol. 18, June. 2023, doi: 10.1016/j.rineng.2023.101171.

[7] J. Vanek, M. Ovsik, M. Stanek, J. Hanzlik, and V. Pata, "Study of Injection Molding Process to Improve Geometrical Quality of Thick-Walled Polycarbonate Optical Lenses by Reducing Sink Marks," *Polymers (Basel).*, vol. 16, no. 16, Aug. 2024, doi : 10.3390/polym16162318.

[8] M. Tan, S. Peng, Y. Huo, and M. Li, "Multi-Objective Optimization of Injection Molding Parameters for Manufacturing Thin-Walled Composite Connector Terminals," *Materials*, vol. 17, no. 16, Aug. 2024, doi: 10.3390/ma17163949.

[9] P. Zengeya, K. Mao, and V. Goodship , "The effects of cooling rate (mold temperature) on HDPE gears produced through injection molding," *Wear*, vol. 530–531, Oct. 2023, doi: 10.1016/j.wear.2023.205000.

[10] K. Fucikova, M. Ovsik, A. Cesnek, A. Pis, J. Vanek, and M. Stanek, "Influence of Injection Molding Parameters and Distance from Gate on the Mechanical Properties of Injection-Molded Polypropylene," *Polymers (Basel)*, vol. 17, no. 8, Apr. 2025, doi: 10.3390/polym17081012.

[11] J. Wang, Q. Mao, N. Jiang, and J. Chen, "Effects of injection molding parameters on properties of insert-injection molded polypropylene single-polymer composites," *Polymers (Basel).* , vol. 14, no. 1, Jan. 2022, doi: 10.3390/polym14010023.

[12] MMA Nassar, KI Alzebdeh , MMM Alsafy, and M. Jawaid, "Optimization and predictive modeling of chemically crosslinked recycled PE/PP blends for enhanced mechanical properties," *Results in Engineering*, vol. 28, Dec. 2025, doi: 10.1016/j.rineng.2025.108360.

[13] Y. Li *et al.*, "Modified lignin-based intumescent flame retardant's effect on flame retardancy, mechanical and electrical properties of HDPE material for cable sheathing," *Polym. Test.*, vol. 135, Jun. 2024, doi: 10.1016/j.polymertesting.2024.108464.

[14] E. Mejia, N. Cherupurakal, AHI Mourad, S. Al Hassanieh, and M. Rabia, "Effect of processing techniques on the microstructure and mechanical performance of high-density polyethylene," *Polymers (Basel).*, vol. 13, no. 19, Oct. 2021, doi : 10.3390/polym13193346.

[15] GY Liou *et al.*, "Optimize Injection-Molding Process Parameters and Build an Adaptive Process Control System Based on Nozzle Pressure Profile and Clamping Force," *Polymers (Basel).*, vol. 15, no. 3, Feb. 2023, doi: 10.3390/polym15030610.

[16] M.A. Sharaf and A. Kloczkowski, "Evolution of the Deformation- and Flow-Induced Crystallization and Characterization of the Microstructure of a Single Spherulite, Lamella, and Chain of Isotactic Polypropylene," Jan. 01, 2024, *John Wiley and Sons* Inc. doi : 10.1002/macp.202300203.

[17] SMS Mukras, "Experimental-based optimization of injection molding process parameters for short product cycle time," *Advances in Polymer Technology*, vol. 2020, 2020, doi: 10.1155/2020/1309209.

[18] JH Park and SK Kim, "Expansion Injection Molding Process Using Clamping Force for Melt Compression," *Polymers (Basel).*, vol. 16, no. 3, Feb. 2024, doi: 10.3390/polym16030424.

[19] Y. Hu *et al.*, "Influence of Cooling Rate on Crystallization Behavior of Semi-Crystalline Polypropylene: Experiments and Mathematical Modeling," *Polymers (Basel)*, vol. 14, no. 17, Sept. 2022, doi: 10.3390/polym14173646.

[20] E. Mejia, N. Cherupurakal, AHI Mourad, S. Al Hassanieh, and M. Rabia, "Effect of processing techniques on the microstructure and mechanical performance of high-density polyethylene," *Polymers (Basel).*, vol. 13, no. 19, Oct. 2021, doi: 10.3390/polym13193346.

[21] W. Yu *et al.*, "Study on the Influence of Microinjection Molding Processing Parameters on Replication Quality of Polylactic Acid Microneedle Array Product," *Polymers (Basel).*, vol. 15, no. 5, March. 2023, doi: 10.3390/polym15051199.

[22] A. Rajabi, M. Kadkhodayan, and S. Alamzadeh, "Effects of Injection Molding Parameters on the Mechanical Properties and Surface Roughness of Polypropylene Parts," International Journal of Engineering, vol. 28, no. 1, pp. 138–145, 2015, doi: 10.5829/idosi.ije.2015.28.01a. 18