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Effect of Processing Parameters and Wall Thickness on the Strength of Injection Molded Products

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Abstract

Polymer materials are getting more and more attention in key industries like the automotive, aerospace, and electrical industries. A long lifetime with sustainable recycling is expected; great results are possible thanks to modern material engineering. Finding a suitable material for the purpose and the appropriate methods to test the required functionality is essential. An important mechanical loading tests is the tensile test. Although the ISO 527-1:2019 standard uses different tensile specimen geometries, none of those consider the possible thickness variations of the injection molded parts. If thickness is reduced to 1 mm, the solid layer will be dominant, which makes the properties of the tensile specimen process-dependent instead of material-dependent. In today's industry, it is crucial to examine both the material and the details of the processing technology together, given the downsizing effect.

Keywords

injection molding, tensile specimens, wall thickness, cavity pressure

1 Introduction

Finding a suitable material is essential for injection molded parts with a long lifetime. Thanks to modern material engineering, there are many materials engineers can use to suit individual needs and requirements. The design process of the plastic part starts with defining mechanical, environmental, electrical and other requirements. Some parts must keep their functionality often for 10 to 30 years. To highlight one segment, the automotive industry uses more and more high-quality plastic parts, especially in electric cars. Reducing and recovering waste is essential to maintaining a sustainable manufacturing process. Tests must be performed to confirm long-lasting functionality before the appropriate material can be selected [1, 2].

There are non-destructive and destructive tests. Several methods can be used to check the behavior of the material as a function of load, load type, temperature, impact speed, and other factors. The most common methods to check the physical properties of materials in a laboratory environment are TGA, DMA and DMTA. These provide much information about the thermal history and physical properties of the material [3]. The final properties of a plastic part are greatly affected by the production parameters. The best way to control the process is to use sensors in the mold [4, 5]. In case of injection molding, melt temperature, mold temperature, injection rate, holding time, and holding pressure significantly affect the properties of injection molded parts [6–13].

Changing the parameters results in a different physical structure of the plastic part. One of the most significant properties of injection molded parts is skin-core thickness ratio. To understand how the structure of polymer materials changes during the process, it's crucial to be familiar with the phase transitions that occur in terms of location, time, and temperature. The cross-section of the plastic part consists of different layers (from the outside):

- Solid layer: the outer layer of the plastic part that solidify immediately as the plastic touches the mold;
- Shear layer: a highly oriented layer between the solid and the core layer;
- Core layer: layer with little orientation – it cools last.

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Different papers state that the average thickness of the skin and shear layer together are roughly 150–320 microns, independently of the thickness of the part [14–16]. Some studies mention that the skin-core layer ratio could depend on the fiber content of the material because the glass fiber restricts the movement of the molecular chains.

The thickness ratio of the skin and core layers highly affects the behavior of the part. If the thickness exceeds 2 mm, the core layer is significantly larger than the skin layer. The processing parameters of injection molding can have a significant effect on the skin and shear layers and less on the core layer. The morphology of the core layer mainly depends on the cooling rate, which means that the process parameters do not affect the properties of the final part considerably if the core layer is significantly thicker than the skin layer. Injection rate, shear rate, viscosity, and melt and mold temperature have an important effect on the morphology of the polymer in the skin and shear layers [17–21]. Under a thickness of 1 mm, the skin and shear regions are dominant, so they determine the mechanical properties of the parts.

When designing a product, a lot of data is required to determine the load-bearing capacity. Tensile and bending tests are the most common tests in the industry to determine the mechanical properties of a material. The test specimen is usually produced by injection molding. The ISO 527-1:2019 standard regulates the production of tensile specimens and tensile testing [22]. The well-known injection molding specimen is the 1A type, which has a thickness of 4 mm. Studies have proved that the 1A specimen is suitable for testing the material itself because its tensile properties do not change more than 3–7% in the normal range of processing conditions [12, 13, 16].

The standard states that thickness shall be between 2 and 4 mm for the 1A specimen. However, the standard states that the smaller version of the specimen (1BA) shall have a thickness between 1 and 2 mm.

In this study, we investigated the wall thickness effect on tensile properties as a function of injection rate and melt and mold temperature using an amorphous material to avoid the effects of crystallization.

2 Experimental method and information

Instead of the commonly used type 1A specimen, I used the 1BA type, which is equivalent to 1A from concerning testing (Fig. 1). The standard states that wall thickness should be equal or bigger than 2 mm (*dimension d*) and does not say anything about its effect on the tensile results.

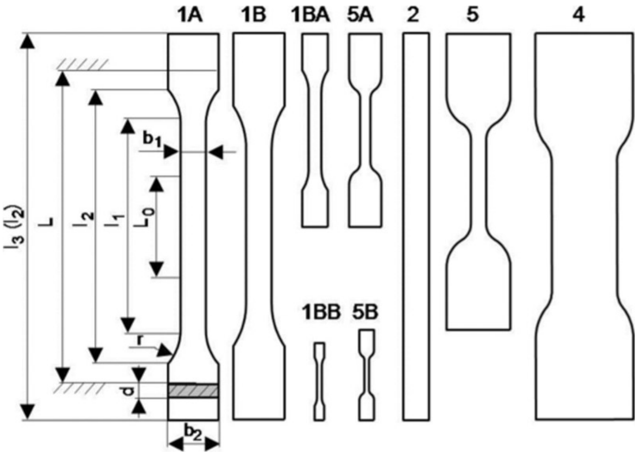

Fig. 1 Tensile specimens according to the ISO 527-1:2019 standard

According to the standard, the middle value of the process data sheet must be used for the sample production.

2.1 Material and equipment

We used ABS Terluran GP35 (BASF, Germany, Ludwigshafen) for injection molding tests. We chose an amorphous material so that crystallization kinetics and morphology do not affect the measurements. The Young's modulus of the material is 2100 MPa.

An Engel EM 170/50 TL full electric machine with a screw diameter of 25 mm was used to produce the parts. Processing parameters (dosing, barrel temperature, mold temperature) were set according to the material standard for ABS.

2.2 Mold

For the experiments, we designed a standard 1BA tensile specimen mold (Fig. 2). The thickness of the test specimens was changed (1 mm and 2 mm) with exchangeable inserts in the injection mold. The dimensions of the gate remained the 1 × 5 mm in all configurations. In order to stabilize the process, pressure sensors were placed in the cavities, in 2 positions both mold halves.

2.3 Testing method

The injection molding experiments were performed with specimen type 1BA. According to the ISO 527-1:2019 standard [22], I used two different thicknesses, 1 and 2 mm. Holding pressure was set according to the target cavity pressure peak (500 bar). The target was determined at the smallest thickness. Holding pressure was maintained until the gate froze. All the other parameters are summarized in Table 1.

The processing parameters were set to high and low values. To check the temperature, a type J thermocouple was placed on the surface of the mold and into the nozzle.

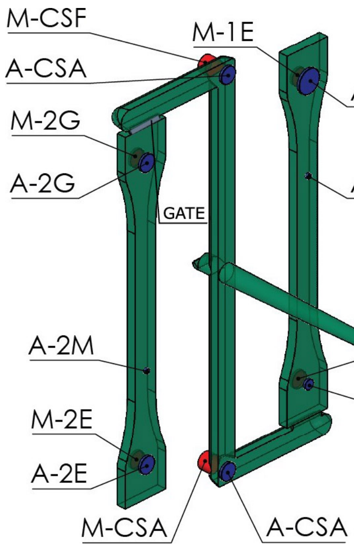

Fig. 2 Dimensions of the tensile specimen (1BA) and cavity pressure sensor locations (1F: cavity 1, gate; 1A: cavity 1, end of flow; CSF: cavity 1 runner)

Table 1 Injection molding parameters

Parameter	Low level	High level
Thickness	1 mm	2 mm
Mold temperature	50 °C	85 °C
Melt temperature	220 °C	240 °C
Injection rate	5 cm^3/s	40 cm^3/s

We measured the part's weight and observed that the weight variance remained within a 1% margin. Consequently, we deemed it unnecessary to pursue further investigation between the cavities. Tensile tests were performed at room temperature with a crosshead speed of 40 mm/s according to the standard on five samples per series. Samples from both cavities were tested previously, but no difference was detected, so only the parts from the first cavity were further investigated.

3 Results and discussion

Firstly, we analyzed the thickness dependence of Young's modulus as a function of injection rate. The switchover point was controlled by cavity pressure sensors (Cavity Eye RC15-1), and holding pressure was set to a constant value. The first goal was to confirm that the thicknesses of 1 and 2 mm are ideal for further examinations. My hypothesis is that thickness affects the tensile results significantly. Therefore, I produced specimens in a wide thickness range (0.8 mm, 1 mm, 1.5 mm and 2 mm (1BA), and 4 mm (1A) and also varied injection rate (Fig. 3).

The preliminary experiments were performed with multiple injection rates. The results confirmed that

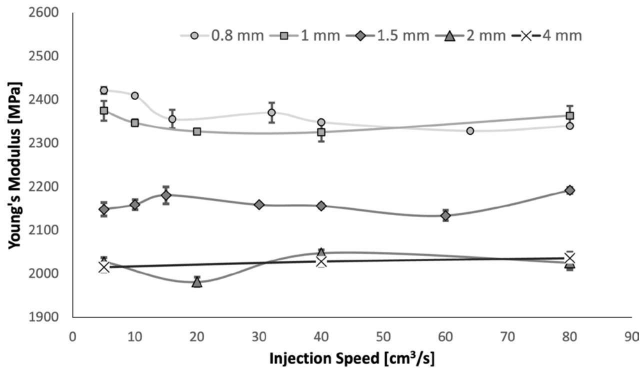

Fig. 3 Wall thickness effect for Young's modulus change as the function of injection rate

a deeper analysis should be enough with a "Low" (5 cm^3/s) and a "High" (40 cm^3/s) injection rate. According to the data of the preliminary experiment, Young's modulus does not depend much on injection rate. However, as thickness gets smaller, the effect of injection rate on Young's modulus becomes greater. The injection rate may influence the modulus by 4–7% when the specimen is 1 mm thick, but it has a hardly noticeable effect with when thickness is 2 or 4 mm. In situations where the injection rate is low and even approaches the threshold of a short shot, there is a potential for Young's modulus to demonstrate an increase of approximately 10–20%, as opposed to filling times below 1 second at the case of 1 mm thickness.

We performed an ANOVA on the measured Young's modulus data to confirm if there is a significant difference between the Young's modulus values of the specimens with different thicknesses. The results showed that at least one data group is significantly different from the others ($p = 1.75 \times 10^{-8}$).

A two-sample T-probe on the measured data showed the significant Young's modulus differences as a function of thickness. We used the results to perform the injection molding experiments with the right thicknesses (Table 2).

The T-probe confirmed with a significance level of 95% that there is no significant difference between the Young's modulus of 0.8 mm and 1 mm thick specimens, and between

Table 2 Two-sample T-probe results

Thickness [mm] / p-value [%]					
–	0.8	1	1.5	2	4
0.8	–	**11.716**	0.015	0.004	0.006
1	**11.716**	–	0.001	0.001	0.003
1.5	0.015	0.001	–	0.030	0.062
2	0.004	0.001	0.030	–	**27.850**
4	0.006	0.003	0.062	**27.850**	–

the Young's the modulus of 2 mm and 4 mm thick specimens. However, it was confirmed that there is a significant difference between the Young's moduli of 1 mm, 1.5 mm, and 2 mm thick parts (p-value is less than 5%). Based on this analysis, I chose 1 mm thickness as "Low" thickness and 2 mm thickness as "High" thickness.

Fig. 4 shows the injection speed dependence of tensile strength for the 1 mm thick part. The first series were injection molded with an injection rate of 5 cm^3/s, and the others with 40 cm^3/s. A comparison of the results shows that modulus (stiffness of the part) did not change with injection speed.

However, yield strength decreased from 53 MPa (5 cm^3/s) to 46 MPa (40 cm^3/s). Also, ultimate strain with the higher injection rate was about half of the ultimate strain with the lower injection rate. This might be the consequence of the change in the skin-core layer ratio and the orientation. With the higher injection rate, the cavity is filled in 0.12 seconds. It means that the skin layer stays thin, and the relaxation process probably takes place inside the core layer, which results in a less oriented part.

In the case of the 1A specimen (4 mm thickness), the increased injection rate means increased orientation and slightly increased yield strength. The opposite can be observed if the thickness is around 1 mm or less. The explanation is that if the part thickness increases to 4 mm the skin-core layer ratio changes so the orientation as well. As the core layer can be 80–95% of the cross-section [15], it determines the tensile properties. If the injection rate is increased, the molecules will be more oriented in the core layer, which results in slightly increased yield strength. At 1 mm wall thickness, the core layer thickness can be 30–50% [15]. This case the skin layer determines the tensile properties. At 1 mm wall thickness, the cooling rate is significantly higher than 4 mm, so the tensile properties are mainly affected by injection parameters.

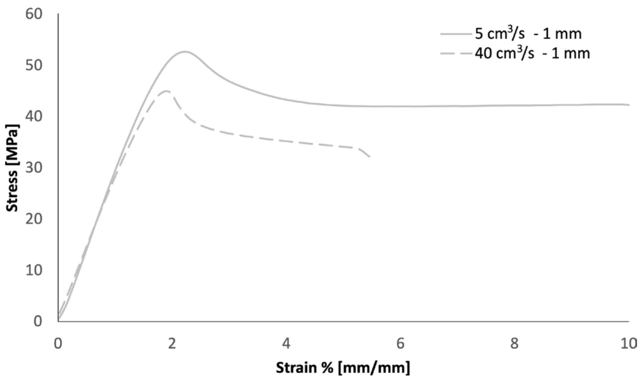

Fig. 4 Tensile strength of the 1 mm thick specimen with injection speeds of 5 cm^3/s and 40 cm^3/s

Orientation is mainly affected by the shear rate and mold and melt temperature. A high shear rate and low melt temperature increase orientation. The frozen skin layer gets thicker if the part wall thickness is thin and the cooling rate is high. As the skin layer is thicker, viscosity increases, and more force is needed to fill the cavity. Also, there is less relaxation due to the lower melt temperature. This means that if the thickness is small, cooling rate induced orientation is stronger than shear-induced orientation.

To prove this theory, we put two 1 mm thick 1BA parts into the heating chamber at 100 °C for 20 minutes to check the frozen molecular orientation. If the molecular chains are more oriented, or the oriented layer is thicker the part will shrink more (total length become shorter) because of heat. (Fig. 5). The part produced with a lower injection rate was shrank more than the part injection molded with a higher injection rate. The explanation is that if the injection rate is slower the cooling rate is higher so the more molecules froze in a well oriented state. If we do the same test with 2 mm thickness parts, the reverse phenomenon happens, means that the fast injected part shrank more.

The effect of injection rate with 2 mm thick parts is almost negligible (Fig. 6). It has no significant effect on either yield or ultimate strain. The measured differences are within the range of standard deviation.

The same injection molding process resulted in significantly different tensile test results with 1 mm and 2 mm thick parts (Fig. 7).

Fig. 5 Heat conditioned 1 mm thick, 1BA samples to check the orientation (5 cm^3/s (left), 40 cm^3/s (right))

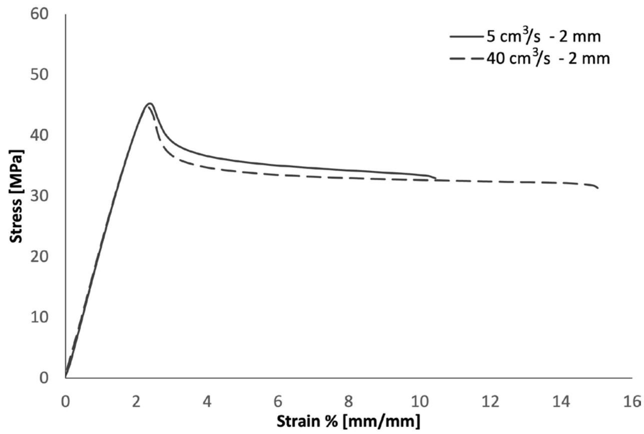

Fig. 6 Tensile curves of the 2 mm thick part produced with injection speeds of 5 cm^3/s and 40 cm^3/s

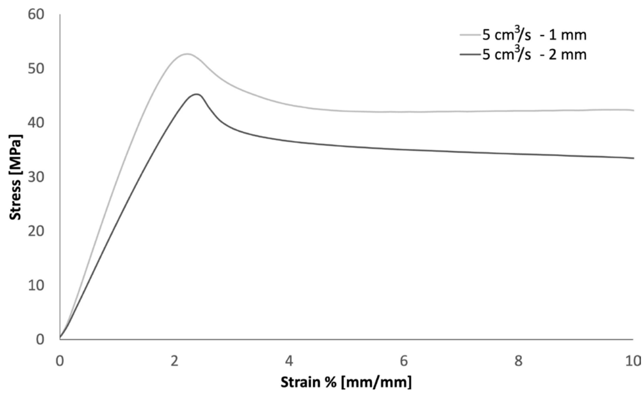

Fig. 7 Comparison of the tensile results of 50 °C and 85 °C mould temperature at 1 mm thick parts, produced with an injection rate of 5 cm^3/s

Using the same injection parameters (the same cavity pressure curve) but changing the thickness resulted in a change in Young's modulus. Also, the maximum yield decreased from 53 MPa to 45 MPa as thickness was increased from 1 mm to 2 mm, which is a 15% change. The Young's modulus of the 1 mm thick part was 2330 MPa, while that of the 2 mm thick part was only 2050 MPa. It is a 13% reduction. Tensile performance is higher when the ratio of the thickness of the skin and sheared layer to the core layer increases.

Increased melt temperature resulted in decreased yield strength with an injection rate of 5 cm^3/s and 1 mm thickness (Fig. 8). With a melt temperature of 220 °C, Young's modulus was 2397 MPa, and with a melt temperature of 240 °C, Young's modulus was 2330 MPa. It confirms the theory that if relaxation occurs in a thicker layer, orientation is lower, and tensile performance is reduced. The difference is 3%, which is more significant than the 1.5% standard deviation of the test results.

When thickness was 2 mm, melt temperature did not cause a noticeable difference in tensile results. The changes were within standard deviation. A possible explanation is that the core layer was significantly thicker than in the 1 mm thick specimen when filling time was the same.

Mold temperature slightly influenced the yield strength of 1 mm thick specimens (Fig. 9). It decreased from 53 MPa to 51 MPa as mold temperature was increased from 50 °C to 85 °C. The same effect was negligible in the case of 2 mm thick parts.

4 Summary

The tensile properties of injection molded specimens highly depend on injection molding process settings. If the thickness of a tensile specimen is changed from 2 mm to 1 mm, its Young's modulus could increase by 13% (Fig. 10). Studies have shown [15–17] that the thickness of the skin layer is around 0.2–0.3 mm, independently of wall thickness, or in this case, part thickness. It means that more than 60% of the cross-section of the 1 mm thick part is highly oriented. However, in the case of the 2 mm thick part, the highly oriented layer is around 30% of the cross-section.

The measured yield strength of the tensile specimens shown injection rate dependency. If we used 1 mm wall

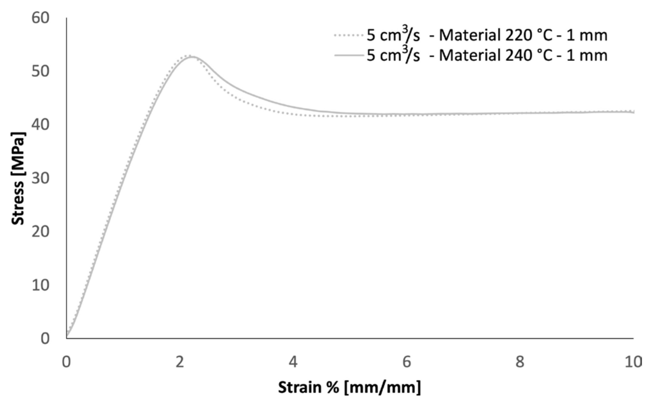

Fig. 8 Comparison of the tensile results of 1 mm and 2 mm thick parts, produced with an injection rate of 5 cm^3/s

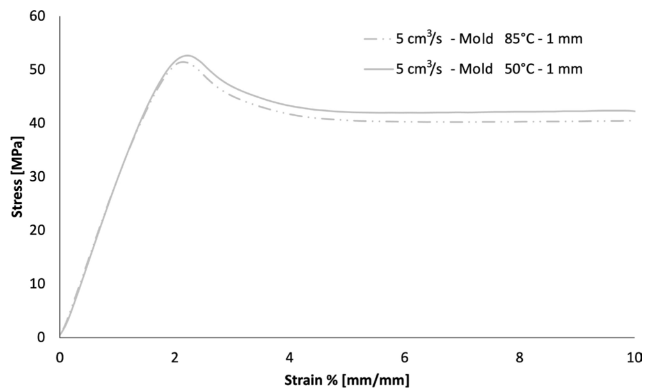

Fig. 9 Tensile curves of the 1 mm thick part produced with an injection rate of 5 cm^3/s and a melt temperature of 220 °C and 240 °C

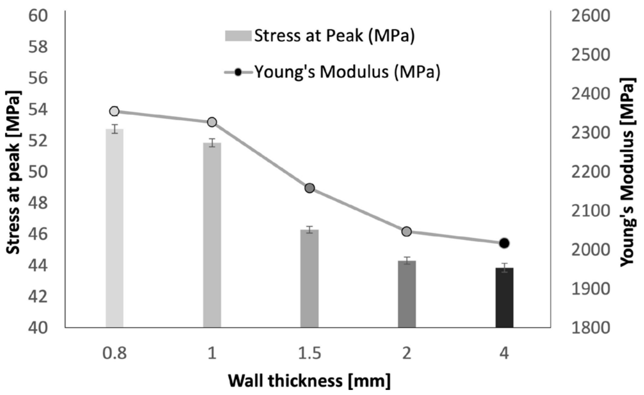

Fig. 10 Tensile results as a function of thickness (mold temperature is 50 °C, injection rate is 40 cm^3/s, and melt temperature is 240 °C)

thickness and slow injection rate the measured yield strength was 12% better than using higher injection rate. However, the effect of the speed for yield strength is negligible in the case of 2 mm specimens.

The measured ultimate strain values of the specimens are increased as injection rate decreased for the 1 mm thick part. When the part was thicker (2 mm), ultimate strain increased as injection rate increased.

Higher melt temperature led to reduced tensile performance (yield, modulus) in both 1 mm and 2 mm thick parts. In the case of 1 mm, the effect is more significant than for the 2 mm thick parts. If melt temperature is higher, more time is available for the relaxation inside the core layer. This results in less orientation and lower tensile performance.

The parts manufactured with a mold temperature of 85 °C did not have a higher modulus than those produced with a mold temperature of 50 °C, but the yield of 1 mm thick parts produced with the lower mold temperature was 4% lower. With thicker parts, the effect of mold temperature disappeared. Strain increased with mold temperature for all part thicknesses.

5 Conclusions

The tensile test is an effective and widely used method to test the mechanical properties of injection molded materials. It can provide valuable information about the strength of an injection molded part in an early stage of developing a new plastic component. The ISO 527-1:2019 [22] standard regulates the shape, dimensions, and manufacturing parameters of injection molded specimens. The tensile test aims to determine the material properties independently from the geometry of the targeted product and its manufacturing conditions.

The ISO 527-1:2019 standard [22] does not consider the effects of injection molding parameter settings to think wall products (1 mm) in the case of 1BA specimens. The recommended specimen thickness is bigger than 2 mm. If a thickness of 1 mm is used, tensile properties depend on manufacturing conditions. The Young's modulus and yield strength of a 1 mm thick tensile specimen may be 13% higher than those of a 2 mm thick specimen. If the mold and melt temperature increased the measured yield strength could decrease by 1–4% for 1 mm thick parts. At the case of 2 mm wall thickness, the effect of the mold and melt temperature for the yield strength values were neglectable with the current experiment conditions.

Injection rate, mold and melt temperature can have measurable effects on tensile properties. In general, at 1 mm thick parts, all the injection parameters show a more relevant effect for tensile properties than in the case of a 2 mm thick specimen. The explanation is that if the skin and core layers are equally thick (or the skin layer is thicker), the tensile properties of the injection molded part improve. Lower injection rate, and lower melt and mold temperature help to improve the mechanical properties of the parts.

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