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3D Simulation of Shrinkage Behaviour of Injection-Molded Poly(lactic acid): Effect of Processing Parameters and Part Thickness†

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The effects of injection molding processing conditions and part thickness on the shrinkage of injection-molded poly(lactic acid) were analyzed using the Autodesk Moldflow package. It was found that the shrinkage of poly(lactic acid) increases with increasing melt temperature and injection pressure, while the change of other processing parameters (*e.g.*, mold temperature, holding time and cooling time, *etc.*) exerted limited influence on the shrinkage behaviour of poly(lactic acid). In addition, the shrinkage of thin-walled products was larger than that of thick-walled ones.

Keywords: Poly(lactic acid), 3D simulation, Injection molding, Shrinkage.

INTRODUCTION

Poly(lactic acid) (PLA), a bio-degradable polymer with both high strength and modulus, has recently found wide application in packaging, construction, medical, *etc.*[1,2]. However, its poor dimensional stability, brittleness and relatively high cost considerably restrict its further application. As is known, the shrinkage of injection-molded products will heavily affect the dimensional accuracy.

Recently, *Moldflow* package has proved to be a useful tool to study the effect of processing conditions on the shrinkage of injection-molded (IM) polymers. Jansen *et al.*[3], reported that the main factor affected processing parameters were the filling pressure and the melt temperature. Mamat *et al.*[4], argued that higher mold temperature resulted in increased shrinkage. Other processing variables (*e.g.*, injection pressure, injection velocity and cooling time) will also affect the shrinkage of polymers (especially, the crystalline polymers, such as, PE, iPP, PA, *etc.*)[5]. So far, the investigation on PLA shrinkage was basically concentrated on the film industry[6,7] and scarce work has been reported on the injection-molded products of PLA. In view to this, we investigated the effects of injection-molding parameters and part thickness on the PLA shrinkage during injection molding process.

EXPERIMENTAL

The materials used in this study were Model: 7032D and 7000D from the Cargill Dow LLC, which were denoted as PLA1 and PLA2, respectively. Table-1 presents the fundamental materials properties of both resins. The dimensions of injection mold cavity were 1 mm × 10 mm × 150 mm and 4 mm × 10 mm × 150 mm, respectively. The PLA specimens were injection-molded under various conditions as listed in Table-2.

TABLE-1
PHYSICAL PROPERTIES OF PLA 7032D AND PLA 7000D

Materials	MFR (g/10 min) [210 ºC/2 kg]	Density (g/cm^3)	Elasticity modulus (MPa)	Shear modulus (MPa)
7032D	8	1.252	2700	978
7000D	7	1.405	3450	1220

RESULTS AND DISCUSSION

Fig. 1 shows the effects of different processing parameters on the shrinkage behaviour of PLA1 at the gate end, middle and far end positions for different thicknesses. Fig. 1a-f showed the mold cavity with 1 mm thickness. With increasing melt temperature, the volume shrinkage displayed an increase; while

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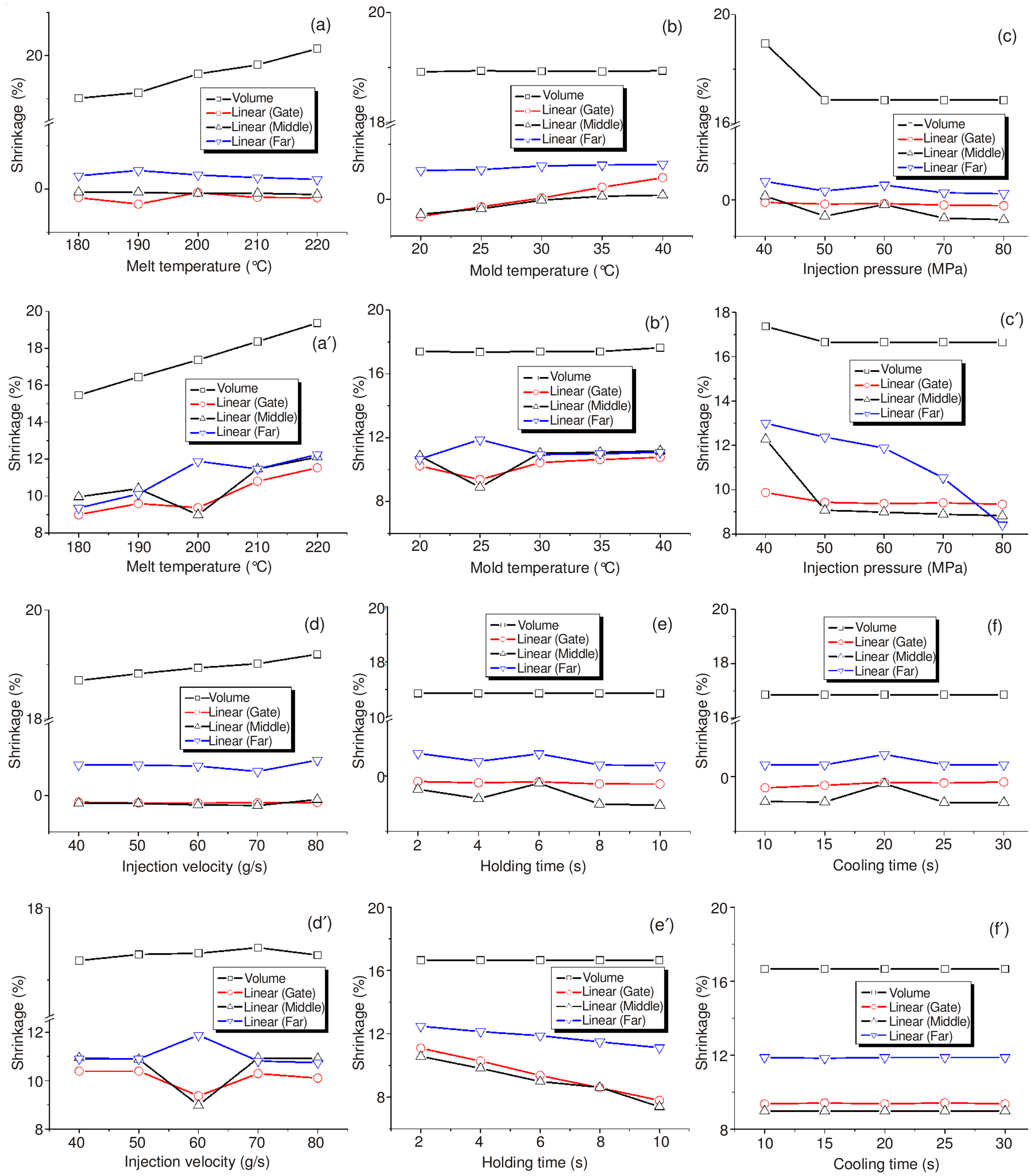

Fig. 1. Effect of operational variables on the shrinkage of PLA1. Thickness of cavity: (a-f) 1 mm, (a'-f') 4 mm

TABLE-2
PROCESSING PARAMETERS USED IN THE INJECTION-MOLDINGS OF POLY(LACTIC ACIDS)

Injection conditions	Parameter values				
Melt temperature (°C)	180	190	200	210	220
Mold temperature (°C)	20	25	30	35	40
Injection pressure (MPa)	40	50	60	70	80
Injection velocity (g/s)	40	50	60	70	80
Holding time (s)	20	4	6	8	10
Cooling time (s)	10	15	20	25	30

the linear shrinkage value was relatively kept constant. It can be explained that the higher melt temperature tends to induce greater thermal constriction, higher degree of orientation as well as higher crystallinity.

Fig. 1b indicates that the shrinkage of 1 mm cavity only shows a slight increase within the range from 20-40 °C with increasing mold temperature, which is mainly caused by higher crystallinity with increasing mold temperature[4]. As injection velocity increases, the volume shrinkage shows an obvious increase; while the linear shrinkage only shows a relatively slight increase (*cf.* Fig. 1d). With increasing injection velocity, the local shearing field is intensified and the melt temperature is also elevated, namely, the ability of macromolecular movement increases, leading to the increased shrinkage[5,7]. Structurally, the crystallization and orientation become stronger as the injection velocity increases. The shrinkage of injection-molded part shows an increasing trend. As the cooling time increases, both volume and linear shrinkage almost remain constant (Fig. 1f), which is because the crystallization rate of PLA is too fast and the polymer melt will reach a high crystallinity during an initial 10 s (including melt injection and packing stages).

The effect of processing parameters on the shrinkage of 4mm cavity is presented in Fig. 1a'-f'. As compared with Fig. 1a-f, the volume shrinkage of 4 mm cavity was generally lower than that of the 1 mm one, while the linear shrinkage was larger. The reason can be explained by the flow resistance of the 1 mm cavity was larger than the 4 mm one and a larger temperature drop would thus be expected. Comparing Fig. 1c' and 1d' with Fig. 1c and 1d, the volume shrinkage change of 4 mm cavity is larger than that of 1 mm one with increasing injection pressure and velocity. The variation of volume shrinkage of both 4 mm and 1 mm cavities is similar to the holding time increases (Fig. 1e' and 1e).

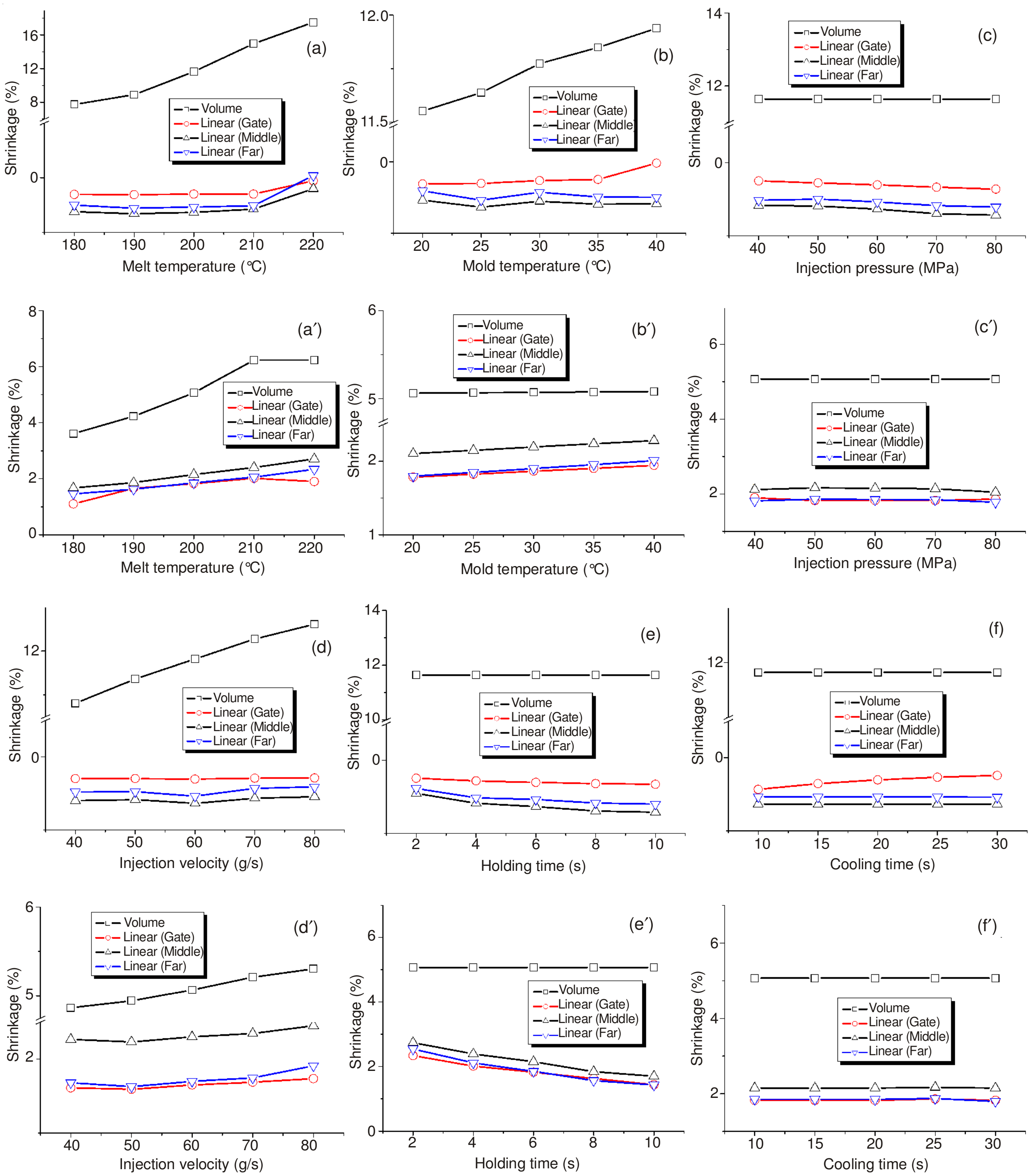

Fig. 2. Effect of operational variables on the shrinkage of PLA2. Thickness of cavity: (a-f) 1 mm, (a′-f′) 4 mm

Fig. 2 shows the effect of the processing parameters on the shrinkage at the gate end, middle and far end positions for different cavities of PLA2. The comparison between Figs. 1 and 2 shows the shrinkage of PLA2 is generally lower than that of PLA1, which is primarily because PLA2 has lower crystallinity. It can be observed that the effect of melt temperature, mold temperature, injection velocity and holding time on the shrinkage of both PLA2 and PLA1 is actually similar, but there are different effects of injection pressure and cooling time on the shrinkage. With increasing injection pressure, the volume shrinkage of PLA2 nearly remains constant as shown in Fig. 2c and c', which can be explained by the facts that the viscosity of PLA2 is lower (due to lower crystallinity) and molding compactness increases with increasing injection pressure.

Fig. 2a-f shows that there is also linear expansion at the gate end, middle and far end positions, while the linear shrinkage of the gate end is greater than the far end and the middle is the lowest. The phenomenon can be explained by the fact that the highest temperature and strongest shear strength are generally located at the gate end and the lowest temperature and weakest shear strength are located at the far end. Owing to the highest temperature at the gate end, there is a large linear expansion and melt relaxation at the middle, the degree of the linear expansion and orientation relaxation is less than the gate end. At the far end, there is a little linear expansion because of the lowest temperature, but there is certain extent of melt relaxation and the linear shrinkage is primarily caused by the effects of linear expansion and orientation relaxation. The linear shrinkage of the middle is greater than the far end and the gate end was the lowest, as illustrated in Fig. 2a'-f', which is mainly because the highest temperature and strongest shear strength are located at the gate end and the lowest temperature and weakest shear strength are at the far end.

Conclusion

In this work, the effects of injection molding processing conditions and part thickness on the shrinkage of two injection-molded poly(lactic acid)s using the MPI-3D flow simulation were studied. The obtained results showed that the higher melt temperature, the larger volume shrinkage. Besides, the shrinkage of poly(lactic acid) increased with increasing melt temperature and injection pressure, while the change of other process parameters (such as, mold temperature, injection pressure, holding time and cooling time, *etc*.) has relatively limited effect on the shrinkage behaviour of poly(lactic acid). The shrinkage of thin-walled products was larger than thick-walled ones.

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