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Study of the ultrasonic molding process parameters for manufacturing polypropylene parts

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Abstract

Applications of polymeric materials are becoming a huge opportunity to innovate in new manufacturing technologies. In this sense Ultrasonic Molding (USM) process is an innovative technology to produce polymeric micro parts. Here, ultrasonic energy is used for melting polymeric pellets and fill a mold cavity. This paper presents a preliminary study to analyse the influence of three process parameters of USM on filling cavity, porosity, part weight and dimension. The process parameters studied are: humidity of the pellets, sonotrode velocity and mold temperature. The results show that dried pellets, velocities lower than 7mm/s or using increasing ramps velocities provide better parts. Although in future works the effect of the ultrasonic time on filling cavity and part dimensions should be studied and more material tested to extend the knowledge to this new technology.

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Keywords: Ultrasonic molding; Micro parts; Polymeric material; Process characterization

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1. Introduction

Polymers and composites are becoming important materials in a huge variety of applications that involves micro parts, such us biomedical applications [1], microelectromechanical systems or microfluidics [2], etc. Injection molding is the commonly used technology for polymeric parts manufacturing, and, nowadays, microinjection molding machines are used to obtain the most of polymeric micro parts. However, recently, a new technology that

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uses ultrasonic energy to melt the polymeric material and produce micro parts has been developed [3]. This process is known as Ultrasonic Molding.

Ultrasounds have been used in different fields in plastic processing, such as in ultrasonic welding [4] to join plastic components, hot embossing to emboss feature or geometry on a polymer substrate [5] or to improve the cooling stage in injection molding [6]. Michaeli et al. [7, 8] produced POM and PP plastic parts using a machine that applied ultrasounds while the molten polymer were injected inside the mold. The obtained results demonstrated the viability of the use of ultrasounds in polymer processing. Sacristán et al. [9] produced PLA parts using Ultrasonic molding with satisfactory results despite polymer degradation was found under certain combination of parameters.

In ultrasonic molding process the ultrasounds are used to melt the material located in the plasticization chamber of the mold. The sonotrode moves downward into the plasticizing chamber and when it gets in contact with the material, the vibration starts at a ultrasonic frequency (30 kHz) melting the material. Finally, the sonotrode pushes this melted material into the mold cavity and generates the pressure needed to finish the parts in the quality expected. The specific process of the plasticization and molding is done in several phases. First, the material in contact with the sonotrode starts to melt and flow through the particles of material that are still in solid form. In the second phase the material is completely melted and it starts to fill the mold cavity. In the last phase, the material fills the mold cavity and the cooling stage starts. During the cooling time, the position of the sonotrode remains constant in its lowest position and produces a compaction pressure to the material. Finally, the sonotrode returns to its initial position and the mold is opened to extract the part. The extraction system consists in a plunger that moves perpendicular to the partition of the mold so that when the mold is opened, the plunger rises and push up the part to extract it.

Ultrasonic molding has several advantages. It is able to melt small amounts of material (less than 2 grs), using low pressures and producing parts just in a few seconds, which means a very short residence time compared with conventional injection molding. The needed amount of material to fill the mold cavity is just the required for the part, because the material is directly introduced inside this cavity. Consequently, the sprue volume is really reduced comparing to microinjection molding [3].

Considering the novelty of this technology this paper is focused on a preliminary study about process characterization issues. The effect of process parameters on final part characteristics is analysed. The process parameters studied are: humidity of the pellets, sonotrode velocity and mold temperature, and the part characteristics analyzed include: filling cavity, porosity, part weight and dimension.

2. Experimental setup

The Ultrasonic Molding Machine used to carry out the experimentation was a Sonorus 1G developed by ULTRASION SL (Fig. 1). A Dechel Maho 64V Linier was used for manufacturing the mold and a CNC coordinate measuring machine Mitutoyo Crysta Apex 544 was used to measure the exact mold dimensions. The porosity and part dimensions were analyzed and measured using a Nikon SMZ-745T stereomicroscope. The mold material was steel and the mold's cavity had the geometry of a standard micro tensile test specimen scaled 1:5 according to applicable regulations [ASTM D638]. The material used for the experimentation was polypropylene (PP) in pellet form.

The main process parameters to be controlled in USM are summarized in Table 1. These parameters can be directly controlled on Sonorus 1G. The quantity of material depends on the weight needed for the shoot although in this process it is translated to the number of pellets necessary for each shoot.

Table 1. Process parameters of Ultrasonic Molding.

Description	Abrev.	Description	Abrev.
Ultrasound Time (s)	UST	Amplitude of Vibration (%)	AV
Sonotrode Velocity (mm/s)	SV	Drying Pellets (no/yes)	DP
Sonotrode Position (mm)	SP	Number of Tests (u)	NT
Mold Temperature (ºC)	MT	Quantity of material (g)	Q
Cooling Time (s)	CT		

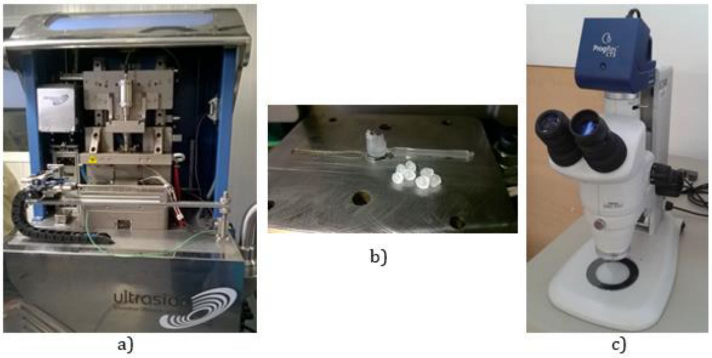


Fig. 1.Experimental setup in: a) Sonorus 1G, b) mold, part and pellets, c) Stereomicroscope Nikon SMZ-745T

3. Experimental procedure

The experimental procedure is divided in two stages: 1) having the mold at room temperature and 2) heating the molt at 35 ºC (Table 2). In the first stage a preliminary study was carried out which was divided in three phases. The aim of the first phase is to evaluate the effect of drying the pellets [DP] and the ultrasound time [UST] in order to determine the minimum ultrasound time to obtain complete parts (fill the cavity). The ultrasound time [UST] was varied from 1 to 5 seconds and the effect of drying pellets [DP] was analyzed using humid and dried pellets (Table 2). In following phases, the main objective was to analyze the effect of the sonotrode velocity [SV]. Considering the best conditions obtained from phase 1, it is using dried pellets and the minimum ultrasounds time to fill the cavity. In the second one the velocity is keep constant along the trajectory varying from 5 to 17 mm/s in each experiment. Whereas in the third one the sonotrode velocity was changed along its trajectory in two different ways: decreasing ramps and increasing ramps. Next, the results from the preliminary study were ascertained with a stage of verification in which the main experiments of the three previous phases were replicated. In each experiment, a minimum of five parts were manufactured. In the second stage, the more relevant experiments were replicated heating the mold at 35ºC. The parameter values used in the experimentation are shown in Table 2. Table 2 contains the USM parameters that were kept constant during the experimentation.

Table 2. Process parameters analysed and level factors of the experimentation.

				Parameters	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7
Stage 1	Experimentation with ambient temperature mold	Preliminary study		MT [ºC]	25						
			Phase 1	UST [s]	1	2	3	4	5		
				DP[no/yes]	no/yes	no/yes	no/yes	no/yes	no/yes		
			Phase 2	SV [mm/s]	5	7	9	11	13	15	17
			Phase 3	SV [mm/s]	6,5,3	3,5,6	10,10,8,2	4,4,6,10			
		Verification of preliminary study		DP[no/yes]	no	yes					
				SV [mm/s]	5	13					
				SV [mm/s]	10,10,8,2	4,4,6,10					
Stage 2	Experimentation with 35ºC mold			MT [ºC]	35						
				UST [s]	1	2	3	4	5		
				SV [mm/s]	5	7	9	11			
				SV [mm/s]	10,10,8,2	4,4,6,10					

Table 3. Constant process parameters of the experimentation.

Parameters		Parameters	
CT [s]	5	AV [%]	100
Q [g]	0,2997	NT [u]	5
SP [mm]	20,15,10,5,4,1		

After the experimentation, four characteristics of molded parts were analysed: filing cavity, porosity, weight and dimensions. The first analysis consists on the visual evaluation of the filling cavity. This analysis is done in every stage of the experimentation and is classified in three qualitative levels: without part, incomplete part and complete part, quantified by 0, 0.5 and 1 respectively. The second analysis consists on a qualitative evaluation of the porosity of the parts. The obtained parts were observed in the stereo microscope in three different parts: beginning, medium and end of the tensile bar. Results were classified in seven qualitative levels of porosity depending on the quantity of pores (many, few or none) and its size (large, medium or small). This study is made also in every stage of the experimentation. The third analysis is to determine the weight of the obtained parts and then compare it with the theoretical weight according to density of the material and mold dimensions measured with the coordinate measuring machine. This analysis is done from the second phase of the preliminary study of the experimentation. Finally, the last analysis realized consists on evaluating the dimensions of the obtained parts in comparison of the real dimensions of the mold cavity. This study is realized from the third phase of the preliminary experimentation.

4. Results

4.1. Stage 1: Preliminary study

The results of the first phase of the preliminary study show complete parts (represented by 1 in Fig. 2) are obtained from three seconds of ultrasound time when dried and non-dried pellets are used (Fig. 2). When the time is less than three seconds, this is one and two seconds, no parts (represented by 0) or incomplete parts (represented by 0.5) are achieved.

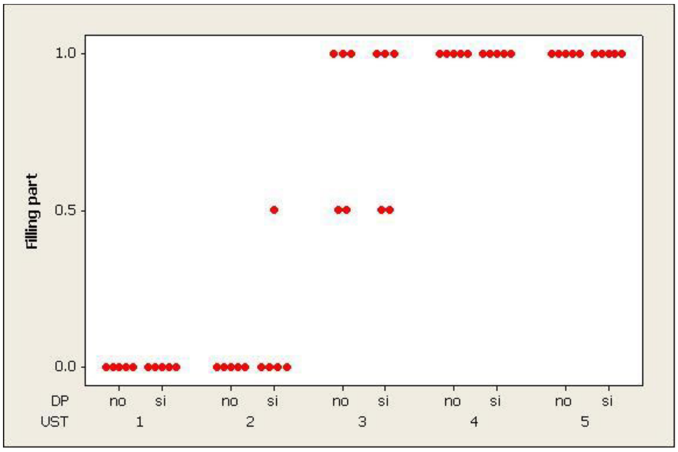
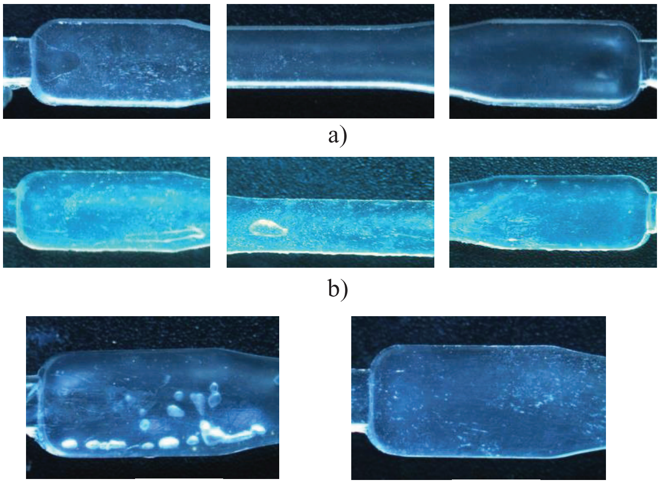


Fig. 2. Part filling for the several samples of the first phase of the preliminary study

Regarding the porosity analysis, there are fewer pores using dried pellets than with non-dried pellets in the beginning and medium part of the part (Fig. 3 (a) and (b)). It is also demonstrated that the porosity is variable throughout the part: intensified at the beginning and reduced at the end. See this variation of the porosity from the left to the right of the parts in the Fig. 3.



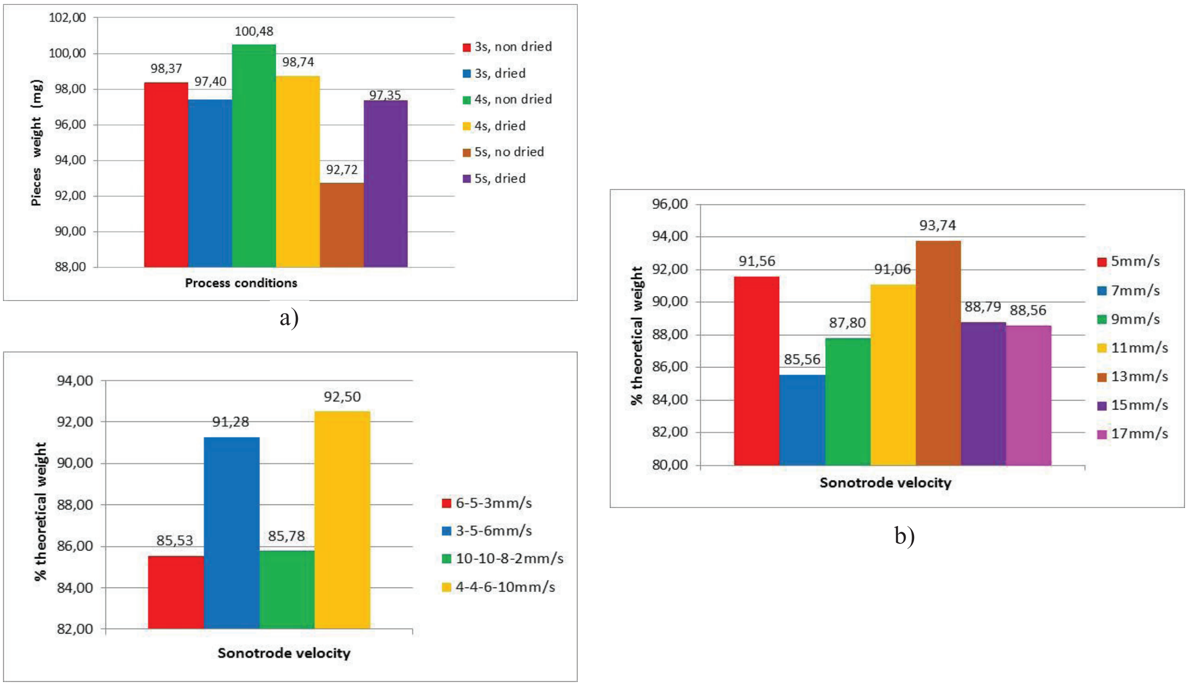
a)

b)

c) d)

Fig. 3. Porosity of a part from the preliminary study: a) dried pellets and b) wet pellets c) decreasing velocity d) increasing velocity

The study of weight determines that parts obtained using dried pellets weights less than the ones obtained with non-dried pellets for three and four seconds of ultrasound (Fig. 4a). The results were the opposite for five seconds of ultrasounds. Results obtained with one and two seconds of ultrasound time are not represented because parts were incomplete.



a)

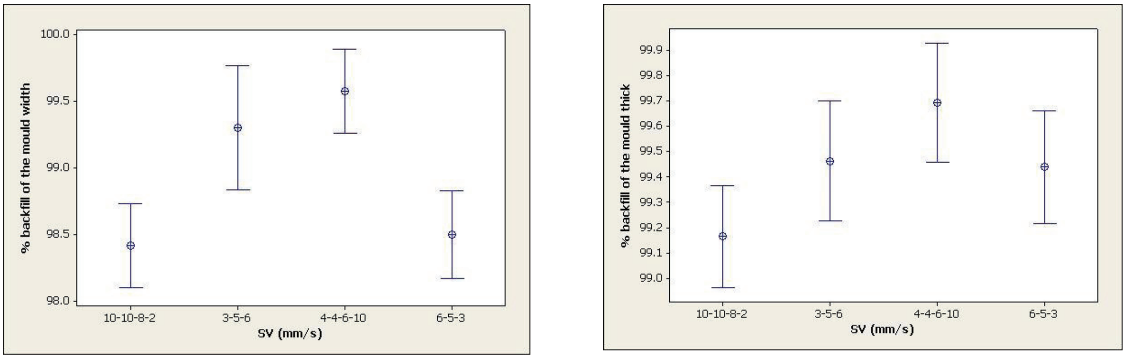
b)

c)

Fig. 4. Weight of the parts from the preliminary study a) first phase b) second phase c) third phase

The results of the second phase of the preliminary study shows that when the sonotrode velocity is lower than 7mm/s all the parts obtained are complete, between 9 and 11 mm/s the 60% are complete and with bigger than 13 mm/s less than 10 % are completed. About the porosity, the pore dimensions increase according to the velocity.In addition, for velocities from 5 to 7mm/s porosity is highly reduced at the end zone of the part in comparison to the rest of the part. For higher velocities porosity trend is not consistent. The weight of the parts does not follow any trend regarding sonotrode velocity (Fig. 4b). The velocities that provide highest percentage of part weight (>90%) are 5, 11 and 13mm/s, and the lowest percentage of weight is for 7mm/s (85.56%).

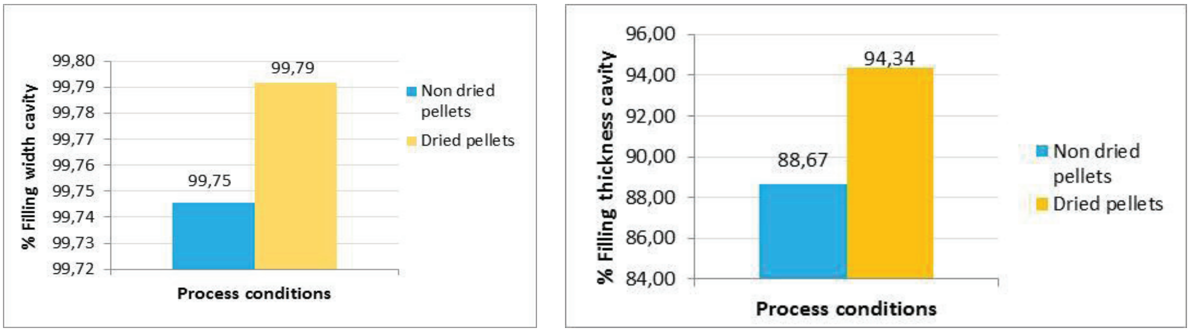
In the third phase of the preliminary study, better percentages of complete parts increasing the velocity ramp than decreasing it. In the same way the porosity and pores dimensions also improve when the ramp of velocity increases. Regarding the weight of molded parts, the average of theoretical weight is higher when increasing velocities are used (92,50% and 91,28% using increasing velocities and 85,78% and 85,53% using decreasing velocities) (Fig. 4,c). The same trend is observed in the case of width and thickness dimensions of the parts, as represented in Fig. 5.



a) b)

Fig. 5. Variance of the percentage of backfill the mold's a) width b) thick

The results of the verification of the preliminary study proved that the trends of the previous results are repeated. Firstly, complete pieces are obtained from three seconds of ultrasounds. The porosity also is reduced when using dried pellets and it is not constant along the part. There are more pores at the beginning than in the end part. Regarding the weight, the values are higher when using dried pellets. The results of the dimensions show that the differences are more evident in the case of thickness than in width as shown in Fig. 6.



a) b)

Fig. 6. Percentage of filling the mold's a) width b) thickness

For the verification of the second and third phase of the preliminary study, the percentage of complete parts obtained is higher when using lower velocities as 5 mm/s and increasing velocity ramps as 4, 4, 6, 10 mm/s. For the porosity analysis, the pores are smaller for 5 mm/s than 13 m/s at the beginning and medium part of the samples. The same occurs with the ramps of velocities: the dimensions of the pores are smaller at the beginning and medium parts when using increasing velocities, but there is no much difference at the end of the parts. The trend for the weight and dimensions is shown in Fig. 7. In both cases better results are obtained for the velocity of 5 mm/s and for the increasing velocity ramp 4-4-4-10 mm/s.

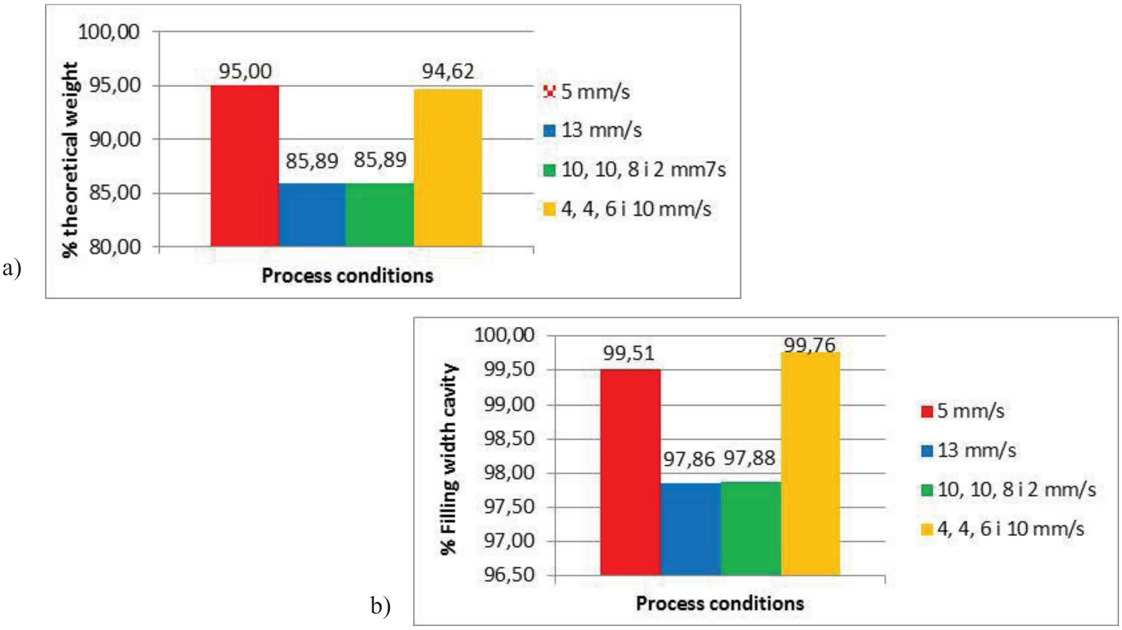


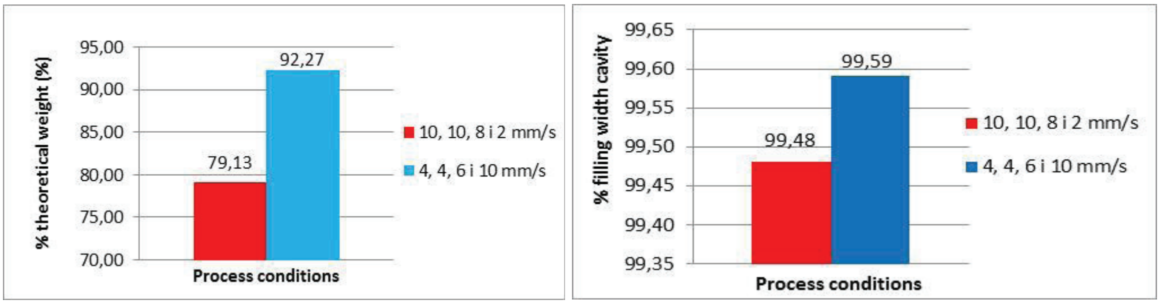
Fig. 7. Characteristics of the molded parts when increasing velocities are used a) weight b) width

4.2. Stage 2: Mold temperature 35ºC

At the last stage of the experimentation, when the mold temperature applied is 35ºC, the minimum ultrasound time to obtain complete parts is also three seconds. About the porosity, for three seconds of ultrasounds there are more small pores at the beginning than at the medium and the end of the part where pores are less intense. When four and five seconds of ultrasounds are used the dimensions of pores are bigger and it is difficult to determine a trend along the part. As the results obtained in the preliminary study, the weight of the parts is higher for three and four seconds than five and the same occurs with the dimensional analysis.

From the analyze of the effects of the constant velocity, complete parts are obtained for 5 mm/s, and the percentage of complete parts is reduced when the velocity increases from 7 to 11 mm/s. About the porosity, small and intense pores appear at the beginning and are reduced throughout the part for 5 mm/s, but for the rest of the velocities the dimensions of the pores are bigger and no trend could be drawn. The weight study shows the positive results for 5 mm/s (91,13%) and the reduction for 7 mm/s (78,32%). The differences of the dimensions are not as significant as the weight ones, almost all percentages of theoretical dimensions are higher than 95%.

Finally, when using ramps of velocity, the results show again the better percentages of complete parts obtained using increasing velocities than decreasing (90% compared to 40%). About the porosity analysis, the variety of pores is higher for decreasing velocities at the beginning and medium parts of the sample, while all the pores are smaller when increasing velocities are used. Regarding the weight study, the percentage of theoretical weight is also higher when increasing velocities are used and the same occurs with the dimensional analysis although the differences in this case are lower, as shown in Fig. 8.



a) b)

Fig 8. Characteristics of the molded parts when increasing velocities are used: a) weight b) width dimensions

5. Conclusions

The ultrasonic molding process parameters, which have relevant influence on the final piece quality, have been identified. In addition this research provides manufacturing knowledge to adjust the process parameter when new materials have to be tested. The results show that drying polypropylene pellets, the porosity decreases and the dimensional accuracy improves. It also has been observed that there is a specific time of ultrasound (three seconds) to obtain complete parts and that the percentage of complete parts can be increased by using velocities lower than 7mm/s or using increasing ramps velocities. With these conditions, which increases pressure applied during the melting process, the weight and the dimensions of the molded parts become better. Finally, it has been shown that the same trends are repeated when a temperature of 35ºC is applied to the mold.

In future works more experiments should be done to analyze the effect of the ultrasonic time on filling cavity and part dimensions assuming that increasing velocity ramps are better. More material should be tested to extend the knowledge of this technology and to create process maps, which relates part properties regarding process parameters.

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