AUTODESK **UNIVERSITY** 2013

New Capabilities in Autodesk® Simulation Moldflow® Insight and Research Directions

Franco Costa – Autodesk

SM1869-P

This class reviews new functionality in Autodesk Simulation Moldflow Insight software and discusses recent and current research directions of Moldflow development. We cover the following capabilities: viscoelastic warp calculations, improved wall slip calculations, the influence of mold deflection, ejection force predictions, analysis of mold fatigue, flow imbalances (airflow), 3D compression molding, 3D conformal cooling, 3D hot runner elements, crystallization analysis, long fiber composites, and mesh preparation.

Learning Objectives

At the end of this class, you will be able to:

- Identify when to use viscoelastic residual stress calculation
- Explain the influence of mold deflection on pressure, shrinkage, and warpage prediction
- Enable a wall slip calculation to simulate jetting effects
- Perform a 3D flow analysis which can capture shear heating induced flow imbalances

About the Speaker

Dr. Franco Costa is a Senior Research Leader for the Autodesk® DLS-Simulation group. Over 21 years with Autodesk Moldflow®, he has contributed to the technologies of 3-dimensional flow simulations, thermal analysis, crystallization analysis, structural analysis, final net part shape prediction and multi-physics for the plastic injection molding simulation industry. Franco now leads key strategic research projects for the Autodesk Simulation technology group. Franco often presents overviews of Autodesk Moldflow research technology directions at Autodesk Moldflow user meetings, has acted as a reviewer for academic journals and internal technical publications. Franco is based in the Autodesk R&D Center in Melbourne, Australia

Franco.Costa@autodesk.com

THE INFLUENCE OF MOLD DEFLECTION ON THE PREDICTION OF PACKING PRESSURE DECAY AND PART SHRINKAGE

Introduction

In recent years, the popularity of injection molding simulation has continued to grow as part and mold designers seek to reduce the number of costly mold trials and mold modifications required to achieve high quality injection molded parts. A key outcome sought from numerical simulation is the prediction of final part dimensions (shrinkage and warpage). Together with a sound material characterization, a basic requirement for accurate shrinkage and warpage prediction is the correct prediction of cavity pressures present during solidification of the molded article. Typically, cavity pressures cannot be controlled after the gate has frozen and so cavity pressure begins to decay as a result of continued material cooling after gate freeze. Therefore, the accurate prediction of cavity pressure decay phenomena is necessary if an accurate final part shape is to be predicted.

In past years, a number of researchers considering cavity pressure decay prediction accuracy have demonstrated the importance of considering the dynamic deflection of the mold due to the forces exerted on the mold by the pressurized polymer in the cavity. Leo and Cuvelliez [1] demonstrated mold elastic deformation by the correlation of residual cavity pressures to part sample thickness and monitored mold backplate flexure by use of a strain gauge. They also achieved improved cavity pressure predictions using an existing commercial simulation package by adding the mold compliance effect into the material PVT characteristic. This method is valid for parts of uniform thickness, but is not generally applicable to parts with variations in thickness. Vietri *et al.* [2] also demonstrated good improvements with a similar PVT based method and proposed a way to determine the approximate mold compliance by a simple beam deformation equation. Pantani *et al.* [3] implemented an injection molding simulation for simplified geometries which included local cavity thickness changes according to the local pressure and with this achieved improved predictions of cavity pressure decay. This method is applicable to simplified part geometries with variable thicknesses. Delaunay *et al*. [4] demonstrated a method for estimating the mold compliance characteristic based on recorded cavity pressures and measured part dimensions.

To date, none of the commercially available injection molding simulation packages (which have the capability to analyze complex part geometries) have include the mold deformation effect in the flow and shrinkage calculations. This present work is a demonstration of the significant role that mold deformation can play in improving the prediction of cavity pressure decay and part shrinkage.

Experimental

Instrumented Mold

In the present work, a set of instrumented shrinkage plaque molds were used. The mold cavities all conform to the geometry shown in Fig. 1, with variation only in plaque cavity thickness of each mold. Plaque thicknesses of 1.7mm, 2mm, 3mm and 5mm where used in the present study. Cavity pressure data was continuously recorded during filling, packing and cooling stages at the No. 1 and No. 3 pressure transducer locations. In addition, a pressure transducer is located in the injection molding machine nozzle to record injection pressure and a thermocouple is located in the mold near the cavity surface to record the mold temperature. The cavity surface has a grid pattern of fine gauge lines inscribed which serve as reference points for part dimension measurement.

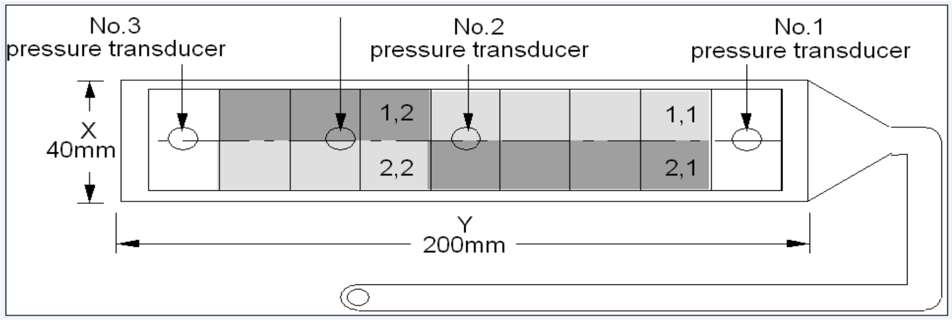

Figure 1 – Geometry of instrumented mold

Polymer Material Grades

Four unfilled amorphous polymer materials were used for the present study. The use of fiber filled materials was avoided in this first study to ensure that part shrinkage in the flow and perpendicular directions would be similar, and so an averaging of the in-plane shrinkage could be performed without significant loss of detail. The use of amorphous materials was preferred to avoid in the first instance the complications in pressure decay response of semi-crystalline materials due to cooling rate effects and abrupt density changes upon solidification. Semi-crystalline and fiber filled materials will be considered in future studies.

The polymer material grades used in this study are listed in Table 1 along with their "Grade Code" reference numbers in the Autodesk Moldflow material database. The problems of mold deflection are in no way restricted to these selected grades, but rather, these grades were selected because their rheological characterization included a Cross-WLF viscosity model which included dependence on pressure as well as shear rate and temperature. The full set of material parameters for each of these polymer grades is available in the Autodesk Moldflow software package.

Table 1 – List of polymer grades

Trade Name	**Supplier**	**Family**	**Reference**
Infino GW-1031	Cheil Industries	PC+ABS	Mat4500
Infino CF-1051T	Cheil Industries	PC	Mat4662
Infino CT-1011T	Cheil Industries	PC	Mat4819
Lexan EXL1414	SABIC Innovative Plastics China	PC	Mat4881

Measurement of Shrinkage

The flow direction shrinkage and perpendicular direction shrinkage on molded samples was measured using an OGP Smartscope Flash 400 system to perform automated optical dimension measurements. To avoid edge and end effects, the shrinkages were determined from intersection points in the gauge lines on the perimeter of the grey shaded grid pattern in Fig. 1.

Processing Conditions

For each polymer material, a set of 25 molding experiments was performed utilizing a range of processing conditions and plaque thicknesses. In each case, the experimental matrix consisted of three packing pressure levels, three plaque thicknesses, three melt temperatures and three injection speeds. The experimental matrix is described in Table 2, while Table 3 lists the range of these parameters for each material.

Table 2 – Experimental matrix for each polymer grade

Exp No.	Thickness	Melt Temp.	Packing Pressure	Inj. Speed
1	H1	Medium	Low	Medium
2			Medium	Medium
3			High	Medium
4			Medium	Low
5			Medium	High
6		Low	Low	Medium
7			Medium	Medium
8			High	Medium
9			Medium	Low
10			Medium	High
11		High	Low	Medium
12			Medium	Medium
13			High	Medium
14			Medium	Low
15			Medium	High
16	H2	Medium	Low	Medium
17			Medium	Medium
18			High	Medium
19			Medium	Low
20			Medium	High
21	H3	Medium	Low	Medium
22			Medium	Medium
23			High	Medium
24			Medium	Low
25			Medium	High

Table 3 – Process parameter ranges

Material	Thickness (mm) H1/H2/H3	Melt Temp (°C)	Packing Pressure (MPa)	Flow Rate (cc/s)
Mat4500	2.0/1.7/3.0	240 - 300	23 - 76	22 - 71
Mat4662	2.0/1.7/3.0	280 - 340	31 - 85	18 - 72
Mat4819	2.0/1.7/3.0	280 - 320	22 - 85	18 - 71
Mat4881	2.0/3.0/5.0	295 - 315	21 - 85	22 - 72

Mold Deflection

Modeling of Mold Deflection

In the present work, a coupled flow analysis and mold-deflection approach is adopted. To model the change in cavity volume due to mold deflection at each time-step, a uniform thickness increment, Δh, is added to the nominal cavity thickness at each location on the parting plane of the cavity geometry. The thickness increment is determined as follows:

$$\Delta h = C_M . F_{clamp} \tag{1}$$

where C_M is the mold compliance and F_{clamp} is the total force of polymer contact projected onto the mold parting plane. While F_{clamp} is readily available at each time-step from existing simulations of mold filling and packing, the mold compliance is a characteristic of the mold which must be determined.

Determination of Mold Compliance

To determine the mold compliance of the molds used in this study, a search was made for molding data set where the final cavity pressures before mold opening were still positive at both cavity pressures sensors. In such cases, the polymer was still fully in contact with the mold prior to the mold opening, indicating that no shrinkage away from the cavity surface have yet occurred. It is useful to note that these over packed moldings cases need not be restricted to the materials which are to be simulated, since it is a mold characteristic which is being determined rather than a polymer characteristic. For the present study, two molding case studies with a high number of over-pack moldings were selected. These were a PC+ABS material and a PET material.

Typically in such over-packed cases, the recorded cavity pressures before mold opening had stabilized to a constant pressure, which indicated that the polymer material had cooled to the mold temperature and no further cooling was occurring. In this way, the complete physical state (pressure and temperature) of the polymer was known at the instant before mold opening. The resulting thickness of the molded plaques was measured using a micrometer. Repeat thickness measurements were taken at 18 locations on each plaque and then averaged to give an overall plaque thickness at room temperature and pressure. Using the PVT (pressure-volume-temperature) characteristic of the molded material, a correction was made to the measured plaque thicknesses to determine what would have been the plaque thickness (and so also the mold cavity thickness) at the recorded cavity pressure and mold temperature immediately prior to mold opening. The assumption used here was that upon ejection the plaque would contract uniformly in all directions due to cooling from the mold temperature to room temperature (and also expand uniformly in all directions due to the pressure release). The mold deflection was then determined by subtracting the nominal cavity thickness (adjusted to account for mold thermal expansion) from these in-cavity plaque thicknesses.

The mold deflections where correlated against the residual cavity force, which can be easily determined from the residual cavity pressures. Shown in Fig. 2 and Fig. 3, the gradient of this correlation gives the mold compliance characteristic to be used. Only the mold deflections for the 2mm thick parts were used to determine the correlation gradient because some uncertainty exists in the nominal cavity thickness values. However, the mold deflections for over-packed moldings of the other cavity thicknesses are also shown in Fig. 2 and Fig. 3 to illustrate the general consistency of the approach. Averaging the determined mold compliance characteristic obtained from these two datasets, the mold compliance used in the present study was 0.187 mm/MN.

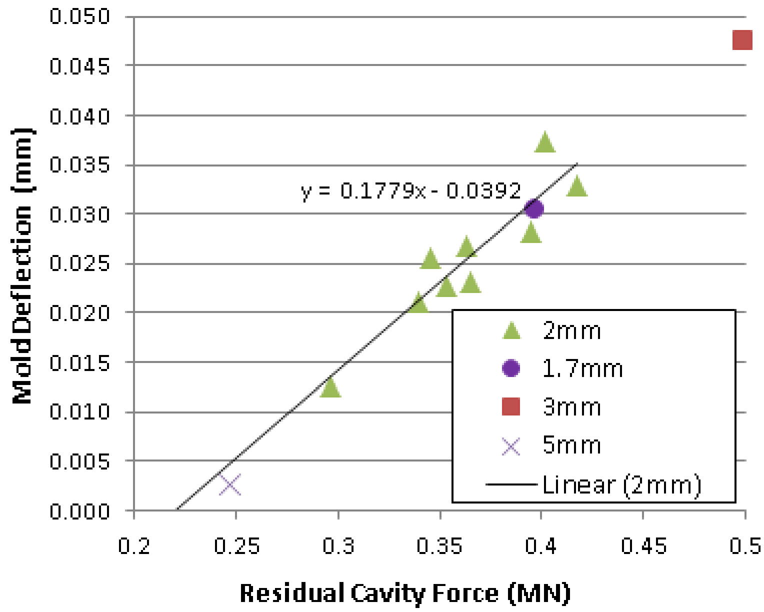

Figure 2 – Mold deflection characteristic for a PC+ABS dataset

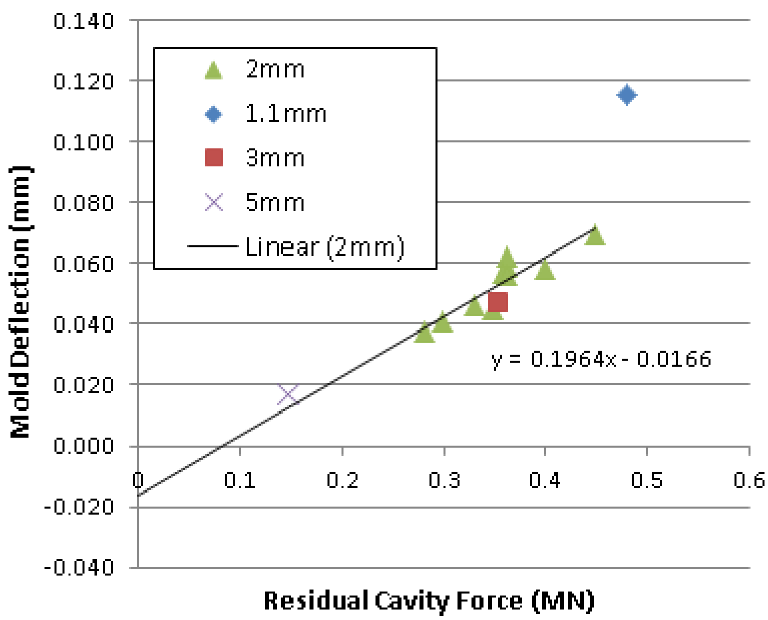

Figure 3 – Mold deflection characteristic for a PET dataset

Simulation

Simulations of the mold filling, packing and subsequent part shrinkage were performed using midplane shell elements in the Autodesk Simulation Moldflow Insight 2014 package. Using beam elements, the sprue, runner and injection barrel geometry were also included in the simulation model in order to correctly account for their effects in material compressibility and pressure losses (Fig. 4). A description of the Hele-Shaw formulation used in the flow calculation for the shell elements is given by Kennedy [5]. In-plane part shrinkage averaged between the flow and perpendicular directions was determined from the prediction of final part shape given by a warp analysis, being a structural analysis of the thermoelastic response of the solidified polymer to the residual stresses induced in the cavity and due to cooling after ejection [6][7]. No empirical shrinkage correction methods such as the CRIMS method [7] were applied in this current study.

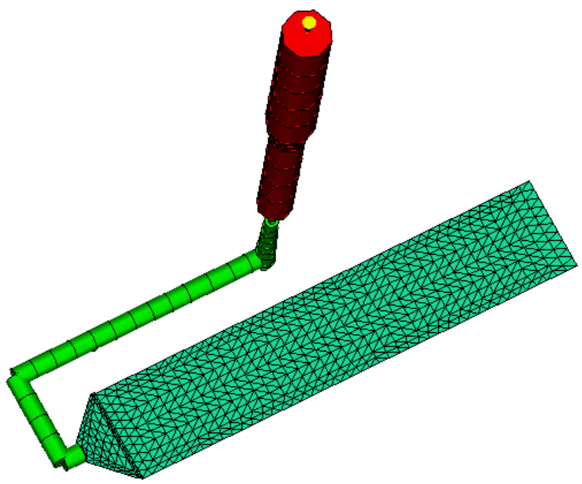

Figure 4 – Finite element model for simulation

In this present study, a modification was made to the filling and packing simulation to consider the changing cavity thickness of all elements according to the mold compliance previously determined. Both the modified cavity thickness and the rate of thickness change (either increasing or decreasing) are considered. Even in the most extreme cases of very high peak cavity pressures, the increase in cavity thickness will only be a fraction of the nominal cavity thickness. In the present study, the increase in cavity thickness is never more than 10% of nominal cavity thickness. Therefore, it is not the increased cavity thickness itself which has the strongest influence on the cavity pressure decay behavior; but rather, it is the changing cavity thickness which has the most influence. As the polymer material cools and shrinks, the reduction in pressure observed will be slower than that which would occur for cooling in a perfectly rigid cavity due to the spring-back of the mold in response to the reducing cavity pressure. This spring-back reduces the cavity volume, thus partially compensating for the pressure decrease which would have occurred due to cooling. In order to include this effect of changing cavity volume in the cavity pressure calculation, a source term, W, is added to each element at each time-step in the filling and packing calculation.

$$W = A \cos(\theta) \frac{(\Delta h_{prev} - \Delta h)}{\Delta t} \quad (2)$$

where *A* is the area of the shell element; θ is the angle between the element normal and the mold opening direction; Δh_{prev} is the mold deflection at the previous timestep; and Δt is the duration of the current time-step.

The resulting change in predicted cavity pressure decay results in a changed volumetric shrinkage and residual stress outcome, leading to a changed prediction of final part dimensions (including in-plane shrinkage).

Results and Discussion

Effect of mold deflection on predicted packing pressure decay

Fig. 5 to Fig. 8 show a comparison of measured and predicted cavity pressure decay for the two pressure transducer locations: P1 (near the gate) and P3 (at the end of flow). Predicted pressures are shown for simulations which assumed a rigid cavity volume and also for simulations which include the mold deflection effect. In these selected examples, it is clear that the cavity pressure decay is predicted much more accurately with the coupling of the mold deflection effect. The comparisons of cavity pressure decay for the majority of all other molding experiments performed also show a similar accuracy improvement when mold deflection in included. However, the difference between the cavity pressure predictions with and without mold deflection is not as strong in those experiments which used the lowest packing pressures. This is to be expected because in those cases the magnitude of mold deflection will be less.

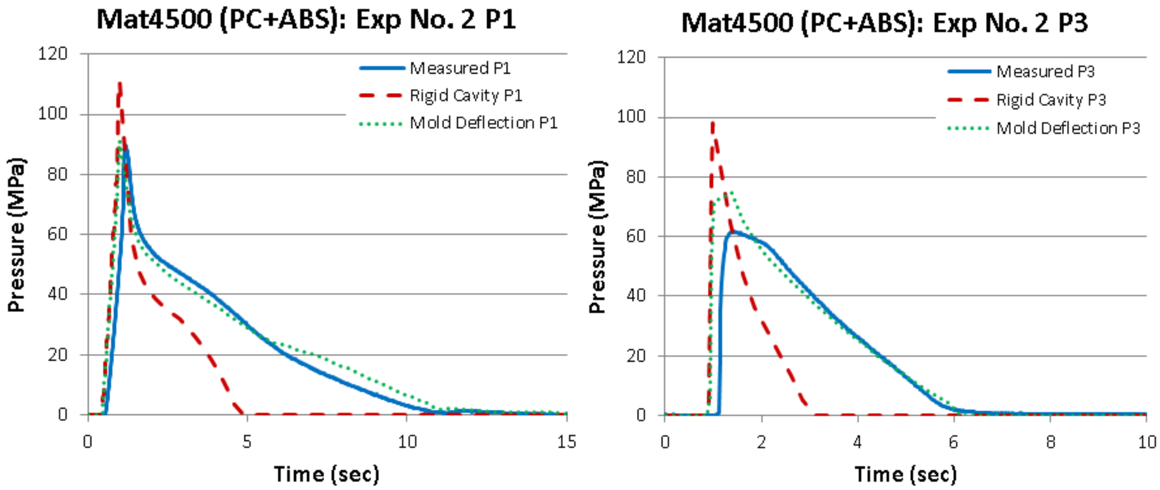

Figure 5 – Cavity pressure traces for Mat4500 Molding Experiment Number 2

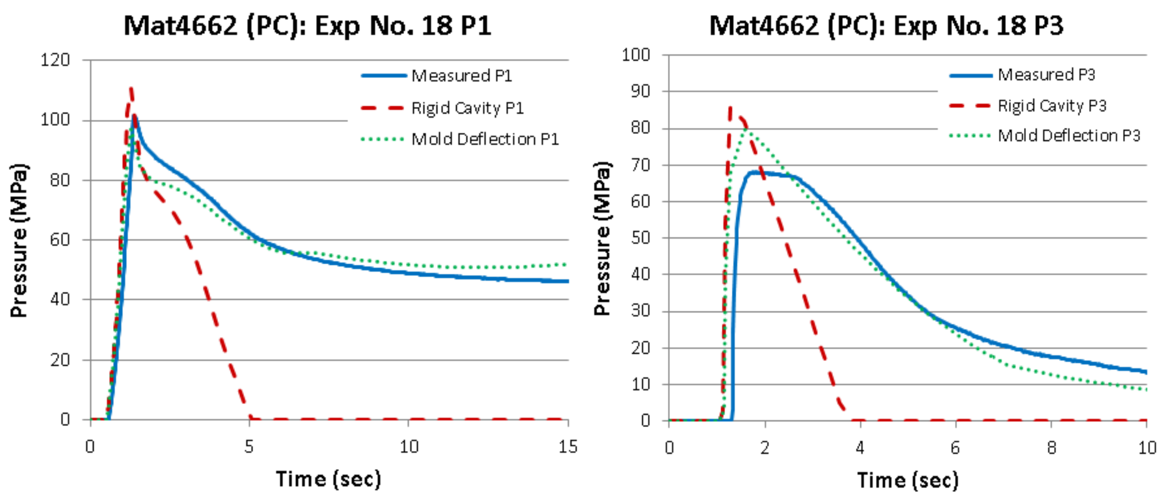

Figure 6 – Cavity pressure traces for Mat4662 Molding Experiment Number 18

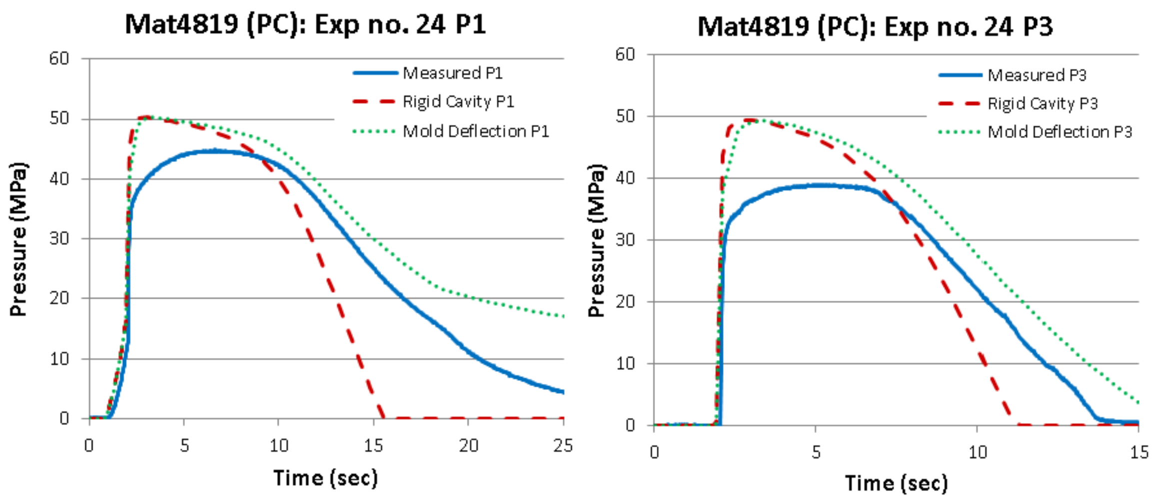

Figure 7 – Cavity pressure traces for Mat4819 Molding Experiment Number 24

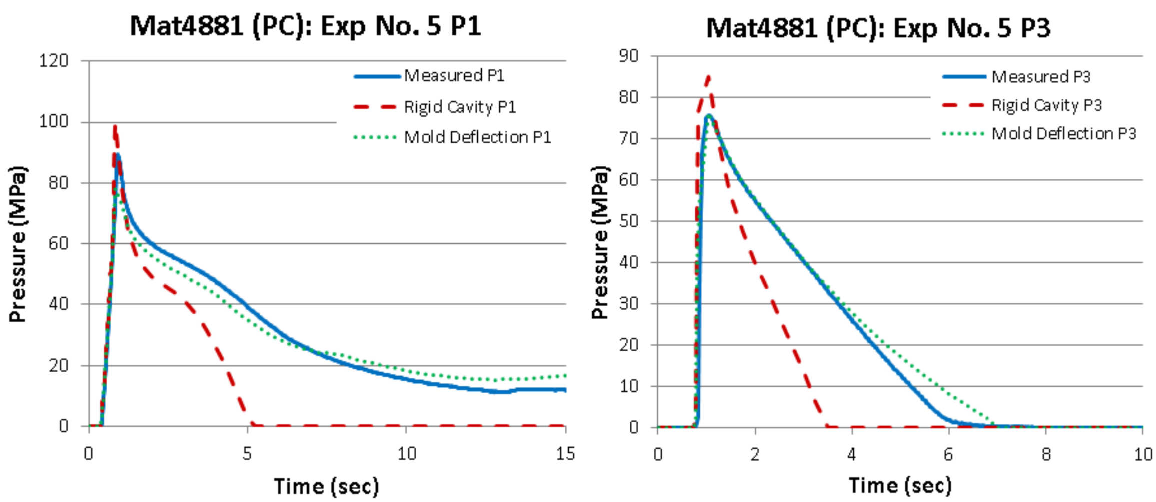

Figure 8 – Cavity pressure traces for Mat4881 Molding Experiment No. 5

Effect of mold deflection on predicted part shrinkage

Fig. 9 to Fig. 12 show the measured and predicted average in-plane shrinkage for all 25 molding experiments for each of the materials studied. The predicted shrinkage is presented for both the rigid cavity and mold deflection simulations. The average magnitude of shrinkage is better predicted when the mold deflection is considered for three of the polymer material grades (Mat4550, Mat4662 & Mat4881). However, of greater interest is that the shrinkage prediction sensitivity to changes in processing conditions or cavity geometry (thickness) is better captured by the simulations which include mold deflection. For example, considering Mat4500 (Fig. 9), the thinnest plaques (1.7mm) were molded in experiments 16-20, while the thickest plaques (3mm) were molded in experiments 21-25. On average, the measured shrinkage of the 3mm plaques is slightly higher than the measured shrinkage of the 1.7mm plaques. This trend is also observed in the shrinkage predictions which included mold deflection. However, the shrinkage predictions which assumed a rigid cavity incorrectly show a strong opposite trend, with higher shrinkage predicted for the thinner moldings.

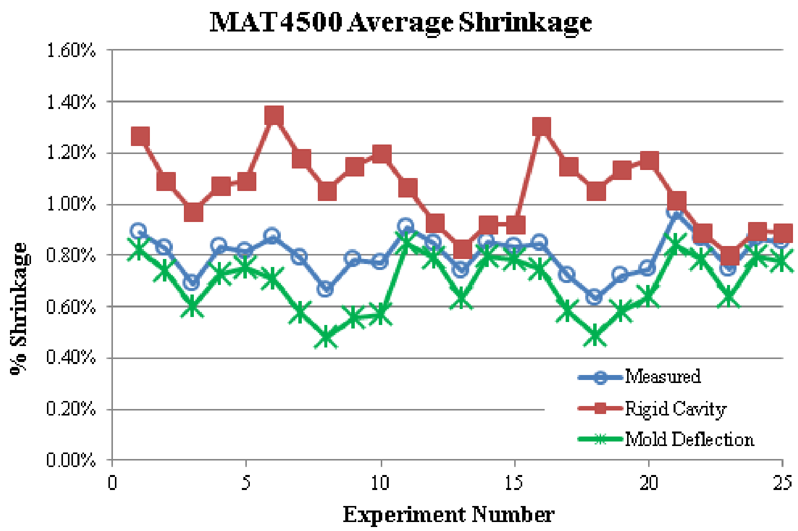

Figure 9 – Average shrinkage for Mat4500

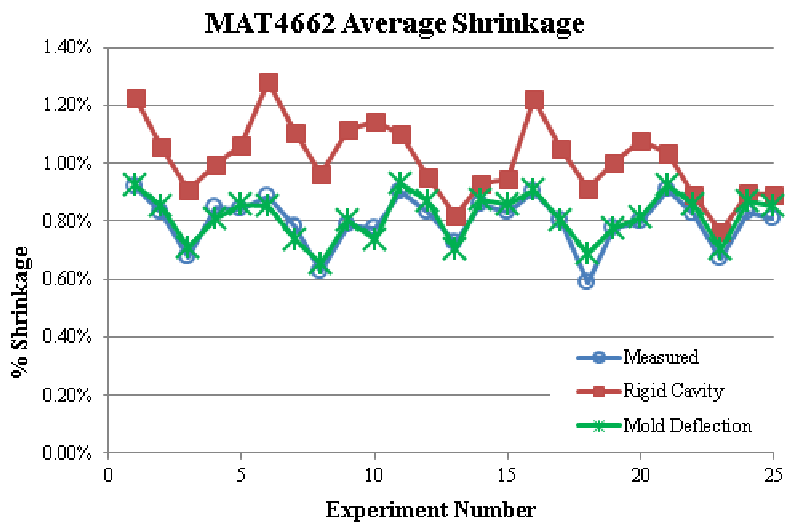

Figure 10 – Average shrinkage for Mat4662

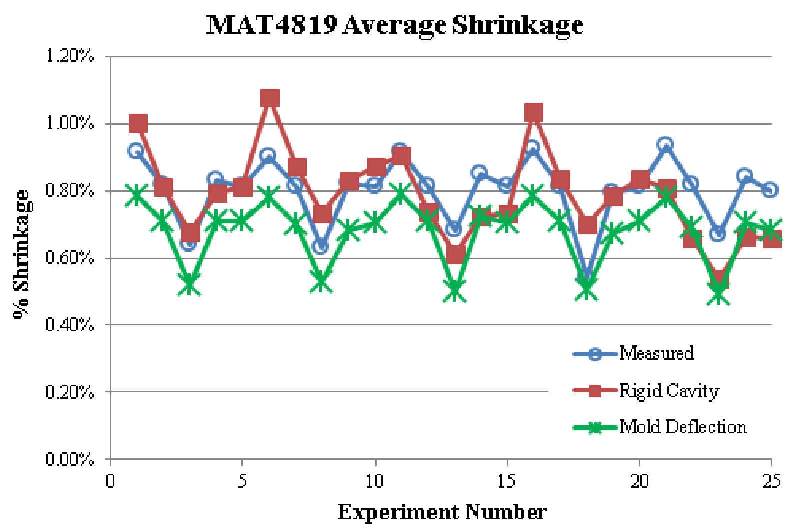

Figure 11 – Average shrinkage for Mat4819

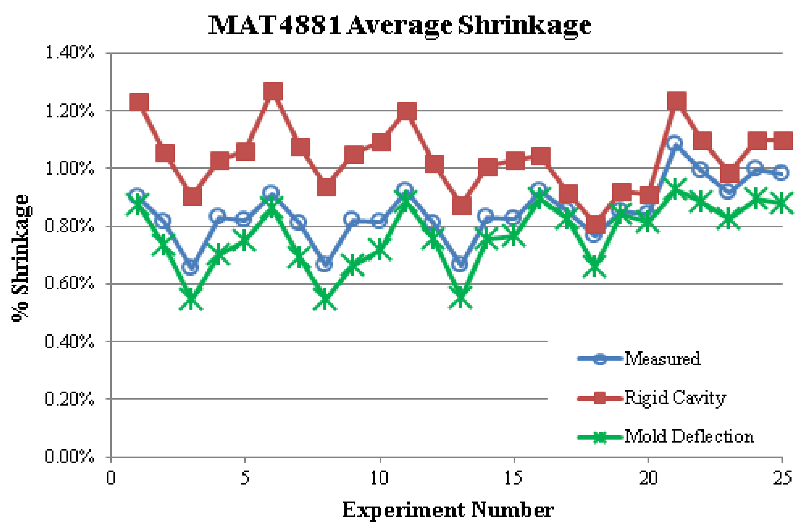

Figure 12 – Average shrinkage for Mat4881

Conclusions

The significant influence of mold deformation on the accurate prediction of cavity pressure decay has been demonstrated by coupling a mold-deflection characteristic into the simulation of injection mold filling, packing and cooling. The beneficial effect of these improved cavity pressures predictions on shrinkage predictions has also been demonstrated, with improvements to both the average shrinkage levels and the sensitivity to process and geometry parameters. A simple method for determining the mold compliance characteristic was also described.

Acknowledgements
The author wishes to thank the Autodesk laboratory staff who conducted the molding experiments and shrinkage measurements used throughout this study.

References

1. V. Leo; CH. Cuvelliez *Polym. Eng. Sci*. 1996, 36, 1961-1971.
2. U. Vietri; A. Sorrentino; V. Speranza; R. Pantani *Polym. Eng. Sci*. 2011, 51, 2542-2551.
3. R. Pantani; V. Speranza; G. Titomanlio *Polym. Eng. Sci*. 2001, 41, 2022-2035.
4. D. Delaunay; P Le Bot; R. Fulchiron; J.F. Luye; G. Regnier *Polym. Eng. Sci*. 2000, 40, 1692-1700.
5. P. Kennedy, *Flow Analysis of Injection Molds, Hanser*, Munich, 1995.
6. R. Zheng; P. Kennedy; N. Phan-Thien; X-J. Fan *J. Non-Newtonian Fluid Mech*. 1999, *84*, 159-190.
7. P. Kennedy and R. Zheng in SPE-ANTEC Tech. Papers 48, 2002.