A. Ananthanarayanan, S.K. Gupta, and H.A. Bruck. Characterization of a reverse molding sequence at the mesoscale for in-mold assembly of revolute joints. *Journal of Polymer Engineering and Science*, 50(9): 1843–1852, 2010.

Characterization of a Reverse Molding Sequence at the Mesoscale for In-mold Assembly of Revolute Joints

Arvind Ananthanarayanan[*,1], Satyandra K. Gupta[+], Hugh A. Bruck[*]

[*]Mechanical Engineering Department
University of Maryland
College Park, MD

[+]Mechanical Engineering Department and Institute for Systems Research
University of Maryland
College Park, MD

[1] Corresponding Author

Characterization of a Reverse Molding Sequence at the Mesoscale for In-mold Assembly of Revolute Joints

Arvind Ananthanarayanan[*,1] , Satyandra K. Gupta[+], Hugh A. Bruck[*]

[*]Mechanical Engineering Department
University of Maryland
College Park, MD

[+]Mechanical Engineering Department and Institute for Systems Research
University of Maryland
College Park, MD

ABSTRACT

In-mold assembly and miniature molding are two technologies that have seen considerable advances in the past few years. These two technologies can be combined to realize miniature assemblies. Our previous work has shown that a significant change in the mold design is necessary to enable in-mold assembly at the mesoscale. Specifically, parts having the pins in the joint need to be molded before parts having holes. This sequence is reverse of the sequence typically used in macroscale assemblies. Moreover, special features are needed in the mold to prevent bending of the pin due to the pressure exerted by the second stage melt. This paper will present methods to characterize the reverse molding sequence from the perspective of: (1) plastic bending of the premolded component, and (2) joint jamming during the mesoscale in-mold assembly process. In this paper we also show that at the mesoscale, the joint jamming is prevented because of the deformation of the pin under the compressive loading during the second stage molding. We also describe features in the mold that can control the pin diameter deformation and hence control the joint parameters. We present experimental data and computational models to enable the choice of the right in-mold assembly process taking the part sizes into consideration.

[1] Corresponding Author

KEYWORDS

In-Mold Assembly, Injection Molding, Plastic Bending, Pin Diameter, Premolded Components

1. INTRODUCTION

Injection molding is a high throughput method for polymer processing and is being used to produce a wide variety of products with varying shapes and sizes [1-4]. Due to the tremendous promise of injection molding in considerably reducing manufacturing cycle time while keeping the production costs low, it is being considered as a viable option for automation of assembly [4-6] as well as miniaturization of products [7, 8].

In-mold assembly processes have been developed to manufacture revolute joints [6, 9, 10]. These processes involve 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 is chosen such that the materials are chemically incompatible (i.e. they have no tendency of adhering to each other during and after injection molding). The appropriate material combinations have been identified for in-mold assembly processes in several previous works [6, 9, 10]. Figure 1 shows the CAD model of a mesoscale revolute joint that can be manufactured using in-mold assembly.

In the past few years, many advances have also been reported in the field of miniature molding. This method can be used to accurately manufacture intricate miniature features such as that. Considering the low cycle time of the injection molding process, this manufacturing method is seen as being highly cost effective. Currently there are several products that can not be realized due to their difficulty in manufacturing and assembly owing to their small sizes. Considering the advances reported in the in-mold assembly and miniature molding technologies, combining the two to realize miniature in-mold assemblies holds promises to extend product possibilities.

We have shown in our previous work that macro-scale revolute joints can be formed by first molding the hole and then molding the pin inside the hole [6]. As the pin shrinks during the solidification process, it moves away from the hole and provides the clearance for the joint to function [11]. From this point on, this molding sequence will be referred to as the normal molding sequence. 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 sequence 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. So a new strategy is needed to realize mesoscale revolute joints.

Our previous work has shown that it is possible to manufacture in-mold assembled revolute joints at the mesoscale by molding the pin first and then molding the hole [9, 10, 12]. For the sake of brevity, we will call this the reverse molding sequence. 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. This will be discussed in further detail in the following section.

To understand the design requirements for different classes of in-mold assembled revolute joints, it is necessary to develop a clear understanding of the effect of the joint size on the choice of molding process. It is necessary to clearly distinguish between the mesoscale and the macroscale from the in-mold assembly perspective. The results reported in this paper can be used by manufacturers to choose the right in-mold assembly process based on the part sizes. There are two distinct aspects that need to be considered to make a clear distinction between the macroscale and the mesoscale.

The first involves the effect of size of the premolded component on its plastic bending as a result of the second stage injection. This plastic bending is of the premolded component is of significance at the mesoscale due to the reversed molding sequence. Our previous work [9, 10] has shown that this plastic bending can be controlled using innovative mold designs. However it is not clear what the effect of part sizes are on the plastic bending of the premolded component.

The second aspect is that of clearances in the revolute joints. For proper functioning of a revolute joint, a clearance fit is required between the pin and the hole. At the macroscale, this clearance is ensured by the shrinkage of the pin after cooling and ejection [11]. This is because the pin is molded in the second stage. However due to the reversed molding sequence at the mesoscale, clearance principles at the macroscale do not apply. The joint size would obviously have a significant role to play in determining the clearances in the revolute joints. Hence to select the appropriate in-mold assembly process, it is important to develop an understanding of the effect of joint size on the assembly clearances.

This paper will present results which can be used to make a distinction between the macroscale and mesoscale from the in-mold assembly perspective. Further it will also provide insight into the size scale at which the reverse molding sequence can not be used. We will consider both the factors outlined above, i.e., the plastic bending and the clearances in revolute joints. Several scenarios also necessitate the clearances to be engineered to meet the design requirements. Hence, there is an impending need to develop manufacturing methods to control the clearances in mesoscale in-mold assemblies so as to give the designer the freedom to choose the appropriate clearance for the functioning of the component. Methods will therefore be presented to characterize and control the final pin diameter of the revolute joints.

2. OVERVIEW

One of the major differences between in-mold assembly at the mesoscale and that at the macroscale is the molding sequence [9]. At the macroscale the part with the hole (Figure 1) is molded in the first stage. The part with the pin is then molded in the second stage with the first stage part acting as a mold insert. However at the mesoscale, the part with the pin is molded first. This is accomplished by molding a hole in the first stage using a side action mold insert (*SAMI*). The size of the *SAMI* is the same as the desired size of the hole. However making a *SAMI* with a small diameter for mesoscale revolute joints is an expensive process. Also a *SAMI* with a small diameter poses alignment problems and is prone to failure due to forces applied by the injection pressure. This is illustrated in Figure 2.

An alternative approach to fabricating a mesoscale revolute joint involves premolding one component in the first stage then forming the second component in a second stage. However, the high pressure, high temperature polymer injected in the mold cavity during the second stage causes the mesoscale features in the premolded component to bend plastically, as illustrated in Figure 3. This bending is caused due to the small size of the premolded component. We have developed two alternate methods to control this plastic bending. These are illustrated in Figure 4.

As mentioned previously assembly clearances at the macroscale are formed due to the shrinkage of the pin away from the cavity after the second stage injection. However due to the reversed molding sequence at the mesoscale, the shrinkage of the hole after cooling and ejection [12, 13] may lead to an interference fit. This may lead to a non functional joint. Figure 5 illustrates this concept. In the figure, d_h is the hole diameter and d_p is the pin diameter. Through several experiments, we realized that joint jamming is prevented at the mesoscale by the plastic extrusion of the premolded component. We have reported preliminary results from experiments and computational modeling in [14]. This effect is caused by the pressure applied on the premolded component during the packing phase of the second stage injection and is responsible for fabrication of functional mesoscale revolute joints [15-19]. However, in order to characterize and control this effect, it is important to understand its dependence on the joint size under consideration [20]. Since macroscale concepts can not be directly scaled down to the mesoscale, we need to develop a better understanding of how clearances are obtained in in-mold assemblies at the mesoscale. This is illustrated in Figure 6. In the figure, d_p is the diameter of the pin and L_s is the length of the support provided to the premolded mesoscale pin during the second stage injection. Subsequently we also need to develop methods to control this diameter using innovative mold design strategies.

In summary, to characterize the in-mold assembly process, we need to understand the effect of the part sizes on the selection of the in-mold assembly process. To accomplish this, we have designed three separate sets of experiments to characterize the process and classify them under macroscale or mesoscale in-mold assembly processes. These experiments are: (1) the effect of the size of the premolded component on plastic bending at the mesoscale, (2) the effect of the size of the premolded component on the final pin diameter of the revolute joint, and (3) effect of the cavity length on the final pin diameter of the revolute joint. The following sections will discuss the approach we have used to conduct these experiments and will go on to discuss the results.

3. EFFECT OF PIN DIAMETER ON PLASTIC BENDING AT MESOSCALE

3.1 Problem Statement

Mesoscale in-mold assembly methods significantly differ from macroscale methods. This is due to the plastic deformation of the premolded components during the second stage polymer melt flow as illustrated in Figure 3. This plastic bending occurs due to the small sizes of the premolded component. However the transition zone at which this deformation becomes unacceptable from the manufacturing perspective is unclear. Hence there is a need to develop numerical methods to understand this transition the perspective of plastic bending. This method can subsequently be used to determine the mold design strategy that needs to be used for in-mold assembly of revolute joints. In this section, we describe a computational approach which has been verified experimentally for identifying excessive plastic bending.

3.2 Experimental Approach

To establish the relationship between the size of the mesoscale pin on the premolded component and its plastic deformation during second stage injection, we conducted experiments by varying the size of the pin while keeping the geometry of the flow constant. We subsequently measured and plotted the deformation of the mesoscale pin. Due to the inherent symmetry in the premolded component, a geometry consisting of only one mesoscale pin sufficed for the experiment. This geometry is illustrated in Figure 7.

We injected the second stage polymer in the cavity as illustrated in Figure 8. For this experiment we fixed the length of the pin $\boldsymbol{L}$ to 2.54 mm. We repeated these experiments for different pin diameters $\boldsymbol{d}$. The pin diameters were fixed at 0.79 mm, 0.99 mm, 1.19 mm, 1.39 mm and 1.59 mm. We created 5 samples for each pin diameter. At the end of the filling for each experiment, we measured and recorded the final plastic deformation of the pin after ejecting the assembly from the mold. We measured and recorded the deformations using the method described by Ananthanarayanan et al. [9].

3.3 Results and Discussion

After ejecting the second stage parts from the injection molding cavity, we measured the overall plastic deformation δ of the premolded component using the strategy illustrated in Figure 9. Figure 10 shows the experimental results of the ratio of the plastic deformation and pin diameter of the premolded component for different pin diameters. The results indicate that the deformation drops considerably for increasing pin diameters.

From the experimental results for plastic deformation of the pin, the force per unit length on the premolded component due to the second stage melt flow could be computed using structural simulations in ANSYS 11.0 [21]. Using this force per unit length, we constructed structural simulations by varying the length of the pin to compute a clear distinction between mesoscale and macroscale based on the effect of plastic bending of the premolded component relative to the pin diameter and the length. The material properties used to define the premolded component in ANSYS 11.0 are shown in Table 1. The boundary conditions we used to conduct the structural simulations are illustrated in Figure 11. From the manufacturing perspective, it can be argued that a deformation of 5% of the pin diameter is acceptable for good quality revolute joints. These results are illustrated in Figure 12. From these results we can make a clear distinction between macroscale and mesoscale from the plastic bending perspective. To inhibit the plastic bending of the premolded components, we have developed two alternate strategies which are illustrated in Figure 4 [9, 10]

4. EFFECT OF SIZE SCALE ON FINAL PIN DIAMETER

4.1 Problem Statement

Plastic bending of the premolded component is a result of its size. This plastic bending can be inhibited by using radial supports [9] or bi-directional filling [10]. However, simply the use of these strategies does not ensure appropriate clearances in the mesoscale in-mold assembled revolute joints. Hence it is important to understand the effect of the size on the final joint dimensions. Figure 6 explains how the premolded component deforms plastically as a result of the pressure exerted by the second stage polymer melt. This deformation is results in formation of appropriate clearances in the in-mold assembled revolute joints. However it is not clear what size scales are responsible for the onset of this plastic deformation which prevents joint jamming. In this section, we will examine the effect of the size of the premolded component from the perspective of this plastic deformation during in-mold assembly.

4.2 Experimental approach

In order to establish the effect of the size scale on the final pin diameter, we conducted experiments on both macroscale and mesoscale. In the first experiment, we fabricated a macroscale in-mold assembled revolute half joint with pin diameter of 6.35 mm. The dimensions of the first stage and second stage parts are the same as illustrated in Figure 13. Subsequently, we conducted experiments at the mesoscale by varying the pin diameter d_p between 0.79 mm to 1.59 mm. The dimensions of the premolded component are the same as illustrated in Figure 7 with the exception of pin length L which was 3.81 mm instead of 2.54 mm. We collected data for five different diameters. We molded 6 samples each data point and recorded the average change in diameter. To measure the change in diameter, the premolded component was separated from the second stage part and it was photographed. Subsequently, the photograph of the premolded component was processed using MATLAB to find the change in diameter relative to the original diameter of the premolded component. The steps taken to find the premolded component deformation are illustrated in Figure 14.

4.3 Results and Discussion

The macroscale premolded pin before and after second stage injection can be seen in Figure 15. However, the pin was not easily removed from the second stage component, indicating that the desired clearance was not achieved. Also, there was no appreciable change in diameter of the part after second stage injection, which indicated that all of the deformation during the second molding stage was perfectly elastic. Hence, macroscale in-mold assemblies can clearly not be produced using the molding sequence suitable for mesoscale in-mold assemblies.

The next experiment involved premolded components of different pin sizes at the mesoscale. We measured the change in diameter of the premolded component after second stage injection using the procedure illustrated in Figure 14. To develop a computational model to predict the final diameter we developed a finite element model using ANSYS 11.0. This model related the final pin diameter to the initial pin diameter under the processing conditions used. The material properties of ABS illustrated in Table 1 were used for the purpose of the FE simulations. The experimental results and the corresponding computational model are illustrated in Figure 16.

The plot in Figure 16 clearly indicates that the change in pin diameter of the premolded component due to the second stage has a decreasing trend as the pin diameter is increased. The model deviates from the experimental results for higher values of pin diameter. This is because the computational model does not account for friction between the pin and the mold piece. This friction between the premolded component and the mold piece is more pronounced for larger pin diameters due to greater surface area of contact between the pin and the mold piece. Incorporating friction into the model will therefore ensure a better agreement between the model and the experiments. However from the manufacturing perspective, it is unnecessary to capture the physics for larger values of pin diameter. This is because for higher pin diameters, the in-mold assembly process developed for the mesoscale can clearly not be used. For a material combination of ABS and LDPE as is the case here, mesoscale in-mold assembly methods can not be used for pin diameters greater than 1.5 mm. This is observed due to two reasons.

(1) The change in pin diameter for premolded components with pins greater than 1.5 mm is not appreciable. This may lead to jammed in-mold assembled revolute joints
(2) The change in cross-section of the second stage melt cavity as the second stage polymer melt encounters the pin in the premolded component increases as the pin diameter increases. This change induces a change in velocity of the second stage polymer melt around the pin. This concept is illustrated in Figure 17. A higher change results in a higher increase in the velocity of the polymer melt. Higher velocities of the polymer melt results in a higher drag force on the premolded component. However the pin is constrained by the radial supports. This inhibits the deformation of the pin. However the pin offers a high resistive force to the drag force. This resistive force may result in shearing of the pin as illustrated in Figure 17.

5. CONTROLLING PIN DIAMETER IN MESOSCALE IN-MOLD ASSEMBLIES

5.1 Problem Statement

As mentioned previously, assembly clearances in the mesoscale revolute joint can be produced by the reduction in diameter of the premolded component after second stage injection. This reduction in diameter is caused by the aforementioned plastic deformation of the premolded component (Figure 6). In order to develop a method to control the pin diameter let us consider the following. L_c is the support cavity length, i.e., the length of the cavity in the radial supports used to constrain the mesoscale premolded component. The support cavity length L_c plays an important role in determining the final diameter of the mesoscale pin after second stage injection, and therefore the level of clearance in the revolute joint.

In order to understand the effect of the support cavity length, let us review the complexity of the mesoscale in-mold assembly process. In the first step, the first stage part is molded and the side core supports are retracted as illustrated in Figure 6. During the second stage cavity filling, the mesoscale premolded component acts as a soft mold insert for the second stage polymer melt flow. The premolded component is made of an elastoplastic material that can plastically deform due to the forces applied by the second stage melt [3, 4]. This bending can be inhibited by the presence of the radial supports. However, in the second step of the molding process, a very high compressive load is applied to the premolded mesoscale component after completion of cavity filling. This compressive load can also cause plastic deformation in the form of extrusion of the premolded component, as previously illustrated in Figure 6. This plastic deformation leads to change the diameter of the mesoscale premolded component from d_p to d_p'. During this plastic compression of the mesoscale pin, the portion of the pin which is supported by the radial support gets extruded into the cavity. The final length of the pin that is supported by the radial supports is L_e as illustrated in the figure. Hence the length of the extrusion can be $L_e - L_s$. However this length of extrusion can not be greater than the support cavity length L_c. This gives rise to the following constraint:

$$L_e \leq L_s + L_c \qquad (1)$$

where L_s becomes the design requirement in order to prevent the plastic bending of the premolded component due to the second stage polymer melt flow. Hence by controlling L_c, we can control the length of the extrusion. This will also have an effect on the final deformed diameter of the mesoscale pin d_p'.

From the mechanics perspective, it is important to keep the change in diameter $d_p' - d_p$ as low as possible. This is because a large change in this diameter induces high levels of plasticity in the mesoscale component. This causes the part to be considerably weaker than the original part because of the reduced cross section area and moment of inertia. However, from the manufacturing perspective this plastic deformation is necessary to prevent jamming in the in-mold assembled mesoscale revolute joint. Hence it is imperative to develop methods to characterize and control this plastic deformation which leads to change in the diameter of the premolded mesoscale component. These methods will enable us to fabricate mesoscale in-mold assemblies with appropriate assembly clearances without compromising on the component strength.

In order to characterize and control the plastic deformation, one should identify the parameters that need to be considered. These include *geometric parameters* which are the dimensions of the premolded component and the second stage component, *mold design parameters* which are the length of the support cavity length L_c, the radial support length L_s and other mold dimensions such as sprue and runner dimensions, *material properties* which are the structural properties of the premolded component and the flow properties of the second stage polymer melt, and *molding conditions* which are used during the in-mold assembly operation, such as temperature and pressure of the melt.

In this section, we will discuss a computational approach to determine the mold design parameters that should be used to control the final dimensions of the mesoscale in-mold assembled revolute joint.

5.2 Experimental Approach

To develop a predictive model for the plastic deformation of the mesoscale premolded component, we need to develop an understanding of the compressive force that will act on the component. Using the parameters described above, this compressive force can be determined. This force can then be applied to a computational finite element solver to obtain the configuration of the deformed premolded component resulting from the second stage filling. In order to validate the change in diameter predicted by the finite element model, it is necessary to compare the results of the FE simulations with experimental results. In the next section we will outline the experimental approach used to understand the size effects during in-mold assembly and to understand the methods to control pin diameter of the revolute joint during in-mold assembly.

In this experiment we used the premolded component illustrated in Figure 7 at a diameter of 0.7984 mm and pin length L = 3.81 mm. We then inserted this premolded component into a second stage mold cavity with cavity length $L_{c.}$ Subsequently we recorded the final deformed pin diameter for 4 different values of $L_{c.}$ These values ranged between 0.254 mm and 2.54 mm. The second stage mold design used for this experiment is illustrated in Figure 18. Finally we ejected the assemblies from the second stage mold and measured the final pin diameters of the premolded component using the method illustrated in Figure 14. We collected 5 samples for each value of support cavity length and averaged the final pin diameters to get statistically significant results.

For all three sets of experiments we chose *Acrylonitrile Butadiene Styrene* (ABS) manufactured by *Ashland Chemicals* as the material for the premolded component. For the second stage material, we chose *Low Density Polyethylene* (LDPE) manufactured by *Dow Chemicals*. This minimizes the thermal softening of the premolded component by the high temperature second stage melt. We used the Milacron Babyplast injection molding machine to conduct the experiments. The processing parameters for injection molding the materials into the mold cavity are illustrated in Table 2.

5.3 Results and Discussion

To characterize the effect of support cavity length on the final pin diameter, 5 samples were produced at 4 different values of support cavity length, and the maximum diameter variation (d_v) of the pin was recorded as a function of the length variation (L_v) due to extrusion (L_e-L_s). To accurately measure the diameter, we employed image processing techniques on photographs of the samples as illustrated in Figure 14. We then obtained the diameter variation obtained from the difference in the maximum and the minimum diameter of the premolded component after the second stage injection. To record the length variation, we recorded the pin lengths of the samples before and after second stage injection. A sample premolded component after second stage injection is illustrated in Figure 19.

In order to explain the results obtained through experimentation, we developed a computational model to predict the diameter variation (d_v) with varying support cavity lengths. The model is based on finite element simulations in ANSYS 11.0 [8]. In order to improve computational efficiency, only the pin was modeled in the finite element simulation. The boundary conditions that were applied to this FE solver are illustrated in Figure 20. In the figure, U_x, U_y and U_Z are the allowed displacements in the x, y and z directions respectively. L_c and L_s are described earlier in the paper, and the pressure in Table 1.

Table 1 lists the material properties that we used for the first stage material for the purpose of our finite element simulations. These values were obtained experimentally from cantilever bend tests [9]. Figure 21 shows the experimental observations and a corresponding computation model relating the diameter variation in the premolded mesoscale components with the length variation. The variation in length was recorded to be equal to the support cavity length L_c for the first three experimental points. i.e. the force applied by the second stage melt causes the pin to extrude till it encounters a mold wall. For the last point, the length variation recorded was 1.3 mm. However the support cavity length was 2.54 mm which was considerably higher than the length variation (i.e., $L_e<L_s+L_c$)

The results clearly indicate that the diameter variation is high for increasing support cavity lengths. However the results also show a tendency of the diameter variation to stagnate for high values of L_c. This indicates that for low values of of L_c, the pin extrudes such that $L_e = L_s + L_c$ as explained in equation 1. However for larger cavity support lengths, L_e reaches a stagnation value such that $L_e < L_s + L_c$. After this point, L_e becomes independent of the cavity support length L_c. Hence the diameter variation reaches a stagnation value such that it becomes independent of the cavity support length. However the experimentally recorded diameter variation for the highest value of L_c is as much as 0.38 mm which is 48% of the original pin diameter. This amount of plastic deformation leads to severe weakening in the premolded component. Hence this would render the mesoscale revolute joint unusable. Therefore, it is necessary for us to develop an understanding of the optimum support cavity length leading to manufacture of functional mesoscale revolute joints. The computational finite element model shown in Figure 21 predicts the relationship between the variation in length and diameter.

The model clearly elucidates that the rise in support cavity length initially causes a larger variation in diameter. However for high values of support cavity lengths, the model over-predicts the change in diameter. This is because the effect of non-linearity in the deformation is more pronounced for higher values of deformation. Hence the complexity of the current model is insufficient to capture the phenomenon for higher values of plastic deformation.

However, as explained previously, higher values of non-linear deformation tend to weaken the part due to strain hardening. This, in turn, affects the joint quality as well. The joint is therefore rendered defective from the quality control point of view. Hence from the manufacturing perspective, it is sufficient to capture the physical phenomenon for low values of deformation.

Figure 22 shows sample results from the finite element analysis that we performed. Figure 22 (a) shows the results for a support cavity length of 0.4 mm. These results show an onset of non-linear stress strain behavior in the deformation of the pin due to the forces applied by the second stage melt flow. These forces cause a variation in both diameter and length as illustrated in the figure. Figure 22 (b) on the other hand shows a clear tendency of *necking* in the pin for high values of support cavity length. This behavior clearly indicates extremely high values of strains in these regions. From the manufacturing perspective, this kind of behavior is clearly unacceptable since it results in structurally weak mesoscale revolute joints. Hence we can safely say that high values of support cavity length are undesirable.

However in order to ensure a smooth running revolute joint, some amount of plastic deformation resulting in diameter change is essential. This diameter change prevents jamming of the joint. A higher value of diameter change will ensure a smoother joint. Lower diameter changes on the other hand will ensure structural integrity of the joint. Hence the diameter variation is a design parameter that should be selected based on the requirements of the product.

In order to select the right support cavity length, the designer can make a decision on the appropriate amount of diameter variation based on his experience with the material being used. Subsequently, with the help of FE simulations, a relationship can be established between the designed diameter variation and the corresponding required support cavity length. The designer can then use this support cavity length to manufacture the in-mold assembled mesoscale revolute joint satisfying the design requirements.

Figure 23 shows a general rule that can be adopted in selecting the support cavity lengths for different pin diameters keeping the other material and geometric parameters same as that described earlier in this paper. This graph was generated based on the computational FE model described earlier in the section for the material and geometry described in this paper.

Using the modeling approach developed in this paper, it will now be possible to focus on developing a theoretical framework in the future that is capable of predicting the forces that are developed within the mold cavity during the second stage injection, which are responsible for the plastic deformation in the parts. Also, there will be a need to quantify the actual clearances in the joints resulting from the diameter variation reported in this paper.

6. CONCLUSIONS

In this paper we present a technique for distinguishing between the mesoscale and the macroscale to choose the appropriate mold design for in-mold assembly. We have developed a method that can be easily used by the industry by conducting minimal amount of experiments to determine when reverse molding sequence can be successfully used. We have conducted extensive experiments to validate the computational approach described in this paper. In order to utilize the proposed approach for a new material, only stress-strain experimental data need to be obtained.

The following new results are reported in this paper. The effect of size is presented distinctly for the following two different aspects of the in-mold assembly process: (1) the plastic bending due to second stage melt flow, and (2) the final joint dimensions after the in-mold assembly process is completed. Next, we report results of dependence of the final pin diameter on the support cavity length in mesoscale in-mold assemblies. Finally, we have developed a computational model which describes the relationship between the pin diameter variation and the support cavity length. 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 presents designers with a tool to select the appropriate support cavity lengths for the desired joint properties.

This paper is the first attempt at presenting a distinction between the mesoscale and the macroscale from the perspective of in-mold assembly. This paper is also the first attempt at characterizing and modeling how the in-mold assembly process affects the plastic extrusion of pins which leads to the assembly clearances required for realizing mesoscale revolute joints. Using these techniques we have successfully molded mesoscale revolute joints with the desired functionality.

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.

REFERENCES

1 J. P. Beaumont, R. Nagel and R. Sherman, *Successful Injection Molding: Process, Design, and Simulation*, Hanser Gardner Publications (2002).

2 D. O. Kazmer, *Injection Mold Design Engineering*, Hanser Gardner Publications (2007).

3 R. A. Malloy, *Part Design for Injection Molding*, Hanser Gardner Publications (1994).

4 G. Menges, W. Michaeli and P. Mohren, *How to Make Injection Molds*, Hanser Gardner Publications (2001).

5 A. G. Banerjee, X. J. Li, G. Fowler and S. K. Gupta, *Research in Engineering Design* **17,** 207-231 (2007).

6 A. K. Priyadarshi, S. K. Gupta, R. Gouker, F. Krebs, M. Shroeder and S. Warth, *International Journal of Advanced Manufacturing Technology* **32,** 350-365 (2007).

7 J. Giboz, T. Copponnex and P. Mele, *J Micromech Microeng* **17,** R96-R109 (2007).

8 M. Heckele and W. K. Schomburg, *J Micromech Microeng* **14,** R1-R14 (2004).

9 A. Ananthanarayanan, S. K. Gupta and H. A. Bruck, *Polymer Engineering Science* **49,** 293-304 (2009).

10 A. Ananthanarayanan, S. K. Gupta and H. A. Bruck, Characterization and control of plastic deformation in premolded components in in-mold assembled mesoscale revolute joints using bi-directional filling strategy, in *All India Manufacturing Technology and Development Research*, Chennai, India (2008).

11 A. Ananthanarayanan, C. Thamire and S. K. Gupta, Investigation of revolute joint clearances created by an in-mold assembly process, in *IEEE: International Symposium on Assembly and Manufacturing*, Ann Arbor, MI (2007).

12 K. Kwon, A. I. Isayev and K. H. Kim, *Journal of Applied Polymer Science* **98,** 2300-2313 (2005).

13 K. Kwon, A. I. Isayev, K. H. Kim and C. van Sweden, *Polymer Engineering and Science* **46,** 712-728 (2006).

14 A. Ananthanarayanan, S. K. Gupta and H. A. Bruck, Characterization and control of pin diameter during in-mold assembly of mesoscale revolute joints, in *North American Manufacturing Research Institute* (2009).

15 D. Delaunay, P. L. Bot, R. Fulchiron, J. F. Luye and G. Regnier, *Polym Eng Sci* **40,** 1692-1700 (2000).

16 V. Leo and C. Cuvelliez, *Polym Eng Sci* **36,** 1961-1971 (1996).

17 R. Pantani, V. Speranza and G. Titomanlio, *Polym Eng Sci* **41,** 2022-2035 (2001).

18 C. H. Wu and Y. J. Huang, *International Journal of Advanced Manufacturing Technology* **32,** 1144-1154 (2007).

19 H. W. Wu, S. D. Zhang, J. P. Qu and H. H. Xu, *Polym-Plast Technol Eng* **46,** 123-127 (2007).

20 J. Zhao, R. H. Mayes, G. E. Chen, H. Xie and P. S. Chan, *Polym Eng Sci* **43,** 1542-1554 (2003).

21 A. Inc., ANSYS 11.0 documentation, Canonsburg, PA.

Table 1. Nonlinear stress-strain curve of ABS

Stress (Pa)	Strain
0	0
1.80E+07	8.00E-03
3.60E+07	1.60E-02
5.40E+07	1.10E-01
6.00E+07	1.25E-01
6.20E+07	1.53E-01
6.56E+07	1.70E-01
7.5E+07	5.0E-01

Table 2. Injection molding Conditions

	Stage 1	Stage 2
Material	ABS	LDPE
Injection Temp.	240°C	140°C
Injection Velocity	12 cc/s	12 cc/s
Injection pressure	600 bars	600 bars
Cooling time	3s	3s

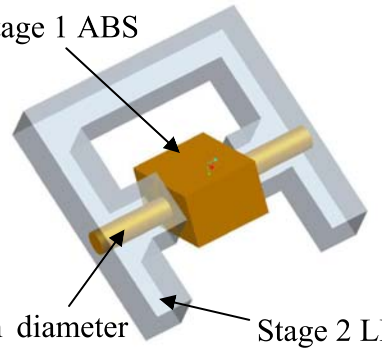


Figure 1 In mold assembled revolute joint.

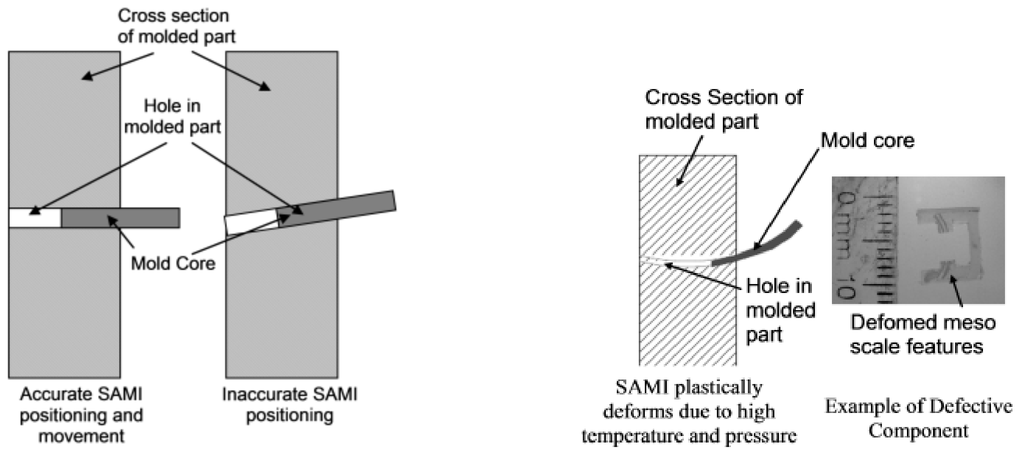


Figure 2 challenges posed by inaccurate alignment of *SAMI* [4]

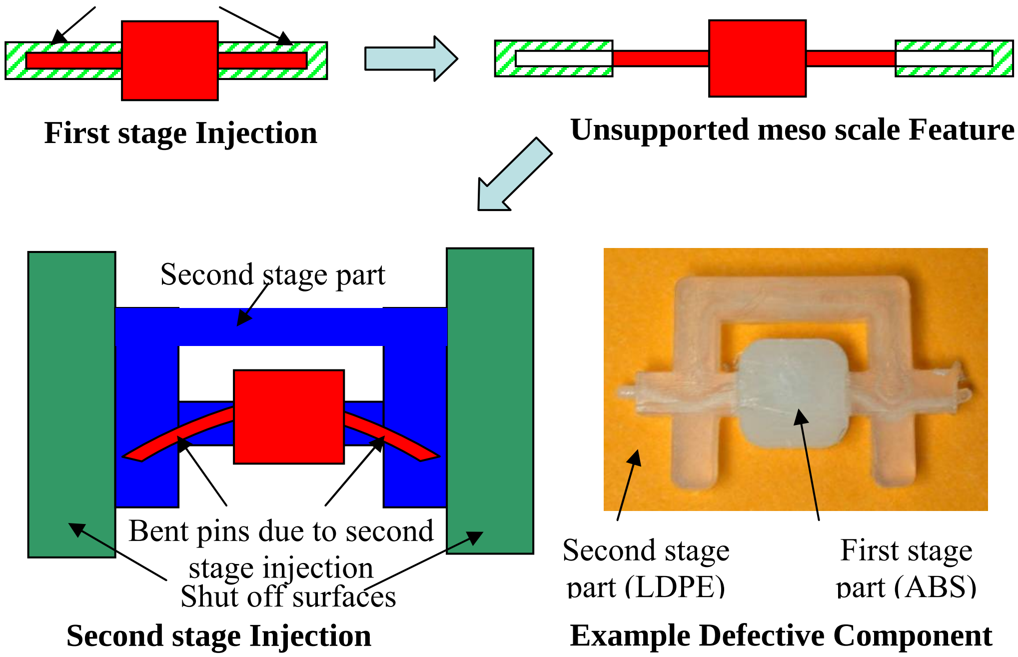
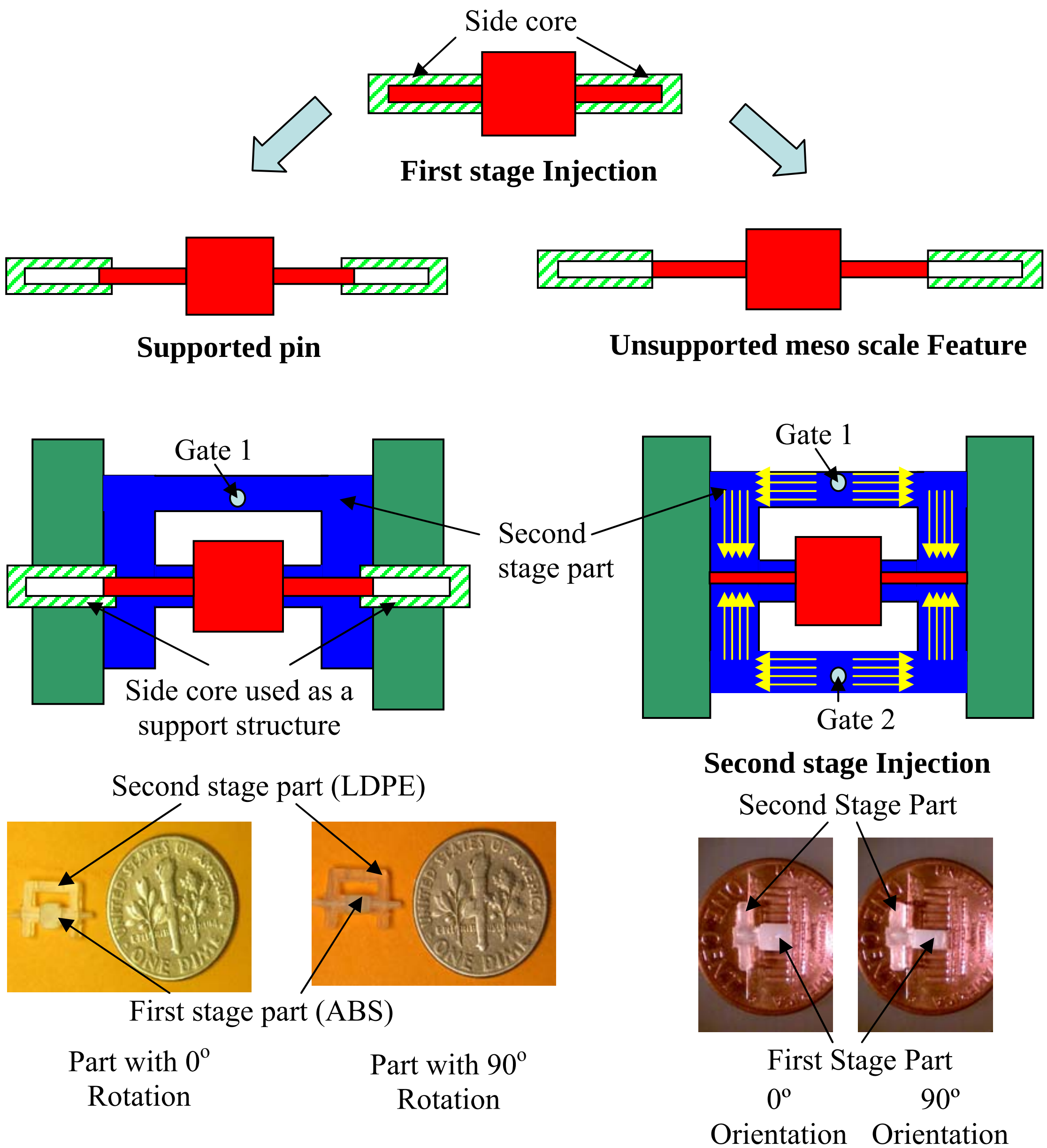


Figure 3 Deformation of mesoscale core due to second stage injection



(a) Mesoscale In-mold assembly using single gated mold design

(b) Mesoscale In-mold assembly using Multi gated mold design

Figure 4 Mold design solutions for realizing mesoscale in-mold assembled revolute joints

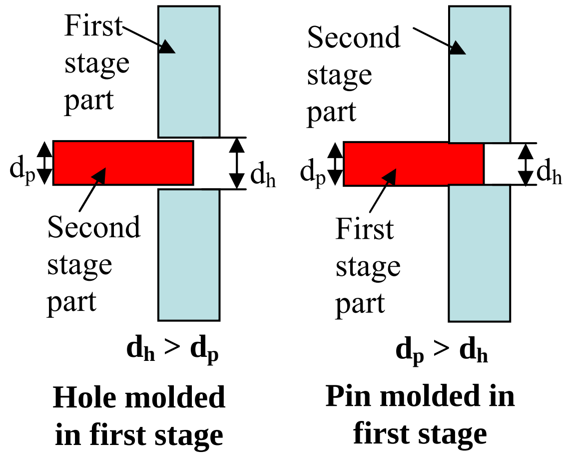


Figure 5 clearances in in-mold assembled Macroscale revolute joints

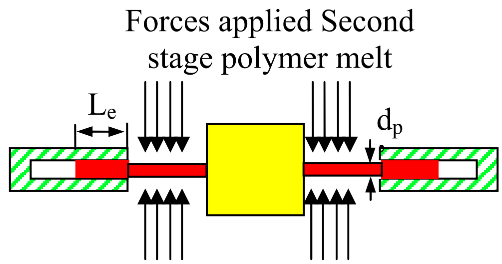


Figure 6 Mold design strategy for creating mesoscale in-mold assembled revolute joints

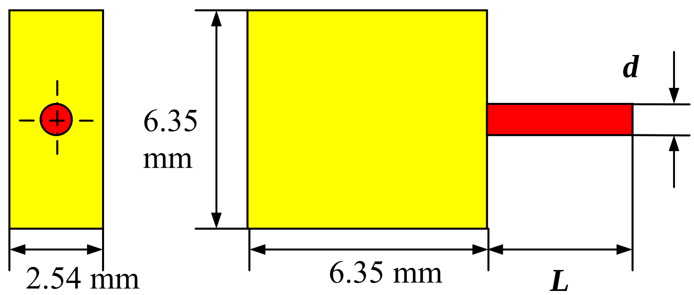


Figure 7 Premolded component for experiments

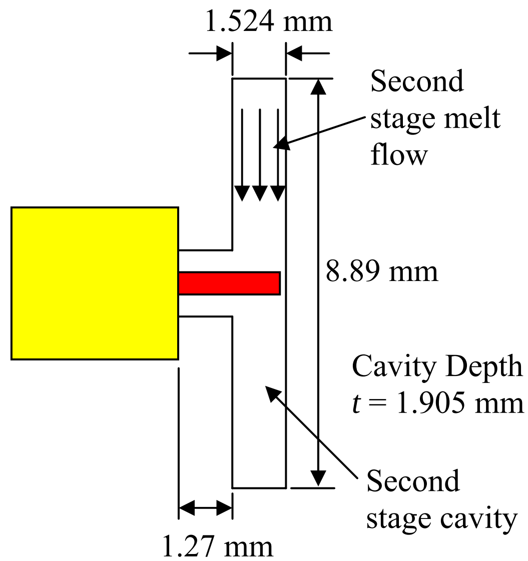


Figure 8 Second stage injection

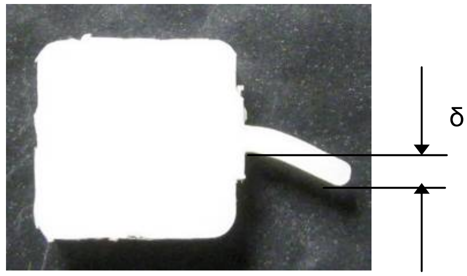


Figure 9 Measurement of plastic deformation of premolded component

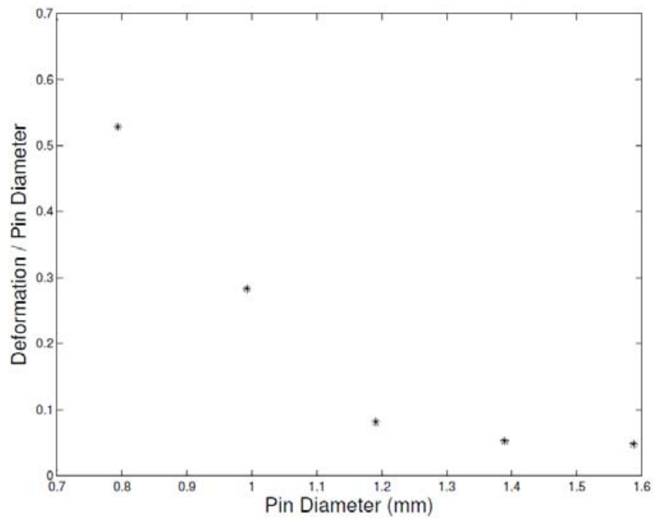


Figure 10 Plastic deformation of pin with varying diameter of the pin

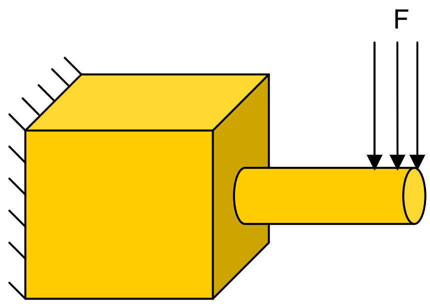


Figure 11 Force modeling on the premolded component

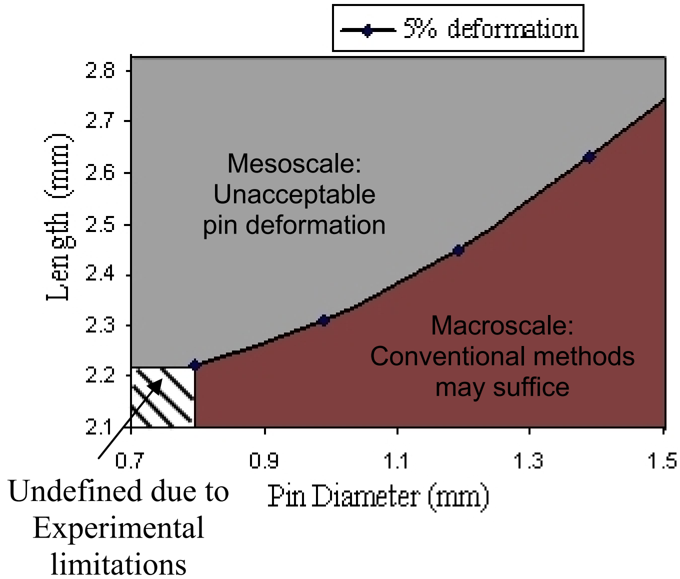


Figure 12 Distinction between macroscale and mesoscale from the in-mold assembly perspective

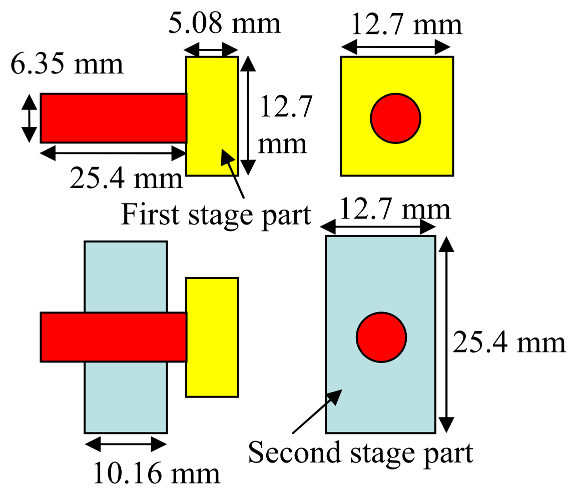
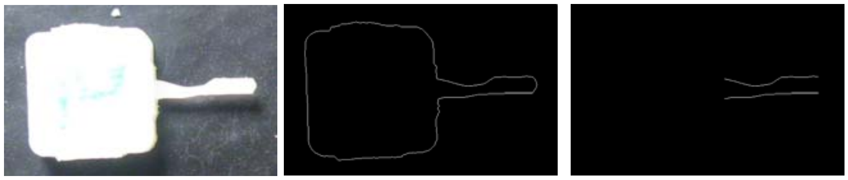
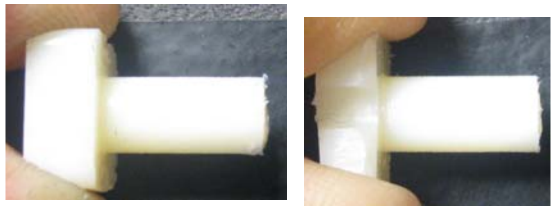


Figure 13 Experimental setup for macroscale experiments



Step 1: Part Image Step 2: Finding Edges Step 3: Mapping pin diameters

Figure 14 Measuring change in pin diameter



(a) Before second stage injection

(b) After second stage injection

Figure 15 Macroscale premolded component before and after second stage injection

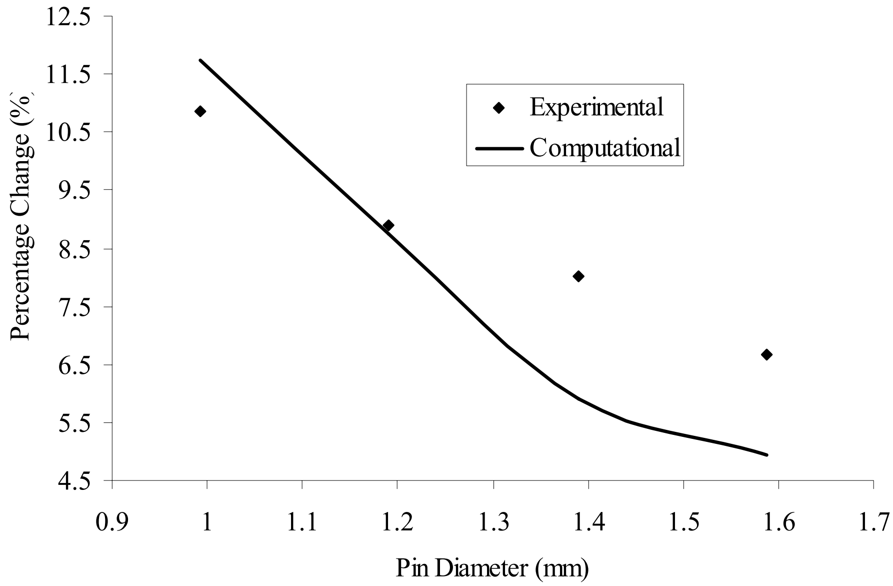


Figure 16 Percentage change in diameter of pin v/s original pin diameter

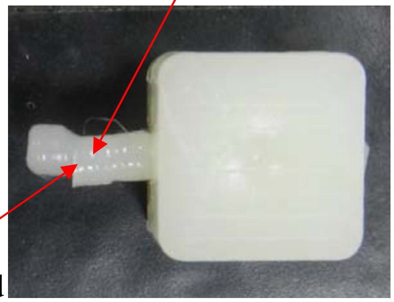


Figure 17 Shearing of pin due to excessive drag resistance

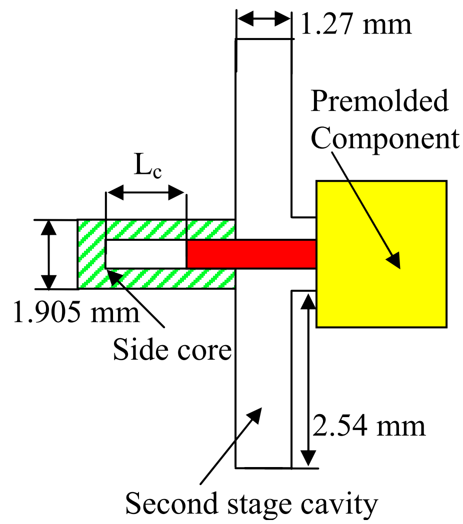
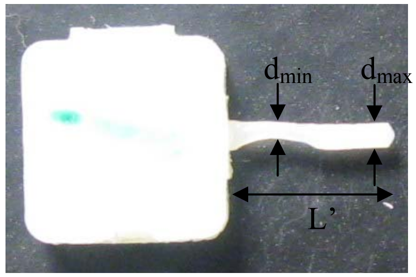


Figure 18 Second stage mold design



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

Figure 19 Measurement of diameter and length variation of premolded mesoscale pin

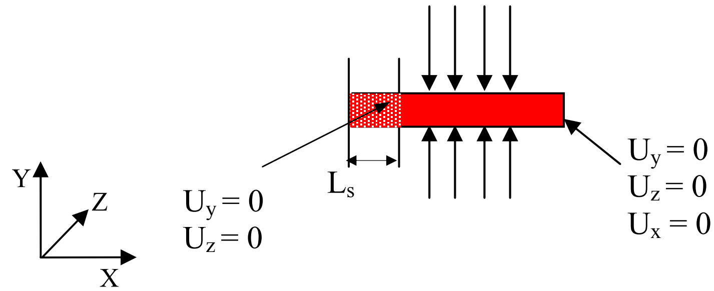


Figure 20 Boundary conditions for finite element solver

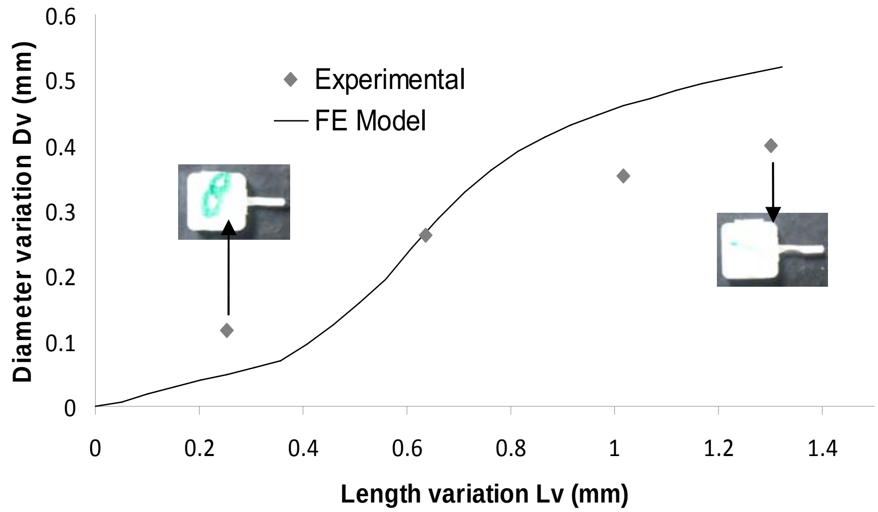
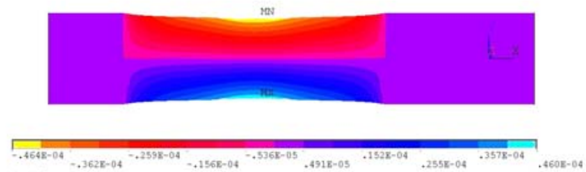
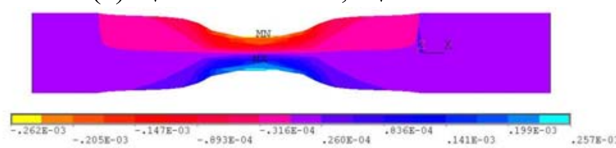


Figure 21 Experimentally recorded diameter variation v/s support cavity length



(a) d_v = 0.0924 mm, L_v = 0.4 mm



(b) d_v = 0.519 mm, L_v = 1.3 mm

Figure 22 Sample results from finite element analysis

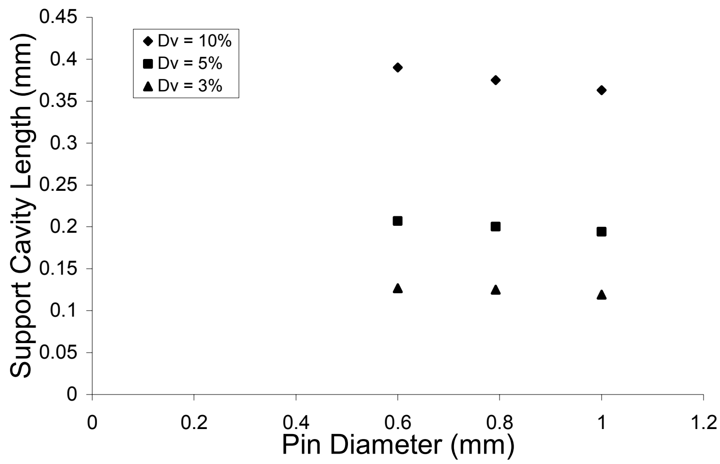


Figure 23 Designed support cavity lengths for desired value of diameter variation