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Development of In-Mold Assembly Process for Realizing Mesoscale Revolute Joints

Arvind Ananthanarayanan, Satyandra K. Gupta, Hugh A. Bruck
Mechanical Engineering Department
University of Maryland
College Park, MD

Zuyuan Yu and Kamlakar P Rajurkar
Department of Industrial & Management Systems Engineering
University of Nebraska-Lincoln
Lincoln, NE

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ABSTRACT

In-mold Assembly process at the mesoscale presents several manufacturing challenges. Results reported in this paper demonstrate the technical feasibility of creating rigid body mesoscale revolute joints using In-Mold Assembly process. The following new results are reported in this paper. First, we describe a mold design with varying cavity shape to perform In-Mold Assembly. This mold design uses an accurate mold piece positioning method to avoid damage to delicate mesoscale parts during the cavity change step. Second, we describe a mold insert fabrication process for making mold inserts with the desired surface characteristics for mesoscale molding. Finally, we describe methods to limit the adhesion at the interfaces and hence create articulated revolute joint. Using the advances reported in this paper we have successfully molded a mesoscale revolute joint. To the best of our knowledge, this is the first demonstration of In-Mold Assembly process using a varying cavity shape mold to create a mesoscale revolute joint.

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 kinematic behavior provides significant performance gains. While manufacturing technologies exist for scaling down 2D articulated devices [1], 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. Recent advances in micro mold insert manufacturing technologies such as micro electro discharge machining (EDM) provide a way to create mold inserts with very small features. Such molds can be used to create parts that are sub-millimeter in size. By combining recent advances in micro EDM and In-Mold Assembly methods [2, 3], we can create a new molding process to enable economically viable fabrication of mesoscopic 3D articulated devices.

Micro- and meso-molding of polymers is a promising process that has gained popularity during the last few years [4, 5, 6]. Parts with features sizes as small as 10 microns are being routinely molded [8, 7]. While significant success has been achieved in molding micron-sized parts, there are still technical challenges associated with micro-molding. These challenges are mainly in the area of mold flow simulations and thermal management [9, 10, 11]. Our work builds on these successes. To the best of our knowledge a scalable In-Mold Assembly method for creating mesoscale revolute joint has not been demonstrated so far. Please note that overmolding is not recommended because inserting a molded component into a new mold is not feasible due to the small component dimensions.

Development of a molding process that combines the benefits of mesoscale molding and In-Mold Assembly requires us to address several challenges. These challenges include: (1) developing mold configurations that support molds with varying cavity shape to perform In-Mold Assembly, (2) developing accurate positioning methods to realize cavity shape change to avoid damage to delicate mesoscale parts created during molding, (3) developing a process for making mold inserts with the desired surface characteristics, (4) developing a method to limit the adhesion at the interfaces and hence provide articulation, and (5) developing a method to successfully remove parts from molds.

This paper reports our progress towards successfully realizing mesoscale revolute joints. The paper describes how mesoscale mold design and mold insert fabrication are different from macroscale In-Mold Assembly process. This paper also describes the mold design, the mold insert fabrication method, and processing parameters that are used for successfully realizing mesoscale revolute joints.

MOLD DESIGN

In-Mold Assembly methods for macro scale rigid body joints have been successfully developed in the past [1]. In order to have a smooth running revolute joint at the macro scale, the pin is usually molded inside the cylindrical hole such that the pin shrinks radially to provide the required clearances. The hole in the first stage component is made by using a side core of the requisite diameter. However, the method used for macro scale In-Mold Assembly method cannot be used for mescoscale joints for the reasons described below.

FIGURE 1 Shows the CAD model of a revolute joint with a meso-scale pin which will be in-mold assembled. After a careful consideration of the part design, it was determined that making a core with small diameter would be an expensive process. Also the core with a small diameter would be prone to failure due to force applied by the injection pressure.

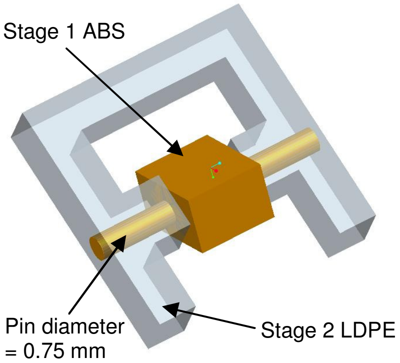
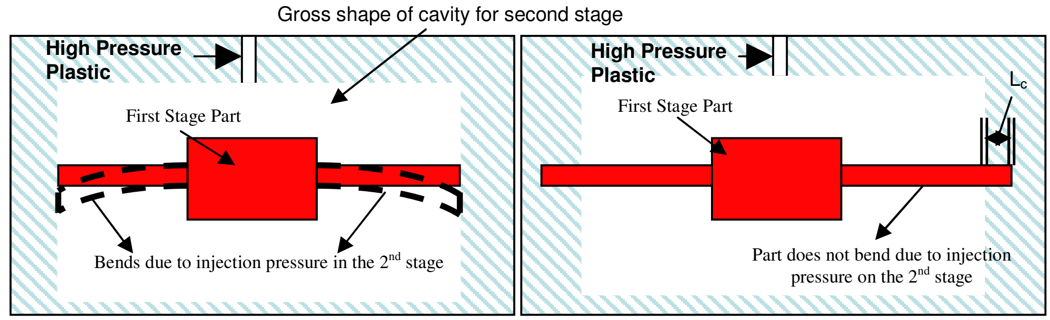


FIGURE 1 IN MOLD ASSEMBLED REVOLUTE JOINT.

The other option was to mold the pin in the first stage and mold the hole in the second stage. Making a hole with small diameter in the mold is much easier than making a core with small diameter. Hence we chose this method because this method simplifies the mold design considerably. The amount of absolute shrinkage is very little due to small dimensions and hence this approach is not expected to jam the joint.

There was a concern that the injection pressure during the second stage will bend or break the delicate pins. However the mold cavity shape can be selected during the second stage such that the pins are well supported. For examples, the molded pins can be supported on both ends and hence the bending problem can be eliminated. FIGURE 2 shows this concept. The pin is supported at each end by a distance of L_c.



(a) Initial Concept (b) Improved Concept

FIGURE 2 BENDING OF PIN DUE TO UNSUPPORTED SECOND STAGE INJECTION.

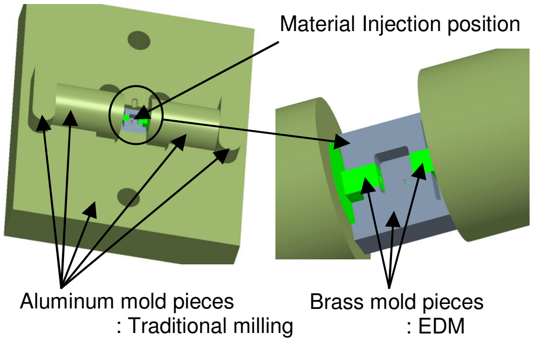


FIGURE 3 MOLD ASSEMBLY FOR STAGE 1.

In most situations, micro EDM is a much more expensive process compared to traditional milling. Hence the gross mold was partitioned into a number of inserts. Some inserts were produced by micro EDM while others were produced by traditional milling. In addition to taking into account cost considerations, such partitioning had to ensure the following insert characteristics: (1) provide the adequate surface condition inside the mold cavity to ensure ease of ejection, (2) are easy to replace in case of failure or during tooling maintenance, and (3) the mating face between two inserts does not leave a seam mark on the part. Our macro scale experiments showed that a seam on the first stage part along the surface of the joint can cause flash and major adhesion problem resulting in jamming of the joint. A key to eliminate joint adhesion is to ensure that there are no seam marks on the joint surface. Often this requires unconventional mold design concepts.

A significant effort was devoted to developing a mold design that meets these criteria. FIGURE 3 shows the parts machined using the EDM process that were used as mold inserts for In-Mold Assembly of the revolute joint with meso scale features. In order to carry out In-Mold Assembly, the cavity shape needs to change after every molding stage. The first stage starts with the first stage material being injected into an empty cavity. The material fills the cavity completely and solidifies. Before starting the second stage molding, the cavity shape needs to be altered to create room for injecting the second stage material. This step requires changing the shape of the original cavity. Cavity shape change can be accomplished by many different ways. One of the most popular ways of changing the cavity shapes is the approach of overmolding. In this process the first stage part is ejected from the first stage mold and inserted into a second stage mold. As mentioned earlier, this is not an option for parts with meso scale features since there is the added risk of causing part defects during ejection at such small scales. Some alternatives include: (1) one or more mold pieces can simply be moved away from the first stage material in the cavity and hence can expand the cavity, (2) change the shape of the cavity by swapping one or more mold pieces in the initial cavity with a mold piece with a different shape,

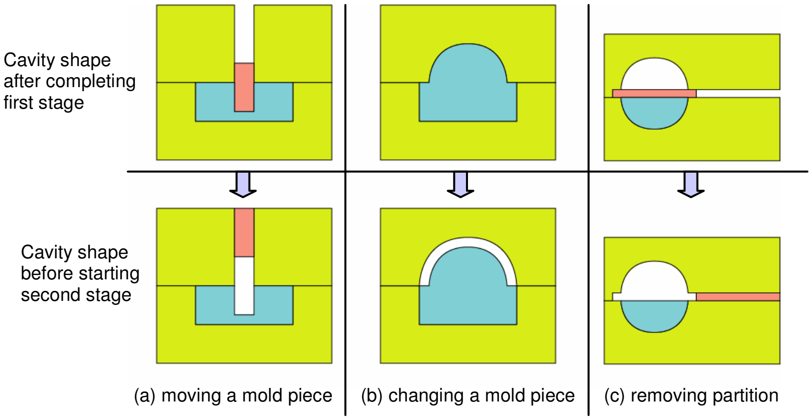


FIGURE 4 EXAMPLES OF DIFFERENT WAYS TO CHANGE CAVITY SHAPE DURING SECOND STAGE.

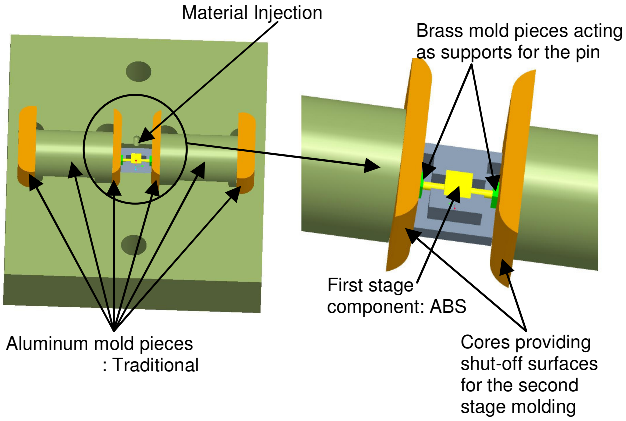


FIGURE 5 MOLD ASSEMBLY FOR STAGE 2.

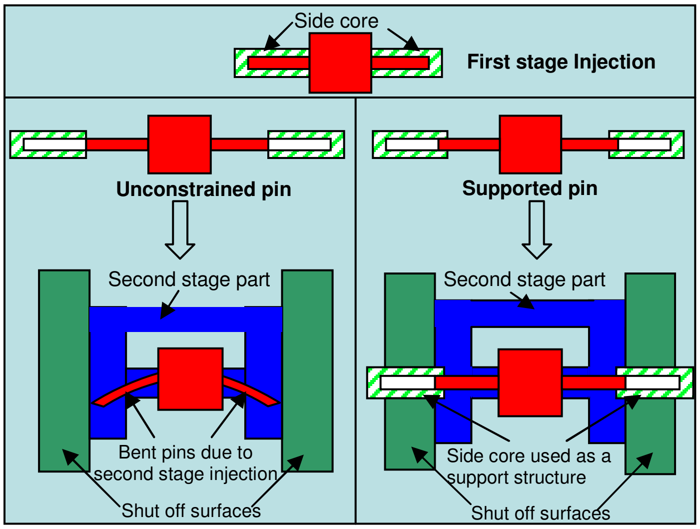


FIGURE 6 MOLD DESIGN ITERATIONS FOR SECOND STAGE INJECTION.

and (3) change the shape of the cavity by adding partitions in the initial cavity and remove them during subsequent stages.

FIGURE 4 illustrates these methods. While the cavity shape is being altered, the already injected material should stay in place and should not move. Moreover, the method should satisfy the assembly and disassembly constraints imposed on the mold pieces. After studying many different cavity shape change methods, it was felt that a combined approach of moving mold pieces and adding partitions to the initial cavity would produce the best results for the problem at hand. The mold assembly for stage 1 is shown in FIGURE 5. FIGURE 6 shows a mold design that ensures that no seam marks are present on the first stage part and hence there are no adhesion problems in the joint. This design also ensured that mold pieces move very accurately and do not cause any damage to the part during the cavity shape change. FIGURE 7 shows the potential problems that can be caused by inaccuracies in mold piece movements. For the second stage mold, the side cores in first stage mold assembly were retracted exposing the pin in the molded first stage part partially. One of the major issues in molding the hole over the pin is the bending of the pin due to the pressure of the second stage molten plastic flowing over it. During the first design iteration, the pin was initially designed to be left as an overhanging structure. When the second stage polymer was injected in this pin configuration, it acts as a cantilever beam generating bending stress that is sufficient to exceed the strength of the pin material and separate it from the base. Hence during the second design iteration, to minimize the bending stress, the pin needed to be constrained on the other end to form a simply supported beam. For this reason, the side core was not retracted completely so as to expose the pin to the second stage part only partially and securing its end. While doing this, it was also ensured that the final in mold assembled part would be fully constrained. A schematic illustration of the two design iterations for the second stage designs are shown in FIGURE 6.

Two new mold pieces were added to the mold assembly for the second stage while reusing all other mold pieces from the first stage mold assembly. These pieces were introduced in order to provide a shut-off surface for the second stage part. The mold assembly for the second stage molding process is illustrated in Figure 5.

A very important consideration is to estimate the length of the pin that need to be secured during the second stage. We have initiated a numerical modeling approach to estimate this length. Accurate computation of this length requires correctly modeling the coefficient of friction between the pin and the side core. We are planning to conduct experiments to estimate the coefficient of friction. In our study we determined this support length experimentally. It was set to the value of 0.03”. This length was found to be sufficient to properly constrain pins and yet provide sufficient surface area for the revolute joint to function.

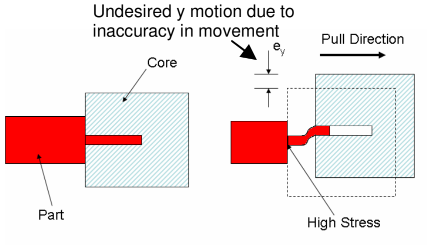


FIGURE 7 BENDING OF PIN DUE TO INACCURACY IN CORE MOVEMENT.

MANUFACTURING OF MOLD INSERT WITH MESO SCALE FEATURES

Any electrically conductive material, regardless of its hardness can be machined by micro EDM. The surface roughness generated by Micro EDM usually is under 1µm [12]. Therefore, it is suitable as inserts for meso/micro molds. The machining operation was divided into two stages: rough machining and finishing. In rough machining, a tool of 0.95mm was used under the machining conditions of 100V and capacitance 3300pF with each layer depth of 0.2mm to remove the large amount of material. To achieve uniform tool wear, in X-Y plane, the width of the remaining part for finishing (W in FIGURE 8) should be larger than the sum of the tool radius and the discharge gap but less than the tool diameter [13]. A tool of 0.7 mm diameter was used for finishing operation. The width was 0.5mm. In Z axis, the remaining thickness (H in FIGURE 8) for finishing was 0.1mm. The thickness of each layer during finishing was 10µm. Therefore, the flatness of finished surface is less than 10µm [14]. The machining parameters for finishing operation were 80V and capacitance of 1000pF. To drill the deep hole in Insert 1, the planetary movement of tool was applied to obtain deep and sharp edge at the bottom of the hole [15]. FIGURE 9 shows the set of meso mold generated by Micro EDM. These brass mold inserts were successfully used in our experiments. The cost of a two stage mold is comparable to the cost of a two cavity family mold. Hence, the use of the In-Mold Assembly process does not increase the tooling cost.

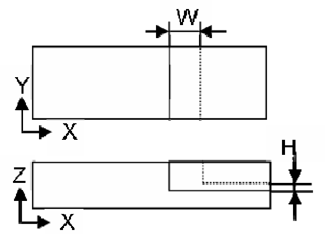
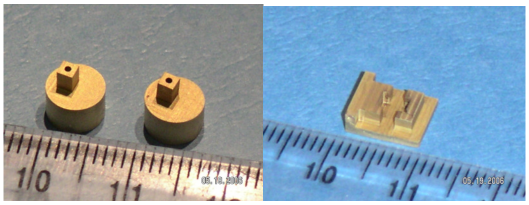


FIGURE 8 DIMENSIONAL PARAMETERS FOR EDM.



(a) Insert 1 (b) Insert 2

FIGURE 9 MOLD INSERTS MANUFACTURED USING EDM OPERATION.

MOLDING PROCESS AND PARAMETERS

In order to have a joint manufactured by In-Mold Assembly methods, it is essential that the first stage material be a polymer with a higher melting point. This is ensured so that the processing temperature for injection molding of the second stage polymer is not high enough to melt the first stage substrate. Moreover, the polymers have to be chemically incompatible to ensure that no cross polymerization takes place. Materials with the possibility of cross polymerization often lead to adhesion problems. Hence we chose Acrylonitrile Butadiene Styrene (ABS) as the first stage material and Low density Polyethylene (LDPE) as the second stage material. Molded ABS is rigid polymer with a tensile modulus of 2.4 GPa and tensile strength of 40 MPa. The processing temperature for injection molding of ABS is around 220℃, it was chosen as the material for the first stage. Molded LDPE, which has a tensile modulus of 0.2 GPA and strength of 10 MPa, was chosen as the material for the second stage because it has a processing temperature of around 130℃.

TABLE 1 lists the injection molding parameters for the In-Mold Assembly of the revolute joint shown in FIGURE 1. We decided to use the lowest possible injection pressure on our machine that could successfully fill the mold. The rationale for using the low injection pressure was to reduce the mechanical load on the second stage part and delicate mold features. We found that injection pressure of 600 bars was sufficient for this part design. We did not use any external cooling lines in the molds. The use of cooling lines can reduce the cooling time. ABS was injected as the first stage polymer, the side cores were retracted outwards exposing the pin partially to the second stage polymer. LDPE was injected as the second stage polymer to complete the In-Mold Assembly process. Finally the part was ejected from the mold manually resulting in the in mold assembled mesoscale revolute joint.

TABLE 1 INJECTION MOLDING PARAMETERS

	Stage 1	**Stage 2**
Material	ABS	LDPE
Injection Temp.	220℃	130℃
Injection pressure	600 bars	600 bars
Cooling time	15s	5s

RESULTS AND DISCUSSIONS

The experiments were conducted on a Milacron Babyplast injection molding machine. FIGURE 10 shows the first stage part successfully molded using the methods described in the previous sections. This component was subsequently used to continue with the In-Mold Assembly process. During the first experiment we used our second stage mold design with unconstrained pins (as an overhanging structure) as described earlier. This resulted in large scale bending of the pin when the second stage polymer was injected, finally leading to shearing of the pin rendering the joint unusable.

FIGURE 11 illustrates the second stage injection molded part for this case. It can be clearly seen that a large scale deformation of the pin resulted from the injection of the second stage polymer.

In subsequent experiments the pin was supported on both sides as described in the mold design section. This solved the problem of the shearing due to high bending moments applied by the flow of the second stage polymer.

Using this method, a fully functional in mold assembled revolute joint was then manufactured. This is illustrated in FIGURE 12.

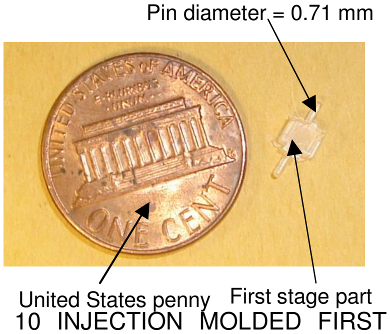


FIGURE 10 INJECTION MOLDED FIRST STAGE COMPONENT.

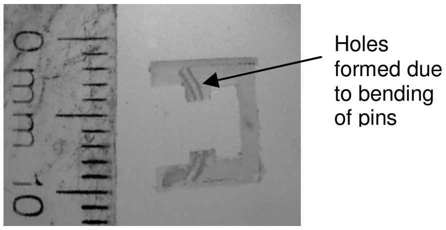


FIGURE 11 INJECTION MOLDED SECOND STAGE PART FOR UNCONSTRAINED PIN.

After getting the mold assembly to function properly and discarding the few initial parts, we successfully made 8 functioning parts. We disassembled the parts and did the measurement on them. Average measured pin diameter on these parts was 0.71mm. The standard deviation of the pin diameter was 0.009. The estimated average shrinkage on the pin was 0.66%. We did not observe any appreciable warpage on the parts.

During the second stage injection the second stage polymer sometimes seeps into some of the cavities in the first stage mold created due to shrinkage of the first stage part. We observed this problem to some extent on all part. However, there was no consistent pattern. Excessive seeping may result in jamming of the joints and defective parts. We estimate that our current mold design may produce as high as 20% defective parts as a result of this problem. We believe that this problem can be eliminated by creating carefully machined shut-off surfaces that from a good seal between first stage plastic part and the mold cavity.

We designed our experimental molds to be modular in nature so that different pieces can be easily changed to accommodate changes in the mold design. However, with around 10 parts constituting the mold assembly, the sum of the manufacturing tolerances resulted in gaps in the mold assembly. These gaps gave rise to significant molding flash. On some regions of the parts we got flash as high as 4mm. However, the flash was quite consistent among parts. Hence it was clearly produced by excessive clearances in the mold assembly. Our design of the mold eliminated the possibility of the flash on the joint surface. Hence the flash did not interfere with the functioning of the joint. In order to overcome this drawback, the mold would be redesigned in future work to reduce the part count for the mold assembly which would result in lesser room for creating flash.

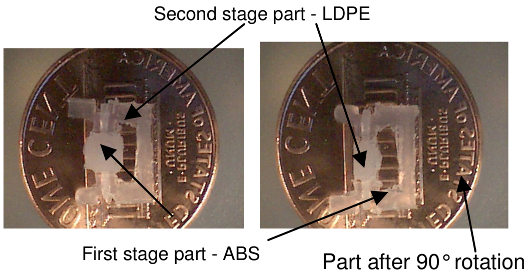


FIGURE 12 TWO CONFIGURATIONS OF THE IN MOLD ASSEMBLED REVOLUTE JOINT WITH MESO SCALE FEATURES DEMONSTRATING ROTATION OF THE JOINT

One of the most critical issues that need to be addressed is the issue of ejection. Currently the parts are manually ejected from the mold using mechanical tools. Since there would be little control in the amount of force applied in ejection when done manually, the molded part is exposed to the prospect of getting damaged. This is of exceeding importance owing to the scale of the features under consideration. One of the possible ways of dealing with this issue is the use of a surface ejection system. This idea is being explored in further detail to obtain a better ejection solution.

CONCLUSIONS

This paper establishes the technical feasibility of using In-Mold Assembly process for creating mesoscale revolute joints. The following new results are reported in this paper. First, we describe a mold design with varying cavity shape to perform In-Mold Assembly. Second, we describe methods to limit the adhesion at the interfaces by carefully choosing chemically incompatible materials and designing molds to eliminate parting lines at the joint surface. Using these techniques we have successfully molded a mesoscale revolute joint. To the best of our knowledge, this is the first demonstration of In-Mold Assembly process to create a mesoscale revolute joint.

We expect that the work presented in this paper will lead to a novel manufacturing technology that will (1) eliminate need for post-fabrication assembly operations in mesoscale devices, and (2) reduce the number of component parts leading to a finished product that may be less expensive to build, lighter in weight, and more resistant to malfunction.

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