Overview of In-Mold Assembly Research at the Advanced Manufacturing Lab

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Technical Report, Advanced Manufacturing Lab, University of Maryland, College Park, MD 20742, 2011

1. Introduction

3D articulated devices involve moving parts with significant out-of-plane motion. There are many applications such as hard disks, cameras, photonics, cell phones, micro air vehicles, and drug delivery systems where the ability to scale down size and deploy mesoscale (size range of 0.1mm to 1mm) joints will be highly desirable because their unique behavior provides significant performance gains. While manufacturing technologies exist for scaling down 2D articulated devices, a scalable and cost effective manufacturing method does not currently exist for making 3D articulated devices. Even though individual parts can be easily fabricated, assembling them into devices remains a challenge (e.g., current assembly methods require manual assembly under a microscope to realize mesoscale 3D articulated devices). Therefore, despite their superior performance characteristics, mesoscopic 3D articulated devices are not used in practice due to throughput and cost considerations.

Injection molding is a high throughput method for polymer processing and is being used produce a wide variety of products with varying shapes and sizes. Micro- and meso-molding of polymers is a promising process that has gained popularity during the last few years. Parts with features sizes as small as 10 microns are being molded. New methods have been developed for mold flow simulations, thermal management and time dependent flow during filling for miniature parts. In-mold assembly has also been successfully demonstrated in the macroscale. This has proven to be an effective manufacturing process to develop articulated parts with reduced production times and lead times. Considering the success of micro and mesomolding and in-mold assembly at macro scale, it is envisaged that mesomolding and in-mold assembly can be potentially combined to develop a manufacturing process for making mesoscale articulated parts.

Swash plate with revolute joint

Prismatic joint

Rotor structure with universal joint

Ball in socket joint

Figure 1: Joints developed at Advanced Manufacturing Lab using in-mold assembly (no post-molding assembly operation is required)

2. Macroscale In-Mold Assembly

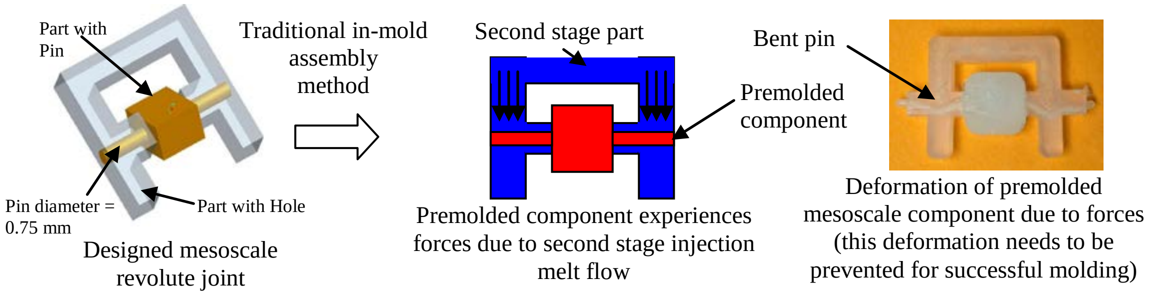
We use the term in-mold assembly to describe molding process that carries out both molding and assembly functions. In addition to acting as mold during the fabrication process, this type of tooling also acts as an assembly fixture by holding the previously molded parts during subsequent molding stages and hence establishes relative position and orientation between different components in a multi-material object. Unlike traditional objects consisting of many single-material components that are assembled via some form of standard fastening technique, multi-material assemblies come out of the molds pre-assembled after the in-mold assembly process. This allows for significant reduction in part count and eliminates several assembly operations thus improving the overall productivity.

We have successfully developed a multi-stage molding process that allows us to produce macroscale (features sizes from 2 to 200 mm) objects with articulation. Unlike traditional in-mold assembly, where adhesion is used to completely constrain the motion between two components, our process creates non-binding mechanical interfaces to allow for selective degrees of freedom between components. Figure 1 shows representative examples of the four classes of joints that we have developed in the Advanced Manufacturing Lab at the University of Maryland.

We have shown that articulated structures made out of traditional unfilled polymers can be used in miniature rotorcraft applications. For example, Figure 1 shows a 2-DOF swash plate for a rotary wing micro air vehicle (MAV). The prismatic joint and the ball in socket joint that we have developed also find applications in several areas, such as bio-inspired robotics.

3. Mesoscale In-Mold Assembly

The in-mold assembly process at the mesoscale behaves differently and poses new challenges due to reduced structural rigidity of the mesoscale premolded component. One of the major challenges that needs to be addressed is minimizing plastic deformation of the premolded component during the second stage injection (Figure 2). To address this challenge, we have developed a mold design strategy and a detailed modeling approach to characterize and control this deformation. This section describes our main results in the area of mesoscale in-mold assembly with unfilled polymers.



Designed mesoscale revolute joint

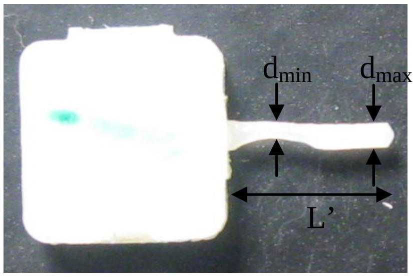
Premolded component experiences forces due to second stage injection melt flow

Deformation of premolded mesoscale component due to forces (this deformation needs to be prevented for successful molding)

Figure 2: The plastic deformation of premolded component during in-mold assembly poses significant challenge at the mesoscale

3.1 Identification of defect modes unique to mesoscale in-mold assembly

In order to develop an understanding of the relationship between the size of the mesoscale pin on the premolded component and its plastic deformation during second stage injection, we identified the defect modes that are unique to the mesoscale in-mold assembly process. As part of our research we observed that one of the main defects that occur during in-mold assembly at the mesoscale is the plastic deformation of the premolded component during second stage injection. There are two primary types of deformation that we observed. 1) Lateral deformation of the pin due to the flow of the second stage polymer as illustrated in Figure 2 and 2) the radial deformation of the pin resulting in change in effective diameter of the pin due to the application of packing pressure after completion of the filling stage. This is illustrated in Figure 3. Subsequently we developed experimental and computational methods to determine the size scale of the pin which begins the onset of plastic deformation of the premolded components during the in-mold assembly process.



$d_v = d_{max} - d_{min}$ $L_v = L' - L_0$

Figure 3 Measurement of diameter and length variation of premolded mesoscale pin

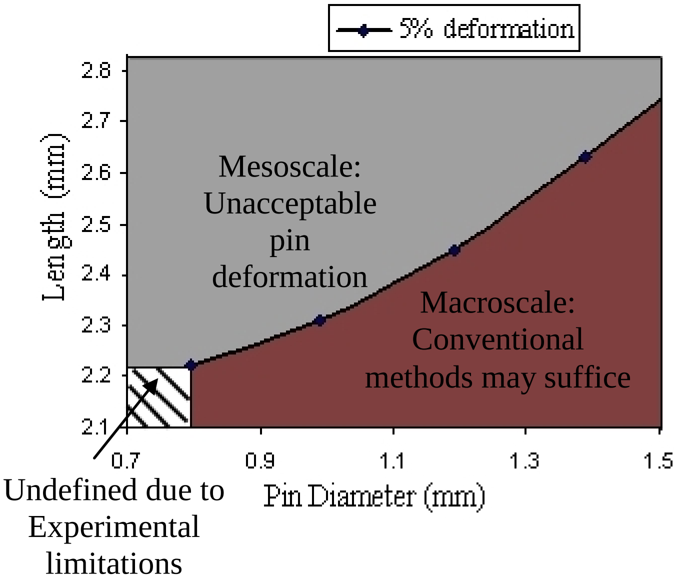


Figure 4 Distinction between macroscale and mesoscale from the in-mold assembly perspective

From the perspective of transverse deformation of the premolded component, our studies for using ABS as the premolded component and LDPE as the second stage material are illustrated in Figure 6. From the perspective of radial deformation of the premolded component due to application of packing pressure after the filling stage, the results are illustrated in Figure 7.

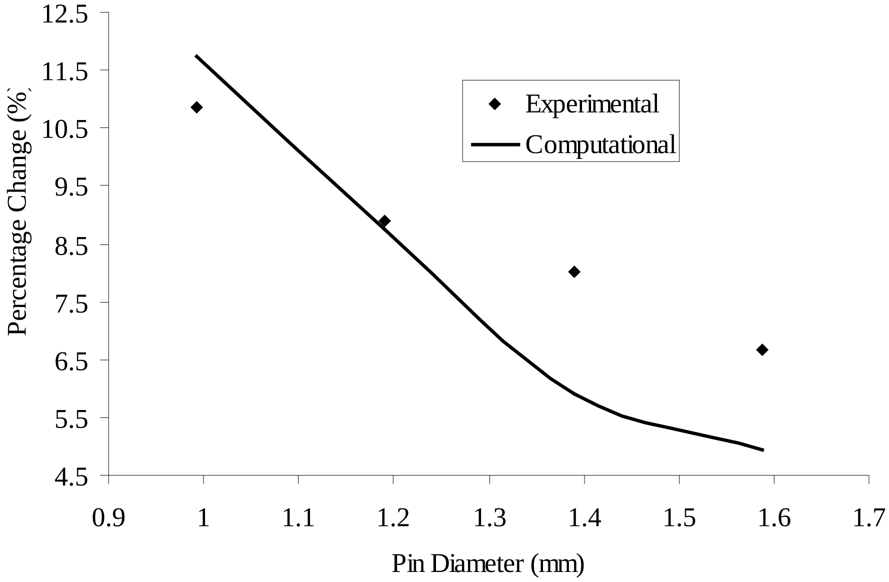


Figure 5 Percentage change in diameter of pin v/s original pin diameter

3.2 Unidirectional Filling for Fabricating Mesoscale In-mold Assembled Revolute Joints

One of the causes of deformation is the flow of the second stage polymer melt around the mesoscale premolded component. As part of this work, we have reported the following results. First, we have described a mold design with varying cavity shape to perform in-mold assembly. This mold design is illustrated in Figure 6.

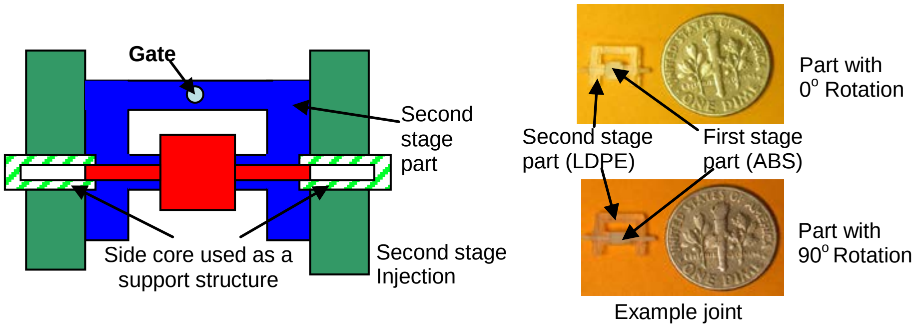


Figure 6: Mold design involving radial support part constraining feature to prevent deformation of premolded part (first successful demonstration of in-mold assembly at the mesoscale)

Second, a modeling method is described to determine the forces on the premolded component due to the second stage injection. Third, a modeling method is described to determine the deformation of the premolded mesoscale component due to the second stage injection. These methods are then used to select the required radial support length for obtaining functional mesoscale revolute joints. These joints are fully functional and can be manufactured repeatably using the process described. The deformations of the mesoscale premolded component fall within acceptable joint tolerances. To the best of our knowledge, this is the first demonstration of in-mold assembly process to create a mesoscale revolute joint.

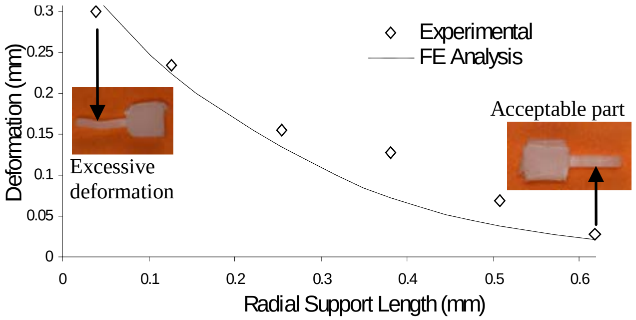


Figure 7: Finite element analysis for deformation versus radial support length for a flow rate of 12 cc/s

As part of the modeling effort, we developed a process to estimate the effective pressure experienced by a cylinder which falls in the flow path of an injection molding melt. We have used a non-Newtonian flow CFD model to estimate this pressure. The estimate provided has an error margin of up to 20%. This model is the first attempt at understanding the physics of interaction between the melt flow and free-standing structures in multi-shot molding processes, and suggests a non-intuitive influence of the mold geometry on the loading experienced by the free-standing structure. We have also described a nonlinear FEA model for predicting the deformation of a mesoscale core when placed in the polymer flow environment. This model agrees with the experimental deformation with an error of around ±2%. This is illustrated in Figure 7.

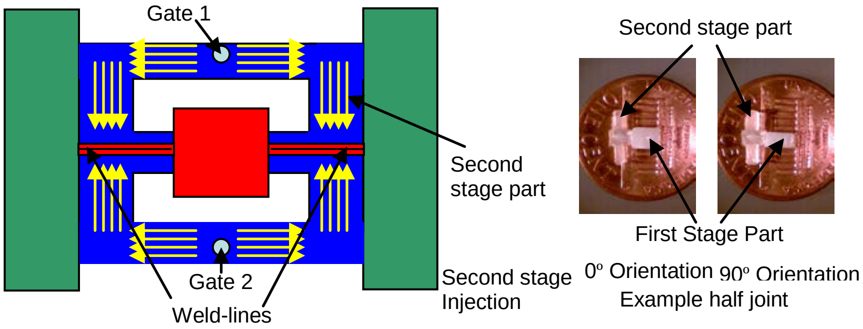


Figure 8: Mold design involving bi-directional filling to balance forces on the premolded component to prevent deformation

3.3 Bi-directional Filling for Fabricating Mesoscale In-mold Assembled Revolute Joints

Introduction of an opposing force to neutralize the drag force applied on the premolded component will enable us to overcome some of the technical challenges posed by the unidirectional filling strategy. As part of this work, we reported an alternate mold design solution. This is illustrated in Figure 8. The force caused by the flow of the second stage polymer melt is fully neutralized if the gates are placed exactly equidistant to the mesoscale premolded component. However, it is important to understand the effect of misalignment in the gate placement on the plastic deformation of the premolded component in order to understand the parameters that will control manufacturing tolerances. As part of this work, we have developed a computational model to characterize the plastic deformation of mesoscale premolded components resulting from the use of the bi-directional filling strategy. This is illustrated in Figure 9.

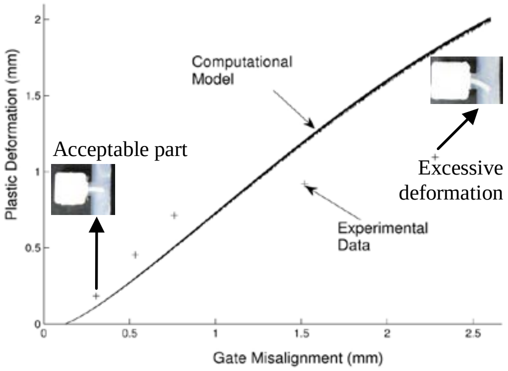


Figure 9: Plastic deformation of mesoscale premolded component relating to the gate misalignment

3.4 Characterization and Control of Clearances during In-Mold Assembly of Mesoscale Revolute Joints

Another significant challenge in in-mold assembled mesoscale revolute joints is how to obtain adequate clearances. Macro-scale revolute joints can be formed by first molding the hole and then molding the pin inside the hole. As the pin shrinks during the solidification process, it moves away from the hole and provides the clearance for the joint to function. The value of clearance in the macro-scale joint can be controlled by carefully selecting the process parameters and the material for the pin.

However, in order for this strategy to work at the mesoscale, it requires the use of very thin cores to form sub-millimeter holes. Such thin cores are very difficult to make, are easily damaged during the molding process, and very difficult to retract from the hole. We have created successful mold design solutions for mesoscale in-mold assembly that indicate making the pins first and then creating holes on the top of pins leads to successful mesoscale joints. This strategy is counter intuitive based on our experiences at the macro-scale.

At the macroscale, as the hole shrinks on top of the pin, the joint is jammed. So a fundamental question is why this counter-intuitive strategy works at the mesoscale. We have conducted experimental investigations and have developed computational models relating the joint jamming to the support cavity length. We have then used these results to show how jamming can be prevented. Our findings are as follows. First, we report results of dependence of the final pin diameter on the support cavity length in mesoscale in-mold assemblies. Second, we describe a mold design with varying support cavity lengths to control the final pin diameters obtained from in-mold assembled mesoscale revolute joints. Third, we have developed a computational model which describes the relationship between the pin diameter variation and the support cavity length. This is illustrated in Figure 10. This predictive model can be used by the manufacturers as a tool for designing the appropriate assembly clearances in mesoscale in-mold assemblies. This model also provides designers with a tool to select the appropriate support cavity lengths for the desired joint properties.

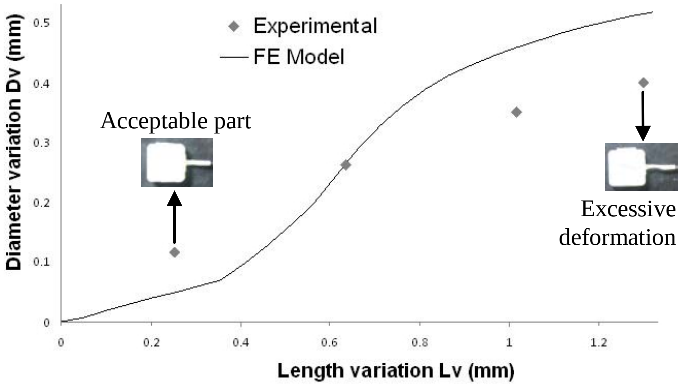


Figure 10: Experimentally recorded diameter variation v/s support cavity length

3.5 In-Mold Assembled Finger-Inspired Robot

To demonstrate the capabilities of the mesoscale in-mold assembled revolute joint, we have conceptualized and fabricated a finger-inspired robot which can potentially be used for Neurosurgery (MINIR). The device that we have developed has a diameter of 0.36”, consists of 6 DOF and is fabricated using mesoscale in-mold assembly methods with Shape Memory Alloy wire actuators. Currently we have fabricated a prototype of this robot. This is illustrated in Figure 11. Figure 12 illustrates a concept of a robotic hand that has been assembled using five finger inspired robots. As expected, the SMA-actuated MINIR prototype revealed thermal softening of the unfilled polymer and SMA wire interface. The SMA wire heats up when in operation and softens the unfilled polymer it is anchored in. We believe that using thermally conductive polymer composites will overcome this issue and make embedding heat generating actuators in miniature structures possible.

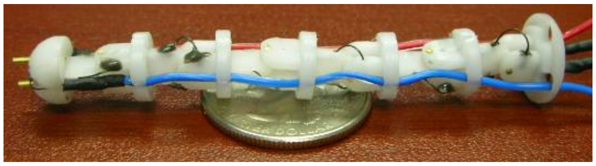
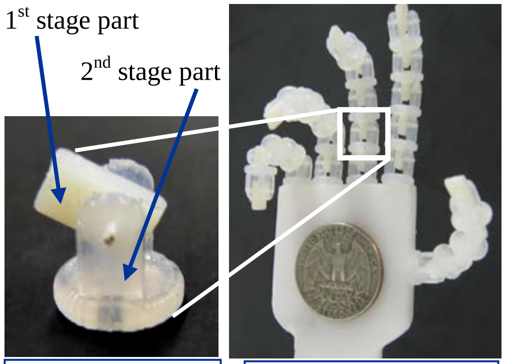


Figure 11: 6-DOF MINIR weighing 2.94 grams



In-mold assembled revolute joint

25 DOF hand created using in-mold assembled revolute joints

Figure 12: Fabricating a robotic hand using mesoscale in-mold assembly

4. Conclusions

As a part of the on-going research at the University of Maryland, we have made contributions in the following areas:

1. Development of mold design templates for realizing macro-scale compliant and rogid body joints.
2. Development of design rules for multi-material molding.
3. Identification of defect modes unique to in-mold assembly at the mesoscale and development of methods to delineate the mesoscale and the macroscale from the in-mold assembly perspective.
4. Development of a mold design which will allow constraining of premolded components to enable mesoscale in-mold assembly,
5. Development of a process utilizing multiple gates placed at appropriate locations to fill the second stage mold cavity and
6. Development of a predictive model to control clearances obtained in mesoscale in-mold assembled components.

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