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The Effect of Injection Parameters on Warpage, Shrinkage, and Tensile Strength of Polypropylene Composites

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Abstract

Polypropylene composite material is an environmentally friendly material when compared to other polymer materials because the composition of polypropylene is only 76% and the remaining 24% is limestone. The use of this composite material is to reduce dependence on the use of Acrylonitrile Butadiene Styrene (ABS) and Acrylic Styrene (AS) resins because both materials are difficult to decompose and recycle. The "base" product made from this material has a warpage defect that causes a gap effect when the product is installed with other components. Therefore, a study was conducted on the effect of mold temperature and holding pressure on warpage defects, shrinkage, tensile strength and surface morphology. This study used an experimental method with variations in mold temperature used were 20°C, 40°C, and 60°C, variations in holding pressure used were 70 bar, 110 bar, and 150 bar. Testing was carried out by measuring dimensions to determine warpage, shrinkage percentage, measuring tensile strength and observing surface structure. The warpage value decreases by 29% at high mold temperatures and increases by 84% at high holding pressure. The shrinkage percentage decreases with increasing mold temperature and holding pressure in the transverse direction by 7.14%-9.52% at constant pressure and 25%-26.29% at constant temperature, in the longitudinal direction by 1.27%-6.21% at constant pressure and 13.92%-17.95% at constant temperature. The optimal parameters to obtain the highest tensile strength of 26.77 MPa are at a mold temperature of 60°C and a holding pressure of 110 bar.

Keywords : *holding pressure; composite; tensile strength; mold temperature; shringkage; warpage*

Abstract

Material komposit polypropylen adalah material yang lebih ramah lingkungan dibandingkan material polimer lain karena komposisi polypropilen hanya 76% dan 24% sisanya kalsium karbonat. Produk “base” yang dibuat dari material ini memiliki cacat warpage yang menimbulkan efek gap ketika produk terpasang dengan komponen lain. Mold temperature dan holding pressure sangat berpengaruh pada besarnya warpage yang muncul, namun belum ada penelitian yang mengarah pada kedua parameter tersebut, maka dilakukan penelitian mengenai pengaruh mold temperature dan holding pressure terhadap cacat warpage, shrinkage, dan nilai kuat tarik. Penelitian ini menggunakan metode faktorial 33 dengan variasi mold temperature yang digunakan adalah 20°C, 40°C, dan 60°C, variasi holding pressure yang digunakan adalah 70 bar, 110 bar, dan 150 bar. Pengujian dilakukan dengan pengukuran dimensi untuk mengetahui warpage, presentase penyusutan, dan pengukuran kuat tarik. Nilai warpage mengalami penurunan sebesar 29% pada temperatur cetakan tinggi dan meningkat sebesar 84% pada tekanan holding yang tinggi. Presentase penyusutan menurun seiring peningkatan mold temperature dan holding pressure pada arah transversal sebesar 7,14%-9,52% pada tekanan konstan dan 25%-26,29% pada temperatur konstan, arah longitudinal sebesar 1,27%-6,21% pada tekanan kostan dan 13,92%-17,95% pada temperatur kostan. Parameter optimal untuk mendapatkan hasil kuat tarik tertinggi sebesar 26,77 MPa adalah pada temperatur cetakan 60°C dan holding pressure 110 bar.

Kata kunci: komposit; warpage; mold temperature; holding pressure; shrinkage; kuat tarik

1. Introduction

1.1 Background

The materials used in the injection process are generally plastic pellets. Plastic pellets have various types of materials, for example ABS, PET, PETG, PP, AS, HIPS and many more. Along with the development of technology, more environmentally friendly resins have emerged , one of which is a composite material based on Polypropylene (PP) mixed with limestone/calcium carbonate ($CaCO_3$) . The addition of every 5% $CaCO_3$ filler can significantly reduce global warming, this occurs because the need for petroleum is reduced by 32% as a raw material for making polymers [1]. The use of pure PP material in practice has a weakness, namely its density is smaller than ABS so that when applied to the product it causes a less elegant impression, therefore calcium carbonate is added to increase its density. The composition of the composite material that uses a filler in the form of calcium carbonate with a percentage of 10-50% causes changes in physical properties, namely increasing the density value of the material [2]. The increased density of the composite material causes this material to have a weight similar to ABS material, so it can be used as a substitute for ABS material.

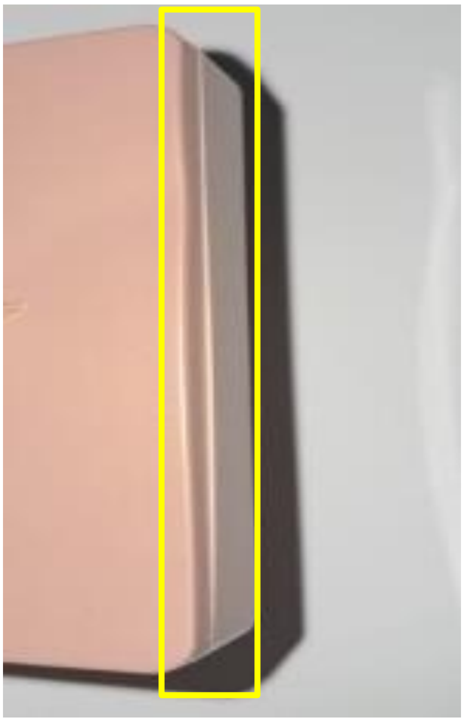


Figure 1 Gap that occurs in the product when installed with the cover

In Figure 1, a warpage defect can be seen in the base part of the eyeshadow product, which can result in a less than optimal visual appearance when the product is assembled due to gaps that appear due to the warping effect. Warping defects are generally caused by many factors, including errors in the mold shape itself, inappropriate parameter settings, and most importantly, inappropriate mold temperature [3].

In a study by Karagoz (2021) on the effect of mold temperature on mechanical properties, sample gloss testing, and warpage magnitude in high-density polyethylene, the results showed that mold temperature affects the crystallization rate, thus affecting the tensile strength of the material. Increasing mold temperature can also increase the potential for warpage and produce a glossy surface [4].

In another study, variations in holding time were determined for 5 seconds, 10 seconds, and 15 seconds, while variations for mold temperature were 30°C, 50°C, and 70°C. From this study, it was concluded that the holding time parameter had an effect on the magnitude of warpage defects by 90%, while the mold temperature parameter had an effect on warpage defects by 8%. The most optimal combination of holding time and mold temperature was obtained with a holding time of 15 seconds and a mold temperature of 50°C [5].

In a study by Agus et al. (2025), a study was conducted on warpage and sink mark defects that cause product stretching. This study varied the injection temperature from 210°C, 220°C, and 230°C, as well as variations in cooling time, namely

8 seconds, 10 seconds, and 12 seconds. Lower injection temperatures can cause an increase in defects that occur in the product, while longer cooling times can reduce defects in the product [6].

Another study also conducted a series of experiments to optimize the injection molding process parameters on biocomposite materials in the form of polypropylene, (Maleic Anhydride Polypropylene) MAPP, and rice husk. The study was conducted to find the right setting parameters to produce products with the best tensile and impact strength, the variables varied were barrel temperature, injection pressure, holding pressure, and injection velocity. The parameters that gave the greatest contribution to tensile and impact strength were the holding pressure and injection pressure parameters [7].

This theory is supported by a study that discusses the effect of injection pressure and holding pressure on the mechanical properties of thermoplastic materials molded using an injection molding system. The variables varied in this study are injection pressure and holding pressure. The tensile strength and compressive strength of the material will increase along with increasing injection pressure within a certain limit. Holding pressure also affects the mechanical properties of the material, increasing holding pressure to a higher level can cause an increase in tensile strength. Holding pressure and injection pressure have an interrelated influence on increasing the tensile strength and compressive strength of the material [8].

Based on the description above, there has been no research on the effect of mold temperature and holding pressure on warpage defects in composite materials with a polypropylene matrix with limestone/calcium carbonate ($CaCO_3$) as filler. The focus of this research is to measure the amount of warpage that will be measured at each point of the product and analyze the possible causes of the warpage, measurement of the amount of shrinkage that is directly related to the final dimensions of the product, and the tensile strength of the material.

1.2 Research purposes

This research was conducted to analyze the effect of variations in injection machine setting parameters , especially holding pressure and mold temperature parameters, on warpage , shrinkage percentage, and tensile strength values in products.

2. Materials, Tools and Methods

This research uses a quantitative method, where in this research a series of experiments will be carried out to produce products that comply with the specified dimensional specifications, including the maximum allowable gap size.

2.1. Material

The test sample material used was a composite with a polypropylene (PP) matrix. This material was mixed with 76% pure polypropylene and 24% calcium carbonate . The mixing process was carried out using an extrusion method, resulting in the two materials being fused together. The mixture is more thoroughly mixed and pelletized . The material is then processed using an injection molding method to produce a product measuring 168 x 85 mm.

2.2. Tool

The composite material is molded into a product using the injection method using an Arburg type 520C 2000-350 injection machine.

2.3. Method

The research method used is the 3^3 factorial method with variations in mold temperature parameters used being 20°C, 40°C, and 60°C, and variations in holding pressure parameters used being 70 bar, 110 bar, and 150 bar.

Table 1of injection machine setting parameters

		Holding Pressure (bar)		
		70	110	150
Mold Temperature (°C)	20	A	B	C
	40	D	E	F
	60	G	H	I

Table 1 above shows the combination of each mold temperature and holding pressure parameter, alphabetically A through I, resulting in nine parameter combinations to be tested. Each parameter setting combination is entered sequentially into the injection machine's parameter settings.

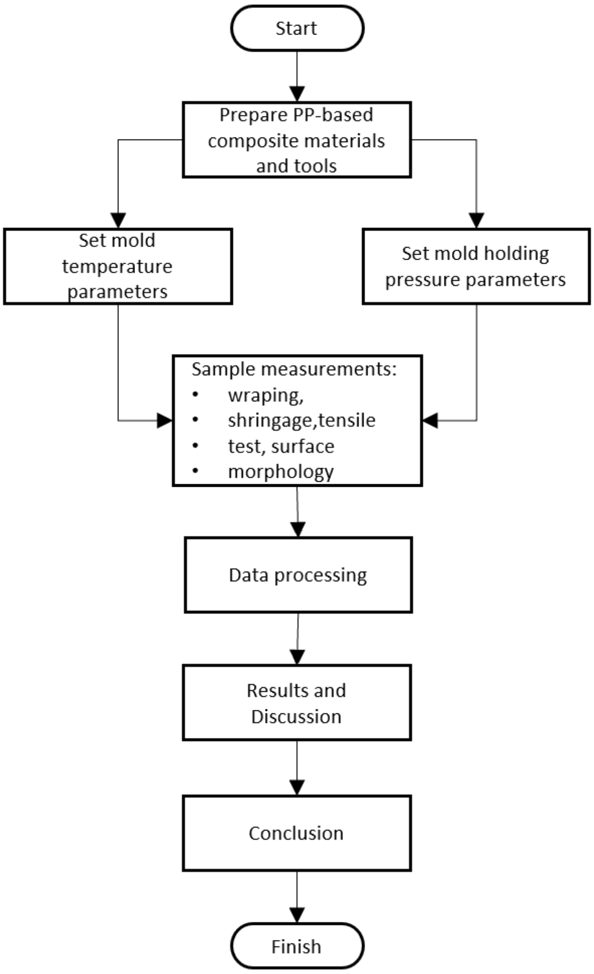


Figure 2flow chart

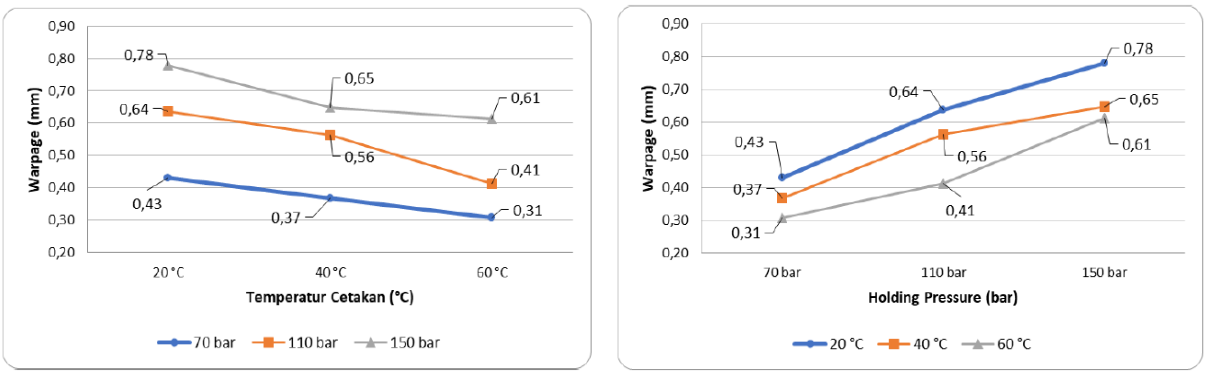
The injected product was then subjected to several tests. Warpage testing was performed using a quick vision machine.

A quick vision machine is used to detect warpage on a surface using a specific magnification scale. The product's outer contour can be duplicated into a line that depicts the curvature of the product being measured.

Figure 3. ARCS Quick Vision Visual Measurement

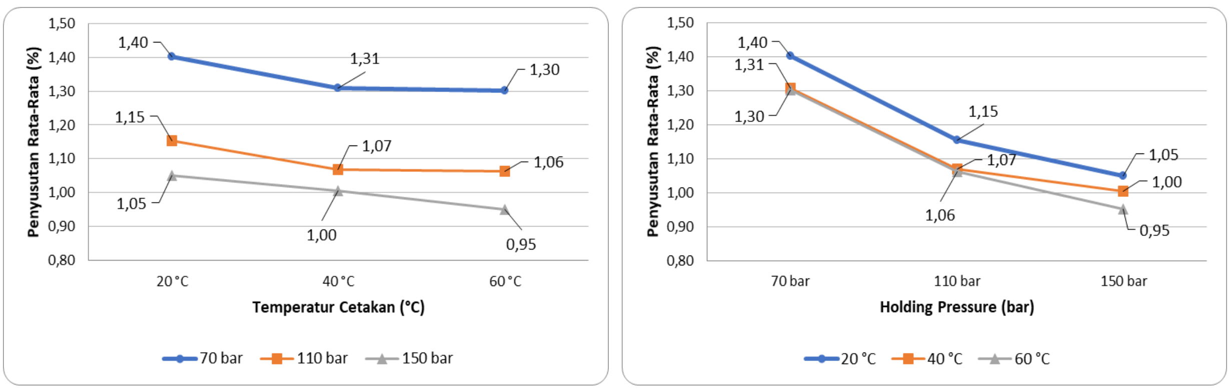
Shrinkage measurements are performed by measuring each sample using a combination of each parameter setting. Measurements are performed transversely (the shrinkage direction is perpendicular to the material flow direction) in the length dimension and longitudinally (the shrinkage direction is parallel to the material flow direction) in the width dimension. Shrinkage in the near-gate (NG) and far-gate (FG) areas is also taken into account.

Tensile strength measurements were carried out using a universal testing machine with a capacity of 20 kN using the ISO 527 testing standard.



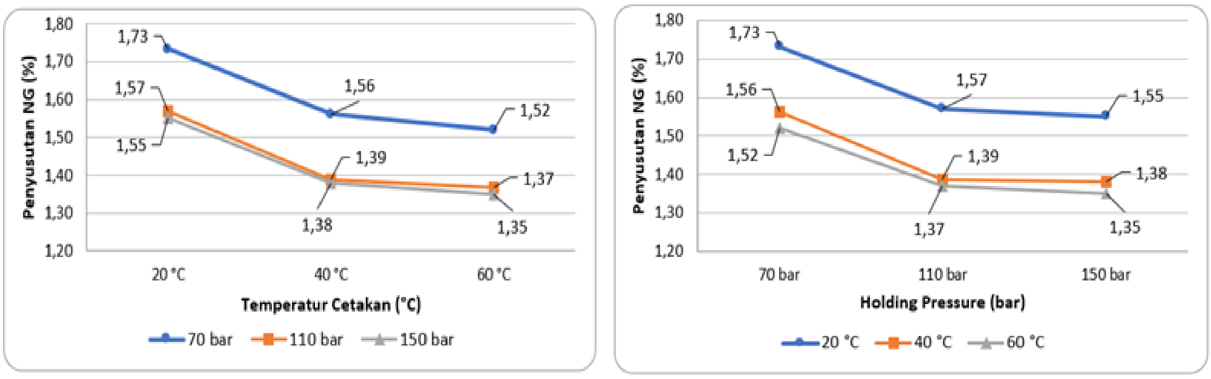
(a) **(b)**

Figure 4. Graph of the influence of parameters on *warpage*, (a) at constant *holding pressure* and (b) at constant *mold temperature.*



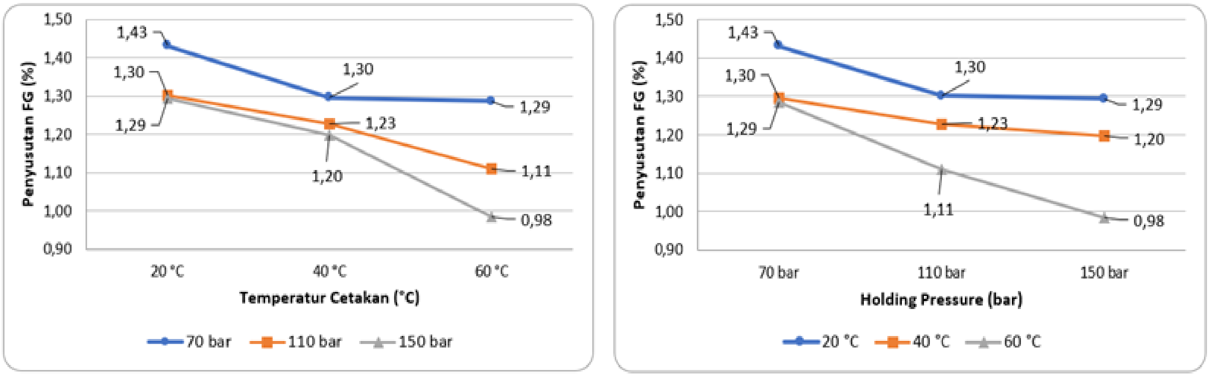
(a) **(b)**

Figure 5. Graph of the influence of parameters on the average *transverse shrinkage, (a) at constant holding pressure* and (b) at constant *mold temperature.*



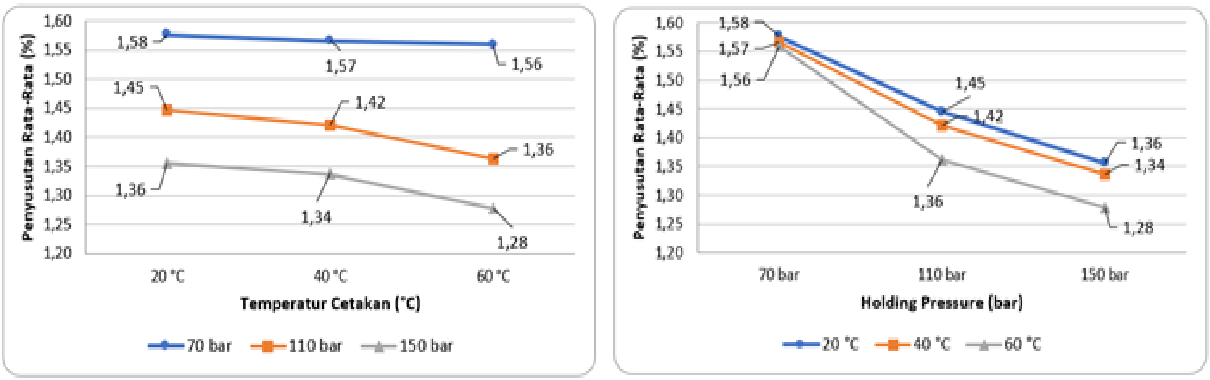
(a) **(b)**

Figure 6. Graph of the influence of parameters on *the transverse shrinkage* of the part near *the gate*, (a) at constant *holding pressure* and (b) at constant *mold temperature.*



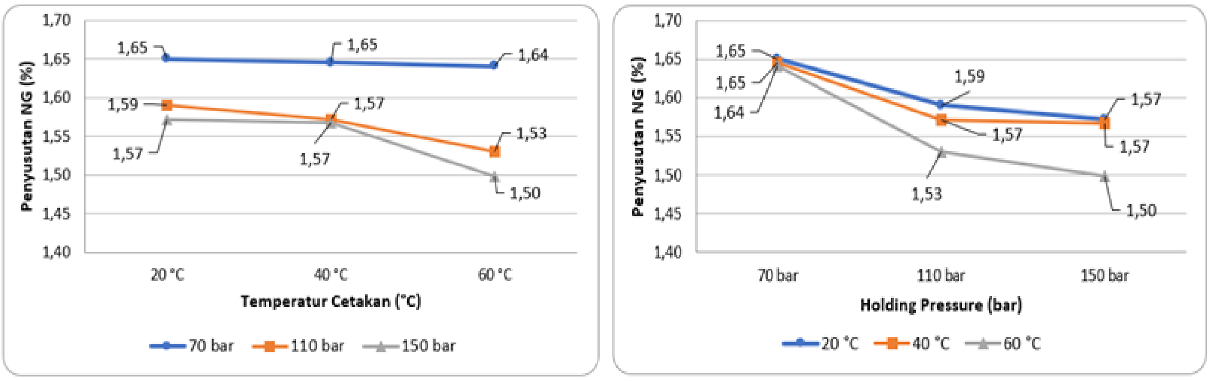
(a) **(b)**

Figure 7. Graph of the influence of parameters on *the transverse shrinkage* of the part far from *the gate*, (a) at constant *holding pressure* and (b) at constant *mold temperature.*



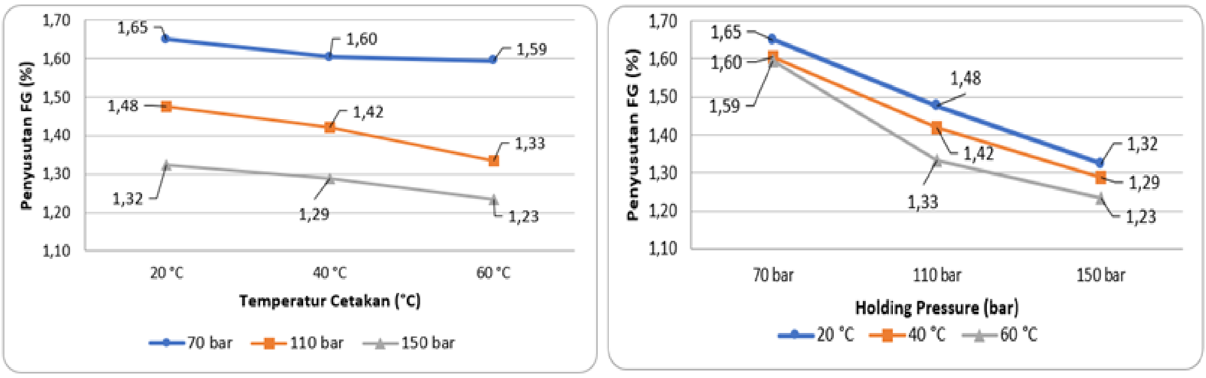
(a) **(b)**

Figure 8. Graph of the influence of parameters on the average *longitudinal shrinkage, (a) at constant holding pressure* and (b) at constant *mold temperature.*



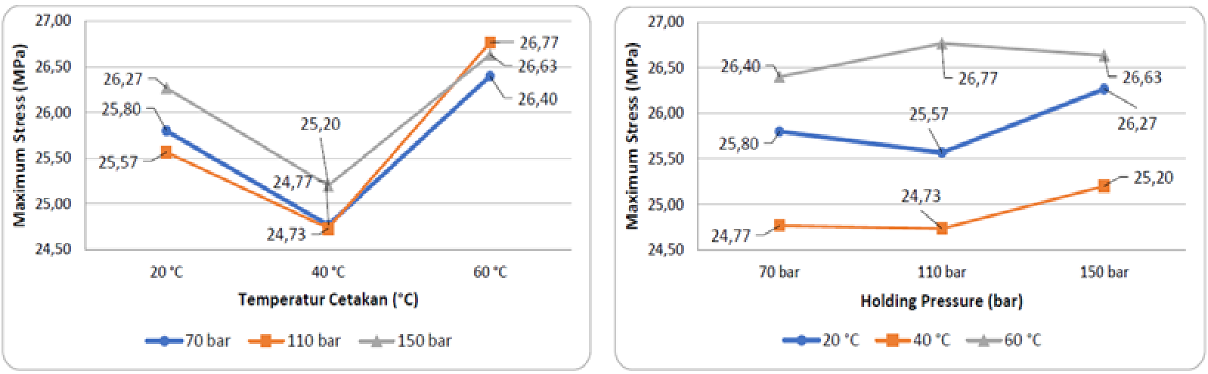
(a) **(b)**

Figure 9. Graph of the influence of parameters on *longitudinal shrinkage* near *the gate*, (a) at constant *holding pressure* and (b) at constant *mold temperature.*



(a) **(b)**

Figure 10. Graph of the influence of parameters on *the longitudinal shrinkage* of the part far from *the gate*, (a) at constant *holding pressure* and (b) at constant *mold temperature.*



(a) **(b)**

Figure 11. Graph of the influence of parameters on tensile strength values, (a) at constant *holding pressure* and (b) at constant *mold temperature.*

3. Results and Discussion

3.1. Warpage Testing

In semi-crystalline materials, high mold temperatures increase the tendency for warpage to occur because high temperatures can slow down cooling, resulting in unbalanced crystallization. However, at even higher temperatures, there is a tendency for warpage to decrease due to a reduction in the thermal gradient and residual stress values. [9]. Based on

Figure 4.a, the percentage decrease at constant pressure and accompanied by an increase in mold temperature, the percentage decrease in warpage defects is greatest at a holding pressure of 110 bar, namely a decrease of 35.94%, while the percentage decrease in warpage is smallest at a holding pressure of 150 bar, namely a decrease of only 21.79%. Speed The largest decrease in warpage defects at a mold temperature of 20°C to 60°C is found at a holding pressure of 110 bar with a speed of 0.0058 mm/°C. At a temperature of 60°C, the thermal gradient is smallest, so that more even shrinkage can occur and reduce the potential for residual stress, thereby reducing the potential for warpage. Holding pressure contributes 57.82%, indicating that holding pressure is a significant factor that influences the magnitude of warpage [10]. Figure 4.b shows experiments at a constant mold temperature and increasing holding pressure, where there is an increase in warpage defects, the smallest percentage increase of 75.68% is at a mold temperature of 40°C, while the largest increase of 96.77% is at a mold temperature of 60°C. The largest rate of increase in warpage defects at a holding pressure of 70 bar to 150 bar is at a temperature of 20°C, which is 0.0044 mm/bar. The use of $CaCO_3$-reinforced polypropylene matrix composites also influences the warpage effect. CaCO3, used as a filler in PP composites, can help reduce the polymer's thermal expansion. The addition of CaCO3 can increase stiffness, which can also help reduce deformations such as warpage.

3.2. Shrinkage Testing

Shrinkage testing is carried out in the transverse and longitudinal directions , where transverse shrinkage is shrinkage that has a direction perpendicular to the material flow, while longitudinal shrinkage is shrinkage that has a direction parallel to the material flow. Shrinkage measurements are also carried out on parts located close to the gate and parts far from the gate.

3.2.1. Transverse Shrinkage

In figure 5.a, the experimental results on increasing mold temperature with a constant holding pressure on the average shrinkage value transversely decreased. The largest percentage decrease was 9.52% at a pressure of 150 bar, while the smallest percentage decrease was 7.14% at a pressure of 70 bar. In Figure 5.b, the graph of the effect of average shrinkage on holding pressure shows the experimental results on increasing holding pressure with a constant mold temperature. The smallest percentage decrease was 23.66% at a temperature of 40°C, while the largest percentage decrease was 26.92% at a mold temperature of 60°C.

Shrinkage in the area near the gate in the transverse position can be seen in figure 6. In figure 6.a, an experiment was carried out increasing the mold temperature with constant holding pressure . The largest percentage decrease was at a holding pressure of 150 bar, which was at 12.90%, while the smallest percentage decrease was at a holding pressure of 70 bar, which was 12.14%. In Figure 6.b, with experiments at a constant mold temperature with increasing holding pressure, the shrinkage value was also relatively the same. The largest percentage decrease was at a temperature of 40°C, which was 11.54%, while the smallest percentage decrease was at a temperature of 20°C, which was 10.40%.

Shrinkage in the part far from the gate in the transverse position can be seen in Figure 7. In Figure 7.a, an experiment was conducted on increasing the mold temperature with a constant holding pressure value. The largest percentage value of shrinkage reduction was at a holding pressure of 150 bar with a percentage reduction of 24.03%, while the smallest percentage reduction was 9.79% at a holding pressure of 70 bar. In Figure 7.b, when the mold temperature was constant accompanied by an increase in holding pressure, the smallest percentage reduction was at a temperature of 40°C, which was 7.69%, while the largest percentage reduction was at a mold temperature of 60°C, which was 24.03%.

3.2.2. Longitudinal Shrinkage

The average shrinkage value in the longitudinal position can be seen in Figure 8. Figure 8.a was carried out on an experiment with an increase in mold temperature with a constant holding pressure value . The largest decrease in shrinkage occurred at a pressure of 110 bar, which was 6.21%, then the smallest decrease in shrinkage was at a pressure of 70 bar, which was 1.27%. In Figure 8.b, when the mold temperature was constant and the holding pressure increased, the largest decrease in shrinkage percentage occurred at a temperature of 60°C, which was 17.95%, while the smallest shrinkage occurred at a temperature of 20°C with a percentage of 13.92%.

Shrinkage in the area near the gate in the longitudinal position can be seen in Figure 9. In Figure 9.a, an experiment was conducted on increasing the mold temperature with a constant holding pressure value. The smallest decrease was at a pressure of 70 bar, which was 0.56% or it can be said that it almost did not change significantly, but the largest decrease in shrinkage percentage was at a pressure of 150 bar, which was 4.66%. In Figure 9.b, when the mold temperature was constant accompanied by an increase in holding pressure, it can be seen that the smallest percentage decrease was at a mold temperature of 20°C, which was 4.72%, while the largest percentage decrease was 8.66% at a mold temperature of 60°C.

Shrinkage in the part far from the gate in the longitudinal position can be seen in Figure 10. Figure 10.a was conducted an experiment on increasing mold temperature with a constant holding pressure value. The decrease that has the largest percentage value is at a pressure of 110 bar, which is 9.63%, while the smallest percentage decrease is at 3.33%, namely at a pressure of 70 bar. In Figure 10.b when the mold temperature is constant accompanied by an increase in holding pressure, it can be seen that the largest decrease in shrinkage is 22.70% at a mold temperature of 60°C, while the decrease in shrinkage with the smallest percentage is at a temperature of 40°C with a percentage of 19.71%.

High mold temperature plays an important role in reducing shrinkage that occurs during the injection process [10]. Higher mold temperatures cause the cooling that occurs in the plastic material to be more even, this can help the material solidification process to be more stable and even so that it can reduce internal stress that occurs in the material. The difference in shrinkage in the transverse and longitudinal directions is caused by factors related to the physical properties and dynamics of plastic flow during the molding process [11]. Longitudinal shrinkage occurs along the direction of material flow, when the material begins to enter the mold cavity, the material will begin to harden along its flow. At high mold temperatures, the material will flow more easily and result in more uniform shrinkage. The shape and dimensions of the mold also affect the cooling process of the molded material, the flow resistance in the transverse direction is lower than the longitudinal direction, this also contributes to smaller shrinkage that occurs in the transverse direction. The type and location of the gate can affect the orientation of the molecules and as a result will result in uneven distribution of shrinkage, a gate located in a non-optimal position can cause uneven material flow and increase shrinkage that occurs unbalanced in certain areas [12]. This occurs because the gate is located on the edge and not at the center of the mold cavity. A gate located on the edge can cause uneven flow direction, especially when using PP composite materials with calcium carbonate ($CaCO_3$) filler. This composite material with added calcium carbonate has properties that are more difficult to flow compared to pure polypropylene due to its higher viscosity. Slower flow can cause material entering the area near the gate to experience a more rapid decrease in temperature, this can cause greater shrinkage in that area.

3.3. Tensile Strength Measurement

In Figure 11.a, an experiment was conducted on increasing the mold temperature with a constant holding pressure value. The tensile strength value of the material tends to decrease at a mold temperature of 40°C for all holding pressure variation conditions, but increases again and reaches the highest tensile strength value at a mold temperature of 60°C.

The percentage decrease in the tensile strength value from a temperature of 20°C to 40°C is the largest, namely 4.06% at a pressure of 150 bar, while the smallest is 3.26% at a pressure of 110 bar. The final result at a temperature of 60°C experienced an increase, the largest percentage increase was at a pressure of 110 bar, namely 4.69%, and the smallest percentage increase was at a pressure of 150 bar, namely 1.40%. In Figure 11.b, when the mold temperature is constant and accompanied by an increase in holding pressure, the largest percentage increase in tensile strength is at a mold temperature of 20°C, namely 1.81%, while the smallest percentage increase in tensile strength is 0.88%, namely at a mold temperature of 60°C.

Giving a higher mold temperature to PP material with semi-crystalline bonds tends to increase its tensile strength value, this occurs because the cooling process occurs more slowly which provides a longer crystallization time and improves the orientation of its microscopic structure [13]. The tensile strength value of the material is closely related to the cross-linking and crystallization of the material. Cross-linking in polymers is a relationship between polymer chains where the bonding relationship will strengthen the three-dimensional structure of the polymer so that it can increase its strength, while crystallization is the ability of the polymer to form a regular crystalline structure. The crystallization rate decreases with increasing cross-linking density, this indicates that pressure and cross-linking interactions play a role in controlling the crystallization process, delays in the material in the crystallization process can result in reduced tensile strength [14]. Polymer materials with higher crystallization are usually stronger because polymer crystals will provide dimensional stability and increase tensile strength. Holding pressure is one of the main parameters that can affect the mechanical properties of the product, including tensile strength [15]. Providing high holding pressure is useful to ensure that the mold cavity is filled perfectly and denser, thereby reducing void defects and increasing the integrity of the molecular structure. The added pressure also helps to arrange the orientation of the crystal structure and filler material to be denser and more regular, thus strengthening the internal network.

4. **Conclusion**

Based on this research, the largest warpage value was 0.62 mm at a mold temperature of 20°C. As the mold temperature increased to 60°C, the warpage decreased by 29%. The influence of holding pressure also affected the warpage. The smallest warpage value was 0.37 mm at a pressure of 70 bar, which increased drastically by 84% at a pressure of 150 bar.

Shrinkage has different dimensions in the area near the gate and in the area away from the gate. The highest shrinkage occurs at a mold temperature of 20°C and a holding pressure of 70 bar, as the mold temperature and holding pressure increase. Shrinkage optimization steps are carried out by increasing the holding pressure and mold temperature until the shrinkage value decreases by 8% to 25%.

The holding pressure parameter significantly influences the increase in tensile strength. Increasing the holding pressure parameter increases the tensile strength from 25.66 MPa at 70 bar, to 25.69 MPa at 110 bar, and then reaches a peak of 26.03 MPa at 150 bar.

Increasing mold temperature and holding pressure can reduce the potential for warpage defects, reduce excessive shrinkage, and increase the material's tensile strength. Increasing mold temperature can reduce warpage defects by 29%, while high holding pressure can increase tensile strength to 26.03 MPa. Increasing mold temperature and holding pressure can optimize product yield by reducing the potential for defects, thereby preventing excessive losses for the company.

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