Characterization and control of plastic deformation in premolded components in in-mold assembled mesoscale revolute joints using bi-directional filling strategy

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Abstract:- One of the major challenges associated with the in-mold assembly processes at the mesoscale is the interaction between the polymer melt and the premolded components that are present in the mold. When a high speed, high temperature second stage melt comes in contact with a premolded mesoscale component having similar melting temperatures, the premolded component undergoes thermal softening and plastic deformation. To overcome this challenge we have developed a novel, multi gate mold design allowing for bidirectional filling. The bi-directional filling balances forces applied on the premolded component by the polymer melt flow. This paper presents experimental results and a preliminary model to understand the sensitivity of gate location to 1) location of weld lines and 2) force responsible for the plastic deformation of the premolded mesoscale component.

Keywords: *Injection molding, In-mold assembly, Mesoscale manufacturing*

1. INTRODUCTION

In-mold assembly is a time and cost effective process for producing articulated joints. It utilizes injection molding to automate assembly operations which may require high labor times for production [1]. Since injection molding is a high throughput process, in-mold assembly holds tremendous promise in bulk production of assembled parts.

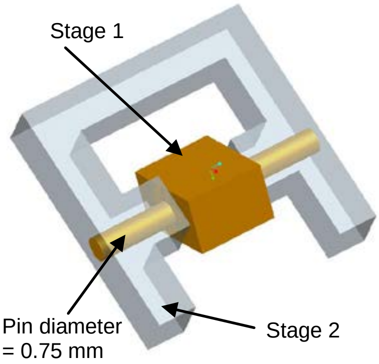


Fig. 1 In-mold assembled revolute joint.

In-mold assembly process has been used to manufacture mesoscale revolute joints. This process involves injection of different components of the revolute joint assembly into a mold sequentially or in different stages. Mold pieces are moved before each injection to create shut off surfaces between different parts of the mold cavity which are filled in each step of the in-mold assembly process. When all steps are completed, a fully assembled mesoscale revolute joint is ejected from the mold cavity. The material combination used for in-mold assembly should be chosen such that they are chemically incompatible i.e. they have no tendency of adhering to each other during and after injection molding. Fig. 1 shows the CAD model of a mesoscale revolute joint that can be manufactured using in-mold assembly.

One of the major challenges in mesoscale in-mold assembly is the interaction between the polymer melt and the premolded components that are present in the mold. The premolded component tends to undergo plastic deformation when it comes in contact with the high pressure second stage melt. Previously, we have developed a process which involves constraining the mesoscale premolded components (such as the pin shown in Fig. 1) using radial supports [2]. Use of these constraints inhibits the plastic deformation of the premolded component. However, this approach is only suitable for polymer combinations having large differences in melting temperature. This difference ensures that the premolded component does not undergo thermal softening during its interaction with the high temperature high pressure second stage polymer melt flow. Also mesoscale features in the premolded components need to be longer than the requirement posed by the design to provide for radial supports. Making such high aspect ratio mesoscale structures increases the mold tooling cost.

To overcome some of the technical challenges posed by the radial support strategy, this paper will introduce an alternate strategy for in-mold assembly of mesoscale revolute joints. However this new strategy introduces some new challenges. This paper will address some of these challenges and suggest methods to overcome them.

2. BI-DIRECTIONAL FILLING FOR IN-MOLD ASSEMBLY

As described earlier, during in-mold assembly of mesoscale revolute joints, the mesoscale premolded component tends to deform plastically due to the force applied by the second stage melt flow. This deformation is caused by the unidirectional lateral force applied on the mesoscale features in the premolded component by the second stage polymer melt flow [3]. However, if an opposing force is applied to the mesoscale feature on the premolded component to neutralize the force caused by the unidirectional second stage polymer melt flow, its plastic deformation can be inhibited. To realize this force, we introduced a bi-directional filling strategy for the second stage polymer melt. This is illustrated in Fig. 2.

However to completely neutralize the force on the mesoscale feature the gates for the two flows have to be placed exactly equidistant from the mesoscale feature. In several design scenarios it may not be possible for the gates to be aligned exactly. Any misalignment will result in a net force on the premolded component. This net force may cause plastic deformation of the mesoscale structures in the premolded component.

Another important consideration while using the bidirectional filling strategy is the formation of cold weld lines at the joint interface. This is illustrated in Fig. 2. Weld-lines are formed at the position where the flows from the two gates meet. For some polymers, weld-lines are a major source of structural weakness [4-7]. Hence a weld-line at this position, if weak, may be unacceptable in several design scenarios. Introduction of misalignment in the gate positions could be a possible strategy to move the weld-lines to a structurally less demanding location.

To address some of these concerns, it is imperative to obtain an understanding of the sensitivity of the plastic deformation of the mesoscale premolded component to any misalignment in the gate locations. There are several types of gate misalignment [8]. We have considered two prominent types of gate misalignments. These are 1) Temporal misalignment and 2) Spatial misalignment. The two misalignments are illustrated in Fig. 3. (b) and (c) respectively. Both misalignments may cause plastic deformation in the premolded component as shown in the figure. This paper will only address the temporal misalignment case. The spatial misalignment case will be addressed as a part of future work.

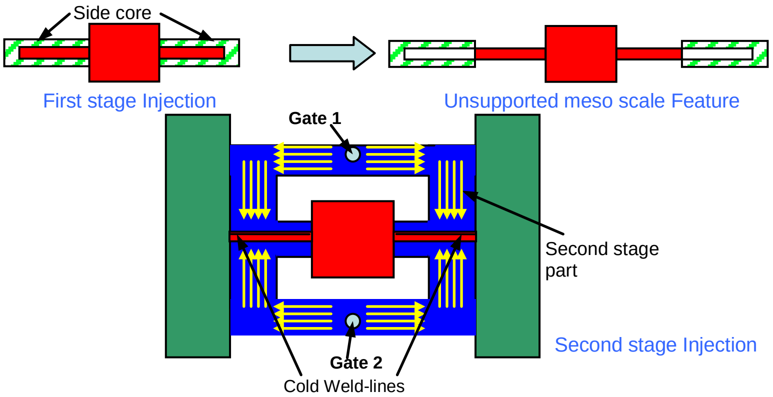
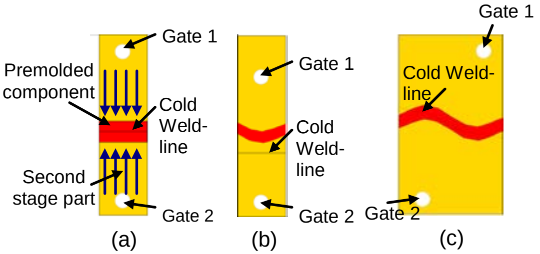


Fig. 2 Schematic of the two stage mold design using multi gate bidirectional filling strategy

Section 3, will describe the experimental setup we used to record the plastic deformation of the premolded component as a function of the temporal misalignment. Section 4 will describe the approach used to build a theoretical predictive model for relating the plastic deformation to the temporal misalignment of gates. Section 5 will report results of the experimental analysis as well as preliminary results of a computational model.



(a) Aligned bidirectional filling

(b) Bidirectional filling with temporal misalignment

(c) Bidirectional filling with spatial misalignment

Fig. 3 Spatial and temporal gate misalignment

3. EXPERIMENTAL SETUP

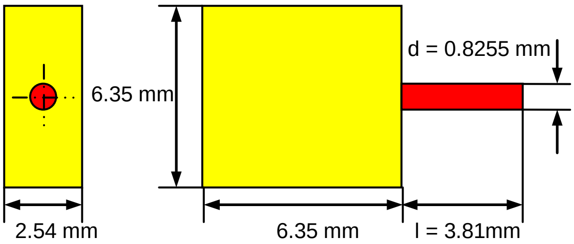


Fig. 4 Premolded component for experiments

We designed the first stage part to have only one mesoscale feature as illustrated in Fig. 4 to collect data for the effect of temporal misalignment on the plastic deformation of the premolded component.

We designed the second stage mold to be modular in nature so as to collect data for different gate locations using the same mold. This mold is illustrated in Fig. 5. This mold could be used to generate two samples in each shot. The mold contained a total of 6 gates. At any given time, we kept 2 gates open and 4 closed. By opening and closing different gate combinations for different shots, we were able to use this mold to obtain 5 different sample points.

While choosing the material combination for in-mold assembly we took the following into consideration. 1) The melting temperatures of the premolded component and second stage polymer should be comparable. 2) The strength of the cold weld-line for the second stage should be at least 70% of the base material. To study the weld line strengths, we used the approach outlined in the literature [5-7].

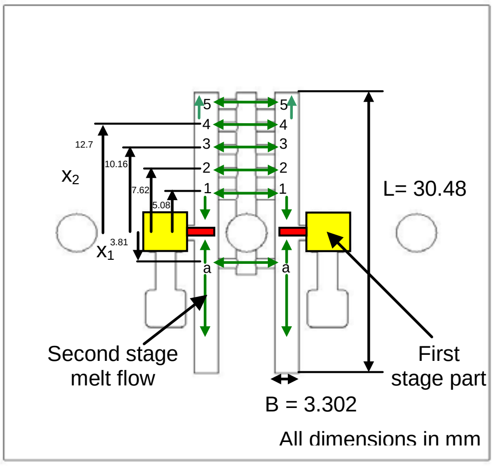


Fig. 5 Modular second stage mold design

4. MODELING FRAMEWORK

In order to develop a complete understanding of the effect of the temporal misalignment on the plastic deformation of the premolded component, we developed a framework to build a simple model. Our objective was to predict the plastic deformation of the premolded component for a given temporal misalignment. In this section, we will outline a generalized framework for predicting plastic deformations in mesoscale features due to temporal misalignment during in-mold assembly. This framework can be applied across any polymer combination and any injection molding parameters.

Before building a modeling framework, let us review the complexity of the problem we are trying to model. During the second stage mold filling of the in-mold assembly operation, the mesoscale premolded component acts as a soft mold insert for the second stage polymer melt flow. The premolded component is made of a Viscoelastic material. The deformation of this material therefore follows a highly non-linear stress-strain curve. The second stage polymer melt flow on the other hand, is a non-Newtonian fluid flow, i.e., the viscosity of the flow is dependent on the shear rate of the flow. Also, there are two independent flows in the mold cavity owing to the presence of two gates. Due to the two independent flows in the mold cavity, the force on the premolded component is dependent on the transient fluid flow effects. In summary, this problem involves time-varying non-Newtonian flow and elastic-plastic deformation. Solving this problem in full generality is almost intractable and may not be necessary from the manufacturing point of view.

From the manufacturing perspective, we are only interested in estimating the plastic deformation of the parts to determine whether the in-mold assembly process is a repeatable process capable of fabricating functional mesoscale revolute joints. Hence, we have attempted to decouple the problem from its full generality to estimate the plastic deformation within acceptable factor of safety limits to meet the needs of manufacturing.

In the first step, one should identify the modeling parameters that need to be considered. These include 1) *Geometric parameters* i.e. the dimensions of the premolded component and the second stage component, 2) *Mold design parameters*, i.e., the temporal misalignment, and other mold dimensions such as sprue and runner dimensions, 3) *Material properties* .i.e. the structural properties of the premolded component and the flow properties of the second stage polymer melt, and 4) *Molding parameters* which are used during the in-mold assembly operation.

To understand the effect of temporal misalignment, we need to appropriately predict the meeting point of the two flows. This meeting point is a weld-line location. Hence it is important to understand the sensitivity of the weld-line location to the gate positions. Mold filling simulations can be used to determine the position of the weld-lines relative to the mesoscale feature on the premolded component for different choices of gate positions.

The force exerted on the mesoscale feature on the premolded component is dependent on the location of the weld-line. This is because the two opposing polymer melt flows for the respective gates, exert forces on the premolded component while they are moving. However, the flows come to a complete stop after they meet each other at the weld-line location. They cease to apply any force on the premolded component once they meet. Flow simulations can be used to reveal the force applied on the premolded component by each polymer melt flow till they come to a complete stop. Finally the forces applied by the two flows can be superposed to predict the net force on the premolded component.

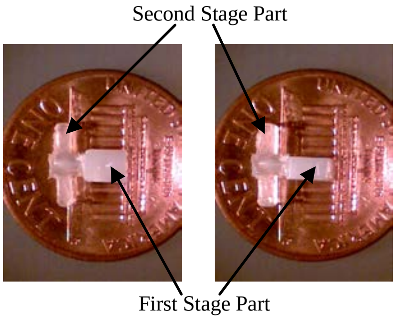
Once the net force on the premolded component is known, finite element simulations will determine the net plastic deformation on the premolded component as a result of the applied force. This plastic deformation can then be used to determine whether the particular temporal misalignment can be used to manufacture acceptable in-mold assembled mesoscale revolute joints. In the next section, we will illustrate this modeling framework by applying it to the particular in-mold assembled mesoscale revolute joint that we have successfully fabricated in the Advanced Manufacturing Lab at the University of Maryland.

5. RESULTS AND DISCUSSION

We conducted the experiments on a Milacron Babyplast injection molding machine. We chose *Acrylonitrile Butadiene Styrene* (ABS) manufactured by *Ashland Chemicals* as the material for the premolded component. For the second stage material, we chose *Grillamid-L16 LM* (Nylon 12) manufactured by *EMS Grivory*. Before choosing the second stage material, we conducted tests to evaluate its weld-line strengths. Our tests revealed that the failure strength of the cold weld-line in Nylon-12 is approximately 82% that of the native material. Also, owing to the low difference in melting temperatures of the two polymers, this material combination was appropriate.

Table 1. Injection molding parameters

	Stage 1	**Stage 2**
Material	ABS	NYLON 12
Injection Temp.	240°C	190°C
Injection Velocity	12 cc/s	12 cc/s
Injection pressure	600 bars	600 bars
Cooling time	3s	3s



0º Orientation 90º Orientation

Fig. 6 In-mold assembled mesoscale revolute half joint

The processing parameters that we used are described in Table 1. Fig. 6 shows a successfully in-mold assembled mesoscale revolute half joint fabricated using the bi-directional filling strategy discussed in this paper. The gates were positioned exactly equidistant from the mesoscale feature on the premolded component for this particular half joint i.e. there was no temporal misalignment.

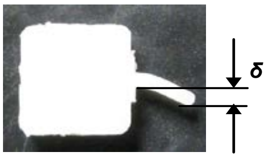


Fig. 7 Measurement of plastic deformation of premolded component

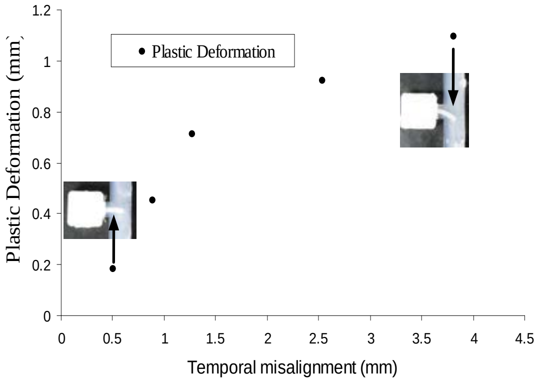


Fig. 8 Plastic deformation of premolded component v/s temporal misalignment

Subsequently we conducted experiments to relate the gate misalignment with the plastic deformation of the premolded component. We measured the deformation of the premolded component as shown in Fig. 7. Fig. 8 shows the relationship between the plastic deformation and the temporal misalignment. As illustrated by the graph, the plastic deformation increases with increasing temporal misalignment. A gate misalignment as low as 0.5 mm results in a plastic deformation of 0.2 mm. However the experimental data seems to suggest that the deformation saturates for high misalignments. This is because the plastic deformation reaches a limit as the mesoscale premolded component encounters the mold wall.

To predict the location of the weld-line in the in-mold assembled part, we conducted mold filling simulations in Moldflow Plastics Insight 7.1. Fig. 9 illustrates the location of the weld-line (***d***) for a temporal misalignment of (L1-L2). The results of these simulations are illustrated in Fig. 10. The simulation shows that the location of the weld lines is linearly related to the temporal misalignment.

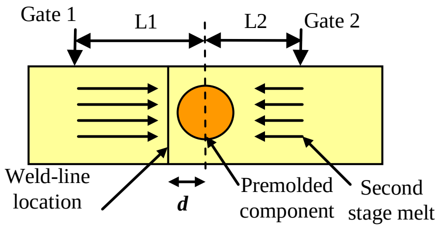


Fig. 9 Weld line location for temporally misaligned gates

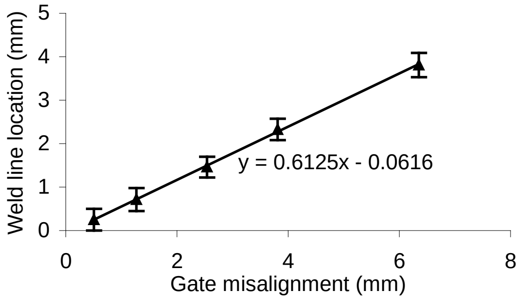


Fig. 10 Weld-line location determined from mold filling simulations

Table 2. Nonlinear stress-strain curve of ABS

Stress (Pa)	Strain
0	0
1.80E+07	8.00E-03
3.60E+07	1.60E-02
5.20E+07	5.00E-02
6.00E+07	1.25E-01
6.20E+07	1.53E-01
6.36E+07	1.70E-01
6.42E+07	1.88E-01
6.53E+07	2.81E-01

Subsequently, we conducted finite element simulations in ANSYS 9.0 to estimate the force required for the plastic deformation recorded experimentally. The non-linear stress-strain curve of the premolded component, which we used for the FE simulation, is tabulated in Table 2. As elucidated by the experimental data in Fig. 8, the plastic deformation reaches a saturation limit as it encounters a mold wall. Hence the part can not deform any further. Hence, our current FE simulation is valid only for the first three experimental points. As discussed in section 4, force estimation for these points will suffice from the manufacturing standpoint. This is because the manufacturing community will be more interested in estimating the lower limit of the acceptable force for making good quality mesoscale revolute joints. Table 3 lists the force estimate responsible for the plastic deformation of the premolded components.

Table 3 Force estimate on premolded component due to temporal misalignment

Temporal misalignment (mm)	Weld line location (mm)	Plastic deformation (mm)	Force estimate (N)
0.508	0.25	0.183	1.588
0.889	0.4825	0.453	1.805
1.27	0.715	0.712	1.98

To computationally estimate the force on the premolded component, we are currently in the process of conducting computational fluid dynamics simulations. We will consequently use the force estimates resulting from these simulation in conjunction with FE simulations to computationally estimate the plastic deformation of the mesoscale component resulting from the temporal misalignment.

6. CONCLUSIONS

This paper establishes the technical feasibility for using bidirectional flow of second stage polymer melt for manufacturing in-mold assembled mesoscale revolute joints. We have described a mold design template which can be used to successfully manufacture in-mold assembled mesoscale revolute joints which 1) can be used without radial supports and 2) can be used for polymer combinations having similar melting points.

This paper is also the first attempt at studying the effect of temporal misalignment of gates on the plastic deformation of premolded components. Our results indicate that mesoscale premolded components are highly sensitive to temporal misalignment in the gates.

This paper also reports a preliminary model which can be used to predict the plastic deformations on premolded components due to temporal misalignment in bi-directional filling of second stage polymer melt during in-mold assembly of mesoscale articulating joints.

7. ACKNOWLEDGEMENTS

This research has been supported in part by NSF grant DMI0457058 and the Army Research Office through MAV MURI Program (Grant No. ARMY W911NF0410176). Opinions expressed in this paper are those of the authors and do not necessarily reflect opinions of the sponsors.

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