Study of ejection forces in injection moulding of thin-walled tubular mouldings

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ABSTRACT: The development and manufacturing of ejection systems in injection moulds can be a complex task, particularly when the parts have long ejection paths. During the injection of tubular- or box shape parts, the shrinkage is constrained by the mould. The mouldings shrink against the core, inserts or pins, thus, during ejection, it will be necessary to overcome the frictional forces resulting from the shrinkage. Understanding the ejection forces could be a useful contribution to improve ejection systems designs and guarantee the structural integrity of the mouldings. This information could be even more useful in the processing of thin-walled parts which are more prone to damage during ejection. Frictional forces could be decreased by using specific coatings in the mould core and by optimization of the processing parameters. This study describes the use of DLC and WS_2 coatings and the effect of mould temperature in the ejection forces of tubular mouldings in poly(lactic acid) (PLA) and polystyrene (PS). The studies were based on tubular cup shaped mouldings (60 mm diameter, 60 mm length, 0.5 mm thickness and 0.35 º draft angle).

Keywords: Injection moulding, Thin-walled, PLA, Ejection forces, Mould coatings

1 INTRODUCTION

Recent environmental and economic concerns influenced some plastics packaging companies to implement a more environmental friendly policy. Thus they introduced new short life products made of biodegradable and renewable raw materials, such as poly(lactic acid) (PLA).

Because of its great flexibility and productivity, injection moulding is one of the most widely used technologies to produce plastics parts for the packaging industry. However, the large amount of processing parameters makes obtaining great quality parts a very complex process.

One important characteristic in injection moulding is the mould design, particularly the ejection system. An incorrect ejection system may increase the ejection forces causing deformation, marks, or even cracking of the parts (Chen & Hwang 2013; Pontes & Pouzada 2004). The ejection system has a relevant importance in the injection of parts with long ejection paths, low draft angles and in the injection of box or tubular shaped parts were the shrinkage is constrained by the mould core (Pontes & Pouzada 2004; Pontes 2002; Pouzada et al. 2006).

In the search for environmental and economic benefits one solution is the injection moulding of thin-walled parts (thickness <1mm) as it allows material savings and reduction of production time (Santos et al. 2013; Weiss 2000).

The reduction of part thickness allows bigger productivity and material savings but makes the mouldings more fragile. Part productivity can be additionally improved by the increase of ejection temperature, minimizing the cooling time. As ejection forces result from the surface interaction between the mould core and the polymer at the ejection temperature, increasing the ejection temperature could make difficult the ejection of the part as at higher temperatures the moulding have poor mechanical properties and can stick to the mould surface (Pouzada et al. 2006).

This study was undertaken to understand the behaviour and limitations of moulding materials during the ejection stage, hence providing helpful information to mould designers and part manufacturers leading them to build better ejection systems to prevent defects and breakage of the parts.

2 INJECTION MOULDING EJECTION FORCES

In injection moulding the ejection phase of a part begins after the polymer solidifies and gains rigidity to be ejected. As polymers solidify they shrink inside the mould, and in the case of box or tubular shaped parts the shrinkage is constrained by the mould. As shrinkage happens against the mould core or inserts, the ejection of a part will only happen once the frictional and adhesion forces between the polymer and the mould core are exceeded (Chen & Hwang 2012; Pontes & Pouzada 2004; Pouzada et al. 2006). Besides moulding shrinkage, the efficiency of the ejection also depends on the surface roughness, draft angles, ejection path length, the properties of the moulding material at the ejection temperatures, the partial vacuum between the moulding and the mould core and the processing conditions (Hopkinson & Dickens 1999; Pontes & Pouzada 2004; Pouzada et al. 2006).

Reducing the mould core surface roughness by high polishing techniques is the usual approach to decrease the ejection forces. This technique shows good results since the static coefficient of friction in the part/mould interface is decreased (Chen & Hwang 2012; Chen & Hwang 2013; Pouzada et al. 2006). However, as shown by Sasaki et al (Sasaki et al. 2000), with surface roughness at the manometer level there is a great increase of the ejection forces. This increment of the ejection forces is derived from the increase of the real contact area between the moulding material and the mould core, increasing the adhesion force.

The use of mould release agents can be a solution when the adhesion force increases. However, using a mould release agent into the resin may cause unstable product quality or poorer mechanical properties. The mould release agent can also be applied into the mould surface, but this only leads to a temporary solution and if not uniformly applied undesirable flow marks may appear in the moulding (Chen & Hwang 2013).

The use of mould coatings have been studied as a possibility to make a more permanent solution to reduce the friction and adhesion coefficients in the mould/part interface (Chen & Hwang 2012; Cunha et al. 2002; Dearnley 1999; Sasaki et al. 2000). Nitride coatings, such as CrN or TiN, besides reducing the ejection forces also allows better wear and corrosion resistance to the steel mould. Sasaki et al (Sasaki et al. 2000) also reported ejection forces reduction with carbon based coatings (WC/C and DLC) in the processing of PP and PET.

Shrinkage and surface finishing of a moulding are a complex function derived from the interconnection between the different processing parameters (Cunha et al. 2003; Osswald et al. 2002). Therefore, besides mould surface roughness, the ejection forces are also influenced by the injection moulding process parameters, such as injection and mould wall temperatures, injection pressure, holding phase pressure and time and obviously the polymer thermal and physical properties.

Chen et al (Chen & Hwang 2013) besides reporting a three-linear-line increase of ejection forces in continuous experiments have also reported an increase of the ejection force with the injection temperature in three TPU grades. However studies of Pontes et al (Pontes & Pouzada 2004) on the influence of the injection temperature suggest an optimum point that minimizes the ejection force. This behaviour may result from the simultaneous combination between the decreased shrinkage due to the increased pressure transmission during the holding phase, and the increased coefficient of friction due to the better filling of the grooves and undulation (Pontes & Pouzada 2004).

Pontes et al (Pontes & Pouzada 2004) also suggested that ejection forces tend to decrease with higher holding phase pressures. This effect results from the decreasing diametrical shrinkage that leads to a lower contact pressure.

The injection pressure also influences the ejection force and is usually towards the increased ejection forces with the rising injection pressure, as it was reported by Sasaki et al (Sasaki et al. 2000).

The mould wall temperature also has a significant influence on the ejection forces, generally in the sense of their decreasing with the rising temperature. Increasing part ejection temperature is responsible for this effect since there is a reduction of the elastic modulus and diametrical shrinkage at ejection, both contributing to reducing the ejection force (Pontes & Pouzada 2004).

3 EXPERIMENTAL WORK

3.1 *Raw materials*

The materials used in this study were a biodegradable thermoplastic PLA Ingeo™ 3251D from NatureWorks LLC® and a traditionally used polystyrene (PS) Edistir® N 1910 from Eni Versalis.

The PLA Ingeo™ 3251D is a semicrystalline resin with a MFI of 80 g/10min (210 °C/2.16 kg).This grade is specifically designed for injection moulding applications and its great melt flowability allows an easier moulding of thin-walled parts. PLA also provides both clear and opaque parts that require high gloss, UV resistance and stiffness. These properties make PLA suitable for rigid packaging parts such as containers and tableware.

The PS Edistir N 1910 is an amorphous polymer with MFI of 27 g/10min (200 °C/5 kg) and improved stiffness. Main applications include cups, packaging containers for food and cosmetics, toys and medical articles.

3.2 *Equipment*

This study was realized using a tubular moulding with a bottom (cup) with 60 mm diameter, 60 mm length, 0.5 mm thickness and draft angle of 0.35 º. The impression was defined by two steel inserts (core and cavity) and the moulding ejection forces were studied on both uncoated and coated inserts. The coatings used were a diamond like carbon hydrogenated and doped with tungsten (DLC) and a tungsten disulphide doped with carbon (WS_2).

Mouldings ejection was performed using an ejector ring placed at the bottom and around the core insert. The ejector ring was connected with two ejector plates by four pins and had an axial movement along the core insert length. The ejection was triggered when the machine ejection pin pushed the back ejector plate.

The ejection forces required for each moulding were recorded using a Kistler 9313AA1 piezoelectric load cell placed inside the ejector plates and in contact with the machine ejection pin.

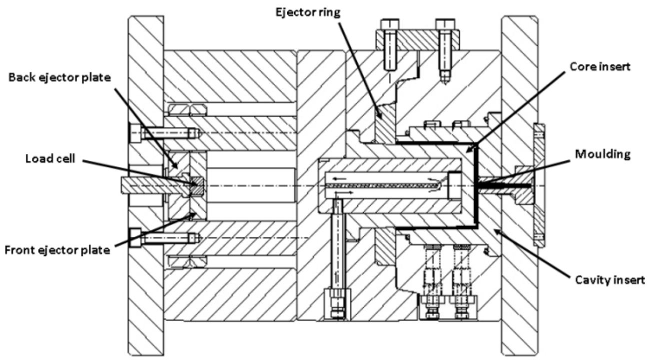

Figure 1. Experimental mould drawing view.

The mouldings were produced in an injection moulding machine (Engel Spex Victory 50) of 500 kN clamp force and a 30 mm screw diameter allowing a 220 MPa maximum injection pressure. A drying system (Motan Colortronic) were used to pre-dry the PLA pellets.

A DCC machine (Tesa micro-hite 3D) with software *PC DMIS 4.2 MR1* was used to measure de moulding diameters.

3.3 *Processing conditions and methods*

The injection conditions used for the moulding processing are established in table 1. Besides the different insert coatings the mould wall temperature was the only processing condition varied for both PLA and PS. A side study varying the holding pressure was also made, but only for the PLA.

The injection commutation between filling and holding phases was controlled by the injected material volume and it was varied with mould wall temperature increase. These injection volume adjustments were made to prevent entrapment of parts inside the mould and allow mould opening. Still all the mouldings were approximately the same volume as the injection filling control was a gradual process until reaching the minimum injection volume that allows a complete filling of the mould print.

The inner and outer diameters of the mouldings were measured 48 h after processing. The diameters were measured by taking 4 points in a DCC machine at the same reference distance (*z* vector). Diameters were recorded at different distances from the moulding bottom, as shown in Figure 2.

Table 3. Moulding processing conditions.

Cylinder temperature profile (°C)	220-210-190-160
Mould wall temperature (°C)	25 – 40 – 55
Dosage (cm^3)	15,5
Injection pressure in Nozzle (bar)	1700
Injection time (s)	2
Injection speed (cm^3/s)	98,3
Holding pressure (bar)	85
Holding time (s)	1
Back pressure (bar)	100
Cooling time (s)	5
Ejectors speed (cm/s)	10

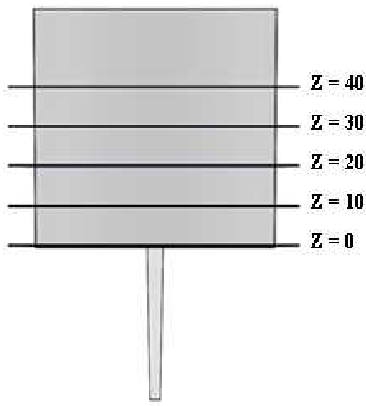

Figure 2. Diametrical measurement distances.

4 RESULTS AND DISCUSSION

The experimental ejection force data for PLA and PS, as a function of the mould wall temperature and mould coatings, are exposed in Figure 3. These results show that the core temperature has a considerable influence on the ejection force. In the case of PS the ejection force decreases with the increasing temperature, at a rate of approximately 11 N/°C. This is the expected result since there is a reduction of the moulding material elastic modulus and shrinkage caused by the increasing ejection temperature. Both this material properties have an influence in the sense of the ejection force reduction (Pontes & Pouzada 2004).

In the case of PLA there is no significant influence of the core temperature in the ejection force. However, there is a slight increase of the ejection forces at the temperature of 55 °C. This effect may happen due to the PLA lower thermomechanical properties, since its heat distortion temperature is only of about 55 °C. At this temperature PLA is less stiff and stickier, resulting in increased frictional forces and higher ejection forces.

As for the influence of insert coatings it is noticed a great decrease of the ejection force with the application of DLC and WS_2 coatings for both PLA and PS mouldings. Whereas WS_2 is the coating that allows further reduction of adhesion force resulting in a lower ejection force.

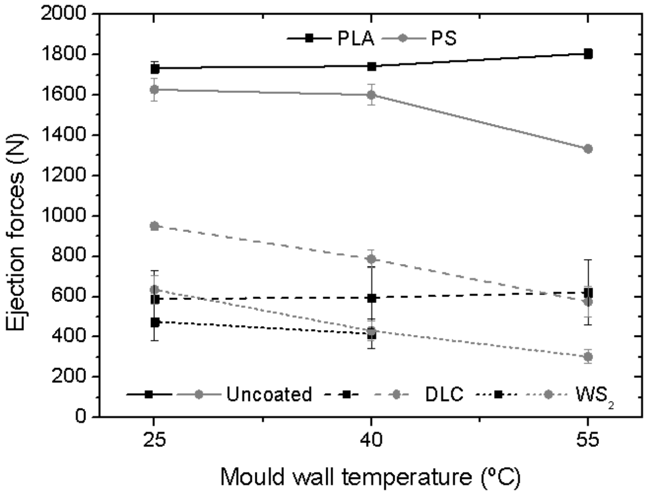

Figure 3. Ejection force for PLA and PS as a function of mould wall temperature and core coatings.

The experimental inner diameter shrinkage data for PLA and PS, depending on the distance from the bottom and the variation of the mould wall temperature are shown in Figures 4 and 5, respectively.

It was reported that mouldings of both PLA and PS have great dimensional stability since the diametrical shrinkage is less than 1 %. PLA shrinkage is between 0.15 – 0.30 % whereas PS is 0.5 – 0.6 %. PLA has lower shrinkage than PS, even being a semicrystalline material. This happens because PLA has low crystallization rate resulting in amorphous mouldings after processing, so there will be no shrinkage due to crystallization. However, slight variations on the injection conditions may also interfere with shrinkage results. This explains shrinkage differences between different mould coatings. Still it can be observed that an increased pressure drop along the distance from the bottom results in a slight shrinkage increase. The mould wall temperature effect on the shrinkage is usually in the sense of increased shrinkage with the temperature increase.

On sorting PLA shrinkage from highest to lowest it is noted that WS_2 < DLC < Uncoated. These results are consistent with the ejection forces, since greater after processing shrinkage means a minor shrinkage during ejection phase, thereby a lower ejection force.

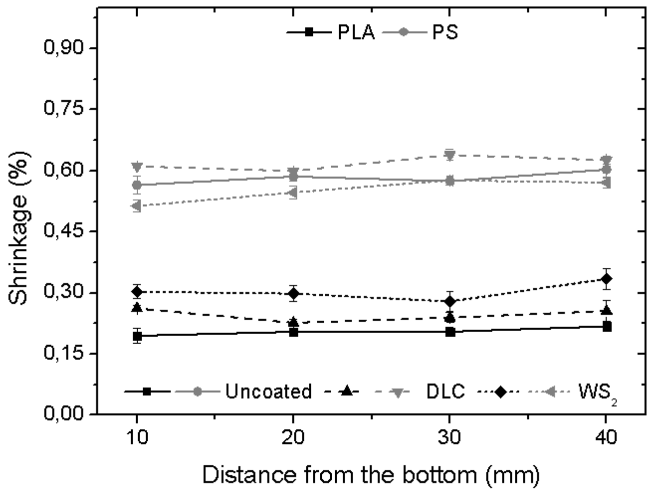

Figure 4. PLA and PS inner diameter shrinkage over the distance from the bottom. Mould at Tw 25 °C.

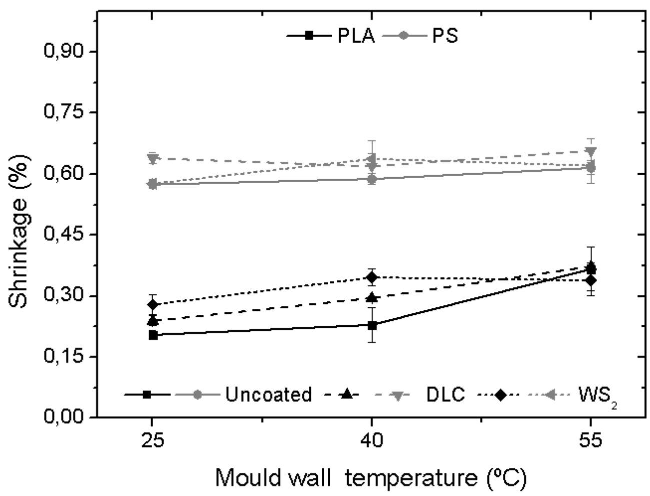

Figure 5. Influence of the mould wall temperature on the inner diameter shrinkage. Diameters at 30 mm from the bottom.

The PS shrinkage studies with WS_2 do not show consistent results since it provided both lower shrinkage and ejection forces. In this case, the main factor contributing to the decreased ejection force was the decrease of the adhesion force.

One great difficult about ejecting PLA mouldings at 55 °C is that the mouldings of almost every cycle stayed stuck in the cavity insert and it was necessary to proceed to a manual extraction, or lower the cooling fluid temperature (approx. 3 °C) to allow automatic ejection. However in the case of WS_2 core coating at 55 °C, the moulding always stayed trapped in the mould cavity and it wasn't possible to measure the ejection force at those conditions. Moulding entrapment happens because frictional forces in the WS_2 core/part interface were lower than DLC cavity/part interface, resulting in part slippage.

Also when used a mould wall temperature of approx. 55 °C it was observed very often that PLA mouldings suffer deformation along the ejection path. This occurs because at that temperature PLA is less stiffness.

Another problem noticed during these studies was that PLA mouldings had a surface roughness (similar to an orange skin). This effect was only showed up in PLA mouldings and it results from the insufficient holding pressure or time. In order to eliminate the “orange skin” more pieces were produced increasing the holding pressure until remove the defect or reach the machine limits. The ejection forces measured during this study are exposed in Figure 6.

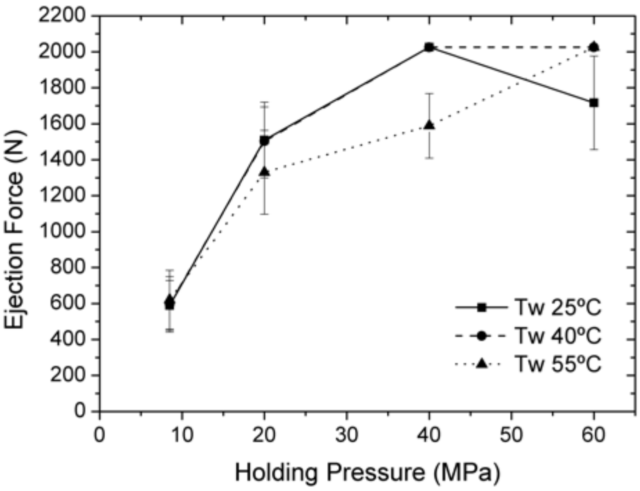

Figure 6. Influence of the holding pressure and mould wall temperature on the ejection force for PLA.

It is expected that increasing the holding pressure results in lower ejection force since there is a decrease of the diametrical shrinkage resulting in less contact pressure (Pontes & Pouzada 2004). However, in this study it was observed an ejection force increase with the rising pressure. The increased contact pressure is responsible for this behaviour, and it results from the “orange skin” removal by compressing more material inside the mould print which increases the contact area between the mould and the polymer.

The ejection force measured at Tw of 55 °C is lower than the others because the “orange skin” was not removed at the same rate with the increasing pressure. That effect may be associated with the moulding temperature being near to the PLA heat distortion temperature.

The influence of the holding pressure on the PLA inner moulding diameters shrinkage, depending on the distance from the bottom and the variation of the mould wall temperature is shown in Figures 7 and 8, respectively.

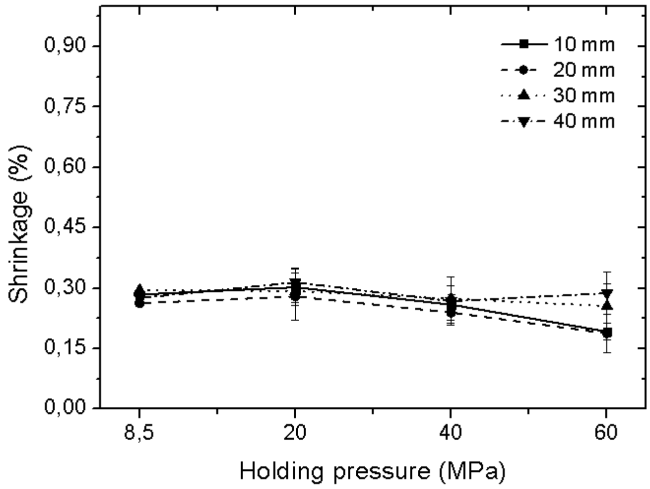

Figure 7. Influence of the holding pressure on the PLA inner diameter over the distance from bottom. Mould at Tw 40 °C.

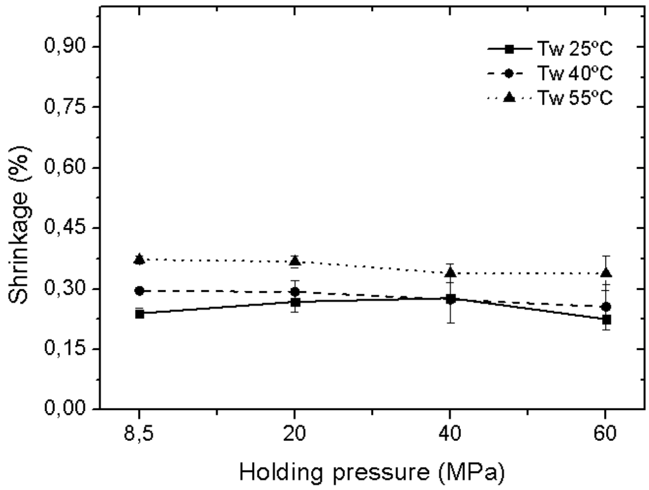

Figure 8. Influence of the holding pressure on the PLA inner diameter. Diameters at 30 mm from the bottom.

In these results it can be noted the usual shrinkage behaviour when the holding phase pressure increases. Higher pressures mean that during the holding phase more material will be compressed into the mould impression in order to prevent stress relaxation and counteract the material shrinkage.

CONCLUSIONS

Through this study it was proved the applicability of DLC and WS_2 coatings in the processing of PLA and PS thin-walled parts by injection moulding, since both coatings allow the reduction of the ejection force, preventing the breakage of the pieces. Comparing both coating results it is noticed that the friction forces are lower when using the WS_2 coating. Therefore WS_2 is the more interesting coating to apply.

The ejection force depends inversely on the mould temperature, as it was observed in PS results. This effect results from the decreasing elastic modulus and shrinkage of the polymer with the increasing temperature.

In thin-walled parts the ejection force reduction rate with the increasing mould temperature is lower than in conventional injection moulding. In this study it was observed a decrease of 11 N/°C for PS, while Pontes et al (Pontes & Pouzada 2004) recorded a 60 N/°C decrease.

The part shrinkage has an inverse influence on the ejection force, since greater shrinkage of the parts after processing means a smaller shrinkage during the ejection phase.

It is not advisable the processing of PLA at mould temperature of 55 °C or higher, since at that temperature PLA parts are less stiff and stickier. The processing of PLA at this temperature results in many difficulties, such as entrapment of parts in the cavity insert, increase of ejection force and deformation of the parts during ejection.

PLA mouldings require a higher holding pressure in order to prevent the "orange skin" surface defect. With mould wall temperature of 55 °C this defect cannot be removed or it requires even bigger pressures that may not be achievable by the injection moulding machine.

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