Arvind Ananthanarayanan

Biomimetics Robotics Laboratory,
Massachusetts Institute of Technology,
Cambridge, MA 02140,
e-mail: arvinda@mit.edu

Leicester Ehrlich

Advanced Manufacturing Laboratory,
Department of Mechanical Engineering,
University of Maryland,
College Park, College Park, MA 20742,
e-mail: lester.ehrlich@gmx.net

Jaydev P. Desai

Robotics, Automation, and
Medical Systems Laboratory,
Department of Mechanical Engineering,
University of Maryland,
College Park, MA 20742,
e-mail: jaydev@umd.edu

Satyandra K. Gupta¹

Advanced Manufacturing Laboratory,
Department of Mechanical Engineering and the
Institute for Systems Research,
University of MA,
College Park, MA 20742,
e-mail: skgupta@eng.umd.edu

Design of Revolute Joints for In-Mold Assembly Using Insert Molding

Creating highly articulated miniature structures requires assembling a large number of small parts. This is a very challenging task and increases cost of mechanical assemblies. Insert molding presents the possibility of creating a highly articulated structure in a single molding step. This can be accomplished by placing multiple metallic bearings in the mold and injecting plastic on top of them. In theory, this idea can generate a multi degree of freedom structures in just one processing step without requiring any post molding assembly operations. However, the polymer material has a tendency to shrink on top of the metal bearings and hence jam the joints. Hence, until now insert molding has not been used to create articulated structures. This paper presents a theoretical model for estimating the extent of joint jamming that occurs due to the shrinkage of the polymer on top of the metal bearings. The level of joint jamming is seen as the effective torque needed to overcome the friction in the revolute joints formed by insert molding. We then use this model to select the optimum design parameters which can be used to fabricate functional, highly articulating assemblies while meeting manufacturing constraints. Our analysis shows that the strength of weld-lines formed during the in-mold assembly process play a significant role in determining the minimum joint dimensions necessary for fabricating functional revolute joints. We have used the models and methods described in this paper to successfully fabricate the structure for a minimally invasive medical robot prototype with potential applications in neurosurgery. To the best of our knowledge, this is the first demonstration of building an articulated structure with multiple degrees of freedom using insert molding. [DOI: 10.1115/1.4005327]

1 Introduction

Current methods to manufacture highly articulating mechanical assemblies involve fabrication of individual parts using machining or rapid prototyping among other processes. Subsequently, these parts are assembled manually using mechanical fasteners. These methods, although highly inefficient, are popular processes for making macro scale mechanical assemblies. However, for fabricating miniature mechanical assemblies (joint dimensions < 1 mm) [1], manual assembly operations become very tedious and, in some cases infeasible. This is because, owing to the individual part sizes, it is difficult for a skilled human operator to assemble the parts. Also fasteners are usually unavailable or are very expensive at the smaller scale. Also, a mechanical assembly consisting of a high overall part count would be more susceptible to failure. Traditional machining and prototyping methods are therefore not suitable for fabricating miniature mechanical assemblies. There is currently no scalable and cost effective manufacturing process that can be used to fabricate such miniature assemblies for large scale production. There is therefore an impending need to develop new strategies for fabricating multifunctional, miniature mechanical assemblies.

Insert molding presents an efficient method of functionally grading the fabricated structure according to the application. The process involves molding over a pre-existing mold insert in the mold cavity. Popular molding processes for insert molding involve injection molding and resin transfer molding (RTM). Insert molding has become a popular process for several applications such as composite fabrication [2], packaging [3], microfluidics [4], etc.

Researchers have studied insert molding of metals in polymers in several applications over the past few years [5,6]. They have developed methods for using metals as reinforcing structures in injection molded polymer parts. Hence, the focus of the research is on developing good bonding between the polymer and the metallic structures. This is usually accomplished by controlling the shrinkage of the polymer on top of the insert. However, these methods are not suitable for developing articulating structures for miniature mechanical assemblies. Hence, we need to develop methods to prevent bonding between the polymer and the metal inserts to allow for articulation after the insert molding process. This paper will address this challenge and demonstrate an innovative manufacturing approach based on the in-mold assembly process [7–9] to realize highly articulating mechanical assemblies. We will also present an analytical modeling based approach to select the optimum joint parameters which enable effective use of this process. Finally, we will demonstrate the capability of this process by using it to fabricate a multiple degree of freedom robot structure with potential applications in minimally invasive surgery.

2 Background: In-Mold Assembly

In-mold assembly provides an effective alternate method for manufacturing miniature mechanical assemblies. These methods have been developed in the past for both macroscale [7] and mesoscale [8,9]. Using this method, a fully assembled articulating rigid body joint could be ejected from the mold. This eliminates the need for any post processing in the form of additional assembly steps, after the injection molding process was complete. This process significantly reduces the overall lead time for production and also substantially reduces production costs. The in-mold assembly process is ideal for large scale production of miniature mechanical assemblies.

Macroscale in-mold assembly methods involve injecting a second stage polymer over a premolded component which contains a

¹Corresponding author.

Contributed by the Mechanisms and Robotics Committee of ASME for publication in the JOURNAL OF MECHANICAL DESIGN. Manuscript received January 24, 2011; final manuscript received August 5, 2011; published online December 14, 2011. Assoc. Editor: James Schmiedeler.

hole. The second stage polymer fills the hole in the premolded component. On controlling adhesion and shrinkage of the second stage polymer, in-mold assembled macroscale joints with appropriate clearance can be manufactured.

However, Ananthanarayanan et al. [10] have demonstrated that this molding sequence does not work for the mesoscale due to mold piece alignment issues. Hence, they have proposed a reversed molding sequence for realizing in-mold assembly at the mesoscale. This is illustrated in Fig. 1. Using this molding sequence ensures that the mesoscale premolded components do not deform plastically during the second stage injection.

At the macroscale, the joint clearance is realized due to shrinkage. After cooling, the pin, which is made of an injection molded polymer shrinks away from the hole [7]. By controlling the injection molding parameters, it is possible to obtain appropriate friction in the in-mold assembled revolute joint at the macroscale [11]. However, the reversed molding sequence at the mesoscale may lead to jammed joints due to shrinkage of the polymer. This concept is illustrated in Fig. 2.

To explain the issue of the jammed joints, Ananthanarayanan et al. [9] have reported a change in final pin diameter due to the second stage injection molding process. This is illustrated in Fig. 3. The forces applied by the second stage polymer melt during the packing phase causes the pin to deform plastically and reduce in diameter. This deformation which is caused by the small size scales of the pin is instrumental in relaxing the radial stresses at the interface of the joint which are caused by the shrinkage of the cavity on the top of the pin. The plastic deformation of the pin, if controlled effectively, can be used as a method of controlling the final clearances in the revolute joint. Hence, although the strategy of molding the cavity over the pin is counterintuitive from the shrinkage point of view, it works at the mesoscale due to the plastic deformation of the pin.

Fig. 1 Mold design solutions for realizing mesoscale in-mold assembled revolute joints [8,10]

Fig. 2 Clearances in in-mold assembled macroscale revolute joints [9]

Current in-mold assembly methods require the use of cavity morphing methods. These molds require use of specialized injection molding machines (rotary platen injection molding machines) consisting of multiple nozzles to inject different materials sequentially into the mold cavity. Also, current in-mold assembly methods require the use of multiple polymers which are chemically incompatible. Hence, for applications which permit use of only one polymer, an alternative process is required.

To overcome the limitations of previously developed in-mold assembly methods, we have utilized the advantages of insert molding for in-mold assembly. This process significantly simplifies the injection molding processes to fabricate in-mold assembled rigid body articulating joints. This paper explains this process in detail and demonstrates modeling methods to select appropriate geometric parameters for enabling in-mold assembly using insert molding at the mesoscale.

In the next section, we will describe the basic principle of the in-mold assembly process using insert molding. Subsequently, we will describe an analytical modeling approach to select the different design parameters for successful realization of an in-mold assembled revolute joint at the mesoscale using the insert molding method with appropriate joint friction. We will then demonstrate the capability of this process by using it to fabricate a multiple degree of freedom robot structure with potential applications in minimally invasive surgery. Finally, the paper will conclude with a detailed discussion on the results.

3 Insert Molding of Articulating Joints

The in-mold assembly process using insert molding involves the use of cylindrical metallic parts made of Brass as mold inserts. The mold design concept for manufacturing an in-mold assembled revolute joint is illustrated in Fig. 4. The metallic inserts illustrated in the figure serve as shut off surfaces between the mold cavities which form the different parts of the revolute joint. This shut off surface ensures that the molten plastic that is injected into the mold cavities do not fuse the two cavities together during the

Fig. 3 Mold design strategy for creating mesoscale in-mold assembled revolute joints [9]

Fig. 4 Mold design concept for in-mold assembly using insert molding

filling phase. Subsequently, after cooling, the in-mold assembled revolute joint is ejected from the mold cavity. This joint consists of the injection molded plastic parts as the joint members and the cylindrical metallic insert as the actuating element.

3.1 Identifying Design Parameters. Figure 5 shows the critical dimensions in a revolute joint that is in-mold assembled using insert molding. As shown in the figure there are five critical dimensions that need to be carefully chosen. These are:

- (1) s : The separation between the two cavities. This dimension is critical because it provides appropriate shut off between the two cavities so that the polymer does not fuse the two cavities together during the injection phase. When s is very low, molding flash during filling can result in fusing of the two cavities. Hence, the separation s should be higher than the flash length. Chen et al. [12] have proposed an empirical formulation to determine the flash length when the polymer and the injection molding parameters are given. We have used the method they have described to obtain the design parameter s .
- (2) r : The radius or the size of the joint. This is usually governed by the overall dimensions of the part. However, to prevent joint jamming, it is important to keep the joint size as low as possible. This is discussed in more detail in the next section.
- (3) c : The diameter of the end cap. The cap prevents lateral movement of the joint. It also geometrically constrains the mold inserts to be a part of the joint. For manufacturing the metal inserts, end caps with an outer diameter c and inner diameter d have to be fused with a rod of diameter d . Hence,

Fig. 5 Critical dimensions in insert molded revolute joint

from the design perspective, the cap size should be sufficient to withstand the axial disturbance forces that may be generated during the actuation of the joint. Using experiments, we have determined that the axial disturbance forces are as low as 1% of the interfacial frictional force. Hence, the cap diameter c can be kept as low as permissible from the manufacturing point of view. From the manufacturing cost and handling perspective we determined the cap diameter based on the lowest size available in the market for the joint size d .

- (4) c_t : The thickness of the cap which is fused to the rod of diameter d . While the cap thickness needs to be kept as low as possible to restrict the overall size of the device, it should be long enough to provide sufficient surface area to be able to fuse the cap to the rod. Hence, this length is determined purely from the manufacturability point of view. For a rod of 0.4 mm radius, we experimentally determined the cap thickness c_t to be 1 mm.
- (5) t : Joint thickness. The joint thickness is determined based on the overall size of the joint. However, to keep the frictional torque for joint actuation low, it is of interest to keep the joint thickness as low as possible. This is discussed in more detail in the next section.

In the following sections, we will provide an approach to select the optimum joint dimensions which will facilitate successful fabrication of an in-mold assembled articulating joint using insert molding.

3.2 Joint Friction. For proper functioning of an in-mold assembled revolute joint, the frictional torque required for joint actuation has to be kept within acceptable limits. In-mold assembly methods developed previously utilized the shrinkage at the macro-scale [7] and the plastic deformation of the polymeric materials at the miniature size scale [9] for ensuring low frictional torque in the joints. However, in the in-mold assembly process using insert molding as illustrated in Fig. 4, a cavity around a metallic cylindrical insert is filled with a high pressure molten polymer during the injection molding process. After the cavity is filled, the polymer melt solidifies and shrinks around the metal insert. This shrinkage induces radial stresses at the interface between the polymer and the metallic insert. This concept is illustrated in Fig. 6. Unlike in the case of a polymer–polymer revolute joint as shown in Fig. 3, neither the packing pressure during the injection molding process nor the shrinkage stresses on the metallic cylinder after cooling of the polymer are sufficient to plastically deform the metallic cylinder to relax the stresses at the interface. This stress is responsible for the frictional torque at the interface. This frictional torque (f_t) as illustrated in Fig. 6, therefore, needs to be overcome for the functioning

Fig. 6 Shrinkage of polymer resulting in jamming of joint

of the revolute joint. To ensure proper functioning of the in-mold assembled revolute joint fabricated using the insert molding process, we have to ensure that the frictional torque required for moving the joint is within acceptable limits. The frictional torque at the interface can be described by Eq. (1) given below

$$f_{\tau} = \int_0^{2\pi} \mu \sigma_{rr} l r d\theta = 2\pi \mu \sigma_{rr} l r^2 \quad (1)$$

Here, μ refers to the coefficient of friction at the interface between the polymer and the metal insert, l is the length of the revolute joint, r is the radius of the cylindrical insert and σ_{rr} is the radial stress at the joint interface. In the Eq. (1), the coefficient of friction μ is a material property. In most cases the choice of materials is restricted by the application for which the device is to be used. Example, if the application is in medical robotics, it is necessary to use biocompatible materials for the polymer and the metal insert. Hence, for the sake of the discussion in this paper, we will consider the material combination as given. Therefore, we will not have any control or influence over the coefficient of friction (μ). The designer provides constraints on the overall size of the joint based on the application of the joint. The manufacturer can therefore select appropriate dimensional parameters to ensure the proper functioning of the joint. The dimensional variables of the joint such as the radius (r) of the cylinder, the joint thickness (t) and the length (l) are concurrently responsible for the radial shrinkage stress (σ_{rr}) at the interface. Also, the radius (r) of the joint and the length (l) of the joint are directly responsible for the frictional torque at the joint interface. Hence, controlling the dimensional parameters of the joint can play a big role in ensuring fabrication of usable in-mold assembled revolute joints. However, some applications may pose constraints on the dimensional parameters. These dimensional constraints may cause the frictional torque to become so high that it will become necessary to explore alternate methods to control the radial shrinkage stress (σ_{rr}). The goal of this paper is therefore to develop a strategy to select design parameters depending on the size scale for manufacturing in-mold assembled articulating joints using the insert molding process.

4 Selection of Design Parameters

As explained in the previous section, to manufacture a functional joint using the insert molding process, the interfacial frictional torque needs to be controlled. This frictional torque develops due to the radial stress at the interface caused by the shrinkage of the injection molded part over the cylindrical metal insert. Hence, by controlling the radial shrinkage stress at the interface, we can manufacture in-mold assembled joints with acceptable friction.

In order to control the shrinkage stress at the joint interface, it is important to understand and model the parameters resulting in shrinkage in injection molded parts. Shrinkage in injection molded parts has been studied by several researchers over the past several years [11,13,14]. The injection pressure holding phase in the injection molding cycle ensures that initial shrinkage in the polymer melt is compensated by additional polymer flow in the cavity. Hence, shrinkage studies conclude that shrinkage of the polymer melt in the cavity begins after the gate freezes. Studies have concluded [11] that the main parameters responsible for the shrinkage are the crystallinity and thermal contraction. For amorphous polymers, the effect of crystallinity is very low compared to the thermal contraction. Hence, for amorphous polymers, the shrinkage needs to be considered only after the temperature of the polymer is below the glass transition temperature. We verified this postulate by performing a simple calculation for an amorphous polymer acrylonitrile butadiene styrene (ABS). We compared the shrinkage due to thermal contraction with the shrinkage reported by the manufacturer. Example, for amorphous ABS (Hival HG6 ABS distributed by Ashland Chemicals), the coefficient of thermal expansion (α_h) is $90 \text{ E-6 m/(m} \cdot ^\circ\text{C)}$. The glass

transition temperature is reported as approximately 97°C . The shrinkage value reported by the manufacturer is $0.005\text{--}0.007 \text{ m/m}$. Assuming the room temperature is 28°C , the estimated shrinkage due to pure thermal contraction is 0.00621 m/m . Hence, for the sake of computing the friction in the in-mold assembled revolute joint made of amorphous polymers it is sufficient to assume that the shrinkage results only from the thermal contraction below the glass transition temperature of the polymer.

This geometry of the insert molded revolute joint consists of a half cylinder beneath the pin as illustrated in Fig. 6. Hence, to obtain an approximate analytical formulation for the interfacial radial stress, we modeled the joint as a thick cylinder with inner radius r and outer radius R as illustrated in Fig. 6. The pressure at the joint interface is generated due to thermal stresses caused by the shrinkage of the polymer around the metallic cylindrical insert. As explained previously, this thermal stress is caused purely by linear thermal expansion in amorphous polymers. This results in an effective interference of $r\alpha_h\Delta T_h$ at the joint interface, where ΔT_h is the temperature difference between the glass transition temperature of the polymer (T_g) and the room temperature. This interference causes a radial stress at the interface which can be computed using classical analytical formulation [15] for an interference fit. This is given by Eq. (2) where E_h is the Young's Modulus of the polymer and ν_h is the Poisson's ratio

$$\sigma_{rr} = \frac{E_h \alpha_h \Delta T_h}{\nu_h + \frac{R^2 + r^2}{R^2 - r^2}} = \frac{E_h \alpha_h \Delta T}{\nu_h + 1 + \frac{2}{(k+1)^2 - 1}} \quad (2)$$

where

$$k = \frac{R - r}{r}$$

The expression given by Eq. (2) clearly shows that the internal stress is independent of the size of the joint. However, the radial stress has a strong correlation with the thickness ratio k as defined in Eq. (2). A lower value of k results in lower interfacial stress in the joint. A lower value of k also results in reduction in overall weight. The lower weight of the mechanical assembly allows for using lighter electronics for actuation. This results in higher power to weight ratio and thereby higher dexterity of device. Hence, the designed value of the thickness ratio k should be as low as possible.

The minimum value of the thickness is usually selected based on the structural integrity of the part. The structural integrity of the part is directly dependent on the material properties of the part. The manufacturing process used for fabrication of the part has a significant contribution toward the final material properties of the part. The revolute joint in this case is fabricated using injection molding. Hence, two primary factors need to be considered while selecting the thickness of the joint. The first factor is the minimum thickness that can be successfully molded using the specific injection molding machine that is being used. This can be determined by the designer based on simple mold filling simulations or by practical experience. The second factor that needs to be considered is the circumferential yield stress. This yield stress is significantly impacted by the formation of weld-lines in injection molded parts. This is because weld-lines are responsible for structural weakness in injection molded parts. Researchers have shown the presence of weld-lines in injection molded parts results in weakening of the structure by upto 50% of the original strength [16,17]. In the insert molded revolute joint, a weld line is formed due to polymer flow around the metallic cylindrical insert. This is illustrated in Fig. 7.

Apart from causing interfacial radial stress, the thermal shrinkage of the polymer around the metallic cylindrical insert causes circumferential stress in the part. This stress also, known as hoop stress, is responsible for joint failure in the thickness dimension. This hoop stress particularly causes joint failure at the weld-line of the insert molded revolute joint as illustrated in Fig. 7. Hence,

Fig. 7 Weld-line formation in insert molded revolute joint

these weld-lines need to be accounted for to choose the appropriate thickness ratio k of the insert molded revolute joint

$$\sigma_{\theta} = \frac{p_i r^2}{R^2 - r^2} + \frac{p_i R^2 r^2}{r_p^2 (R^2 - r^2)} \quad \text{where } p_i = \sigma_{rr} \quad (3)$$

$$\Rightarrow \sigma_{\theta} = \sigma_{rr} \left[\frac{1}{(1+k)^2 - 1} \left(1 + \frac{(1+k)^2 r^2}{r_p^2} \right) \right] \quad (4)$$

The hoop stress for the joints under consideration can also be computed using classical interference fit equations [15]. These are given by Eq. (4). r_p in the equation is defined as the radius at a point of interest at which the hoop stress is calculated. From the equation, it is evident that the maximum hoop stress will be observed at $r_p = r$. To prevent joint failure, this stress needs to be less than the yield stress of the material. However, the yield stress of the material at the weld-line is significantly lower than the base material. Hence, for failure computation, this yield stress needs to be considered. As a rule of thumb, applying factor of safety considerations, the effective yield strength at the weld-line would be σ_y/F_{WL} where σ_y is the material yield strength of the polymer and F_{WL} is the factor of safety due to the presence of the weld line. Hence, using Eq. (2), we get the critical value of the thickness ratio k can be calculated as shown in Eq. (5)

$$\frac{\sigma_y}{F_{WL}} = \sigma_{\theta}(r_p = r) = \frac{E_h \alpha_h \Delta T ((1+k)^2 + 1)}{(\nu_h + 1)((1+k)^2 - 1) + 2} \quad (5)$$

5 Introduction of Bearings for Reducing Frictional Torque

The previous section described a strategy to select the dimensional parameters necessary for realizing the insert molded in-mold assembled revolute joint as illustrated in Fig. 5. However, as described by Eq. (2), the radial stress at the joint interface is independent of the joint size. Hence, the interfacial frictional torque for joint actuation will increase with the second power of the joint size as is evident by Eq. (1). Hence, for developing a general strategy for insert molding in-mold assembled revolute joints at all size scales, there is a need to develop a strategy for reduction of the friction at the interface.

From Eq. (1), we can conclude that the factors responsible for the friction at the interface are the radial stress (σ_{rr}), the coefficient of friction (μ) and the joint size (r). Since we need to develop a scale independent in-mold assembly strategy, our approach needs to be independent of the joint size (r).

The interfacial coefficient of friction can be controlled by lubrication of the joint or by decreasing the surface roughness of the metallic cylindrical insert. Another strategy for controlling the interfacial frictional torque is through control of the radial stress

(σ_{rr}) at the joint interface. The interfacial frictional torque is dependent on the thickness ratio k defined in Eq. (2). However, as the size of the joint increases, it may not be possible to continue reducing the thickness ratio. This is because the critical thickness ratio is independent of the size of the joint.

Another strategy that can be employed to decrease the radial stress is changing the polymer that is used for fabrication of the insert molded revolute joint. However, several engineering scenarios require the use of a specific polymer. For example, in several medical applications, it is mandatory to use biocompatible polymers as the material for the surgical robot. This is to ensure that when the robot is in contact with the cells and tissues, it does not cause a toxic reaction which can be detrimental to the patient health. Also, in several cases, use of a softer material for fabricating the robot may not be feasible from the structural point of view.

Hence, to control the radial stress at the joint interface while satisfying the constraints posed by the material choice, we introduced a sleeve made at the joint interface using multi material molding [18]. The sleeve is made of a softer polymer which results in relaxation of the radial stress at the joint interface. The sleeve therefore acts as a bearing which reduces the net torque required to overcome friction for the joint actuation. This concept is illustrated in Fig. 8. The insert molded revolute joint as illustrated in the figure is manufactured using a two stage process. In the first stage a soft polymer is injected on top of the metallic cylindrical insert. In the second stage, the base material is injected on top of the sleeve encompassing it completely. The second stage molding ensures that the base material completely encompasses the sleeve that was manufactured in the first stage

$$k_s = \frac{r' - r}{r}, \quad k_h = \frac{R - r'}{r'} \quad (6)$$

Although introduction of the sleeve results in relaxation of the radial stress at the joint interface, it results in increase in the overall size of the assembly. Hence, the sleeve thickness $r' - r$ needs to be minimized. However, in order to select the sleeve thickness, it is necessary to understand its correlation with the net reduction in the radial stress at the joint interface. The effective stress at the joint interface can be computed using classical interference/shrink fit models [15]. The effective stress would be dependent on the effective thickness ratios of P_a (k_s) and P_b (k_h). k_s and k_h are

Fig. 8 Multi material molding for introduction of sleeve at joint interface

defined in Eq. (6) where R , r' , and r are as illustrated in Fig. 8. However, to develop an analytical model for relating the radial stress at the interface with the thickness ratio, let us first develop an understanding of the overall manufacturing process.

In the first step, the sleeve made of a soft polymer (P_a) is molded over the metallic cylindrical insert (M_b). The designed inner radius of P_a is r and the outer radius is r' . After mold filling, P_a cools and shrinks over M_b . This shrinkage results in development of an equivalent interference between the M_b and P_a . We define this interference as u_{sA} given in Eq. (7)

$$u_{sA} = \alpha_s \Delta T_s r \quad (7)$$

Assuming a thick cylinder formulation for the sleeve, the outer radius of unstressed P_a after shrinkage will be $r'(1 - \alpha_s \Delta T_s)$. However, since the metallic core is not removed before the injection of the the base polymer (P_b). Therefore, an initial interference stress (σ'_{rr}) develops at the core which is given by Eq. (8). Hence, the outer radius (r'_{Pa}) of P_b on which the base polymer is molded is given by Eq. (9)

$$\sigma'_{rr} = \frac{E_s \alpha_s \Delta T_s}{(1 - \alpha_s \Delta T_s)(\nu_s + (r'^2 + r^2)/(r'^2 - r^2))} \quad (8)$$

$$r'_{Pa} = r'(1 - \alpha_s \Delta T_s) + \frac{r' \sigma'_{rr} r'^2 + r^2}{E_s r'^2 - r^2} \quad (9)$$

Next, the base material (P_b) is molded over P_a . This base material has a designed outer radius of R . After cooling and shrinkage of the base material over the sleeve, a net interference of $r'_{Pa} \alpha_h \Delta T_h$ would develop between the two polymers. This interference would result in an interface stress σ_{int} . This interface stress would therefore result in a new stress at the joint interface between the sleeve and the metal insert called σ_{rr} . Finally, using principle of superposition on classical interference fit equations, these interfacial stresses can be posed in the form of two linear equations. Subsequently, the system of two equations can be solved to obtain the final interfacial stresses σ_{int} and σ_{rr} . The system of linear equations can be seen in the form of matrices in Eq. (10)

$$A\sigma = \delta \quad (10)$$

where

$$A = \begin{bmatrix} -\frac{r'}{E_s} \frac{2r^2}{r'^2 - r^2} & \frac{r'}{E_s} \left(\nu_s + \frac{r'^2 + r^2}{r'^2 - r^2} \right) + \frac{r'}{E_h} \left(\nu_h + \frac{R^2 + r'^2}{R^2 - r'^2} \right) \\ \frac{r}{E_s} \left(\nu_s + \frac{r'^2 + r^2}{r'^2 - r^2} \right) & \frac{-2r}{E_s} \frac{r'^2}{r'^2 - r^2} \end{bmatrix}$$

$$\sigma = \begin{bmatrix} \sigma_{rr} \\ \sigma_{int} \end{bmatrix} \quad \delta = \begin{bmatrix} r'_{Pa} \alpha_h \Delta T_h \\ r \alpha_s \Delta T_s \end{bmatrix}$$

Using the formulation above, the interfacial stress can be related to the respective thickness ratios k_s and k_h given by Eq. (6). From the functionality perspective, three distinct aspects need to be considered for selecting the thickness ratios. These are as follows:

- (1) The overall thickness ratio (k) needs to be as low as possible to ensure minimum weight.
- (2) A high thickness ratio (k_s) would enable a higher reduction in the interfacial stress. This would thereby ensure lower frictional torque for joint actuation. However, the exposed surface area of P_a needs to be kept as low as possible to ensure that material considerations for the assembly are not violated.
- (3) The base material P_b forms the outer shell of the insert molded in-mold assembled articulating joint. Hence, the thickness ratio of P_b (k_h) needs to be selected based on the

Table 1 Properties of base polymer (P_b) and sleeve (P_a)

	ABS (P_b)	LDPE (P_a)
Young's modulus (GPa)	2.7	0.139
Coefficient of thermal expansion	90 E-6	190 E-6
Poisson's ratio	0.4	0.3
Yield strength (MPa)	40	12
Solidification temperature (°C)	97	60

hoop stress considerations at the weld-line. Thus, k_h should be greater than the minimum allowable thickness ratio as calculated using Eq. (5).

Based on these considerations, the optimum thickness ratios which allow for joint actuation can be selected based on the permissible radial stresses at the joint interface. In the next section, we will discuss how we selected the appropriate joint parameters for an in-mold assembled revolute joint both at the miniature size scale and the macroscale.

6 Results and Discussion

In order to validate the formulation described in the previous sections, we performed detailed experimentation using Hival ABS HG6, distributed by Ashland Chemicals, as the base polymer (P_b) and low density poly ethylene (LDPE) 722, distributed by Dow chemicals, as the sleeve (P_a). The properties of ABS and LDPE are tabulated in Table 1. The metallic insert (M_a) was made of brass for miniature insert molded joints and Aluminum for macroscale insert molded joints.

To understand the effect of size on the interfacial frictional torque, we plotted the relationship between the thickness ratio k against the estimated frictional torque for two different sizes. In this case, we assumed that there was no sleeve present between the base polymer and the metallic cylindrical insert. Therefore, the joint was fabricated using a single shot molding process with M_a as the insert and P_b as the base polymer. The coefficient of friction (μ) between P_b and M_a was assumed to be 0.4. The room temperature to which the polymers cool was assumed to be 28 °C. We then calculated the interfacial frictional torque using Eqs. (1) and (2). These results are shown in Fig. 9. From the plot it is evident that the size plays a prominent role in the frictional torque.

To develop a mold design to fabricate a revolute joint as illustrated in Fig. 4, we had to first select the dimensional parameters for the joint. These dimensional parameters are described in Fig. 5. For selecting the thickness t of the joint, we followed the strategy outlined in section 3 to calculate the minimum thickness ratio k . The average weld line strength for ABS was obtained from

Fig. 9 Interfacial frictional torque v/s thickness ratio for two joint sizes

Fig. 10 Hoop stress v/s thickness ratio

Ananthanarayanan et al. [19] to be 75% of the base material. Applying an overall factor of safety of 2, the effective factor of safety FS_{WL} was calculated as 2.667. The yield strength σ_y for ABS is defined as 40 MPa (Table 1). Hence, the maximum allowable hoop stress as defined in Eq. (5) was 15 MPa. Hence, to calculate the thickness ratio k , we plotted it against the hoop stress as described in Eq. (5). This is shown in Fig. 10. The plot shows that the hoop stress in the part decreases with the increasing thickness ratio. From this plot, we obtained the minimum allowable value for the thickness ratio k to be 0.35. We then selected the other dimensional parameters shown in Fig. 5 using the strategy described in section 2.1. These dimensions, for two different sizes, are shown in Table 2. The thickness t had to be selected so that the thickness ratio k was greater than the minimum allowable value of 0.35. For the macroscale joint ($r = 3.175$ mm), we designed the thickness to be 1.1 mm. This led to an effective thickness ratio $k = 0.35$. However, for the joint size of $r = 0.4$ mm, due to the manufacturing constraints posed by the minimum moldable thickness, the thickness had to be selected as 0.4 mm. This led to an effective thickness ratio $k = 1$.

Using the parameters shown in Table 2, we manufactured in-mold assembled revolute joints at both macroscale and miniature scale on a Milacron Babyplast injection molding machine. A functional in-mold assembled revolute joints at the miniature size (joint radius = 0.4 mm) is illustrated in Fig. 11. The force required to overcome the interfacial frictional torque of this joint was low enough to allow for smooth actuation of the miniature revolute joint. Hence, we concluded that for the miniature scale, a single shot molding strategy would suffice, i.e., we did not need to introduce a sleeve at the interface to relax the radial stress at the joint interface.

However, at the macroscale, the strategy resulted in realization of jammed revolute joints. This resulted in high forces required to overcome interfacial frictional torque required for joint actuation. Hence, to successfully fabricate functional revolute joints at this size scale, it was necessary for us to introduce a sleeve to reduce the radial stress at the joint interface. In order to select the appropriate dimensions for the in-mold assembled revolute joint, we had to understand the effect of the sleeve on the stress relaxation. To model this effect we adopted the approach described in the previous section. To validate the theoretical approach that was described in

Table 2 Dimensional parameters for in-mold assembled revolute joint fabricated using insert molding strategy

	$r = 0.4$ mm	$r = 3.175$ mm
s	1 mm	1.27 mm
c	1.5 mm	8.9 mm
ct	1 mm	1.5 mm
t	0.4 mm	1.1 mm

Fig. 11 In-mold assembled miniature revolute joint fabricated using insert molding

the previous section, we also performed finite element analysis using ANSYS 11.0 to predict the radial stress at the joint interface. This analysis was setup as a simple shrinkage simulation of a composite ring as illustrated in Fig. 8. Subsequently, we conducted the simulation independently for seven different combinations of k_s and k_h . The results of this evaluation are plotted in Fig. 12. The plot shows the stress relaxation caused by the sleeve, made of LDPE, for a revolute joint of three different overall thickness ratios (k). The results of the finite element analysis are overlayed on the analytical model. The results show excellent agreement between the analytical model and the finite element simulations.

The thickness ratio (k_s) can be increased only until the resulting thickness ratio (k_h) of the base polymer (ABS) does not fall below the permissible limit. This permissible limit is defined based on the allowable hoop stress at the weld line as defined by Eq. (5). This point, for the three different values of overall thickness ratio (k), is illustrated in the plot shown in Fig. 12.

Figure 13 shows a successfully actuating in-mold assembled macroscale revolute joint using the insert molding strategy described in this paper. For successful manufacturing of the macroscale revolute joint (diameter = 3.175 mm), the permissible interfacial frictional torque was approximately 0.075 N-m/mm. This resulted in an allowable radial stress of 3 MPa at the joint interface. After adopting manufacturability constraints for injection molding such as mold machining, mold filling, and ejection, the designed thickness ratios and the resulting dimensions of the revolute joint are shown in Table 3.

7 Case Study: Minimally Invasive Surgical Robot

Surgical robots have been defined as a powered computer controlled manipulator with artificial sensing that can be reprogrammed to move and position tools to carry out a range of surgical tasks [20]. Due to the high dexterity and maneuverability desired for surgical robots, the need for higher degrees of freedom is becoming increasingly important. However, due to the requirement of several delicate medical procedures to have minimally

Fig. 12 Radial stress relaxation due to presence of sleeve made of soft polymer

Fig. 13 Functioning in-mold assembled macroscale revolute joint fabricated using insert molding

invasive robots to perform surgery, there is also a significant need to miniaturize surgical robots [21,22].

One of the most significant challenges associated with development of miniature multiple degree of freedom robots lies in its fabrication. Traditional fabrication methods such as machining and assembly are not suitable at the small scale paradigm at which minimally invasive surgical robots lie. To address this problem, researchers at Carnegie Mellon University and Stanford have developed the shape deposition manufacturing (SDM) process [23] for making fully embedded smart robotic structures. These processes make intelligent use of both standard joints and flexures to realize multiple degree of freedom structures. Hence, they are very powerful prototyping methods for fabricating highly articulating robotic structures. However, SDM requires several fabrication and post fabrication steps to complete the manufacturing. This increases the overall cycle time for fabricating each robot and thereby the cost of the robot. To offset sterilization costs of medical robots used in minimally invasive surgery, it is desirable to have disposable medical robots [24]. However, to accomplish this, it is essential that the manufacturing process used for fabrication of the robots be cost effective. Bejgerowski et al. [25] have previously developed a method for using injection molded flexures for high strength to weight ratio structures. As part of their work, they presented a powerful paradigm for low cost manufacturing of mechanisms. However, the available choice of materials for injection molded flexures is limited. Rigid body joints on the other hand have a much wider pool of material options. Hence, when a constraint on the material is posed by its biocompatibility (in surgical devices), it is essential to develop a more material independent fabrication method.

The in-mold assembly method using insert molding, illustrated in this paper, provides a powerful alternative to fabricating highly articulating miniature structures. Using an innovative mold design, the insert molding method described in this paper, can be used to fabricate multiple degree of freedom robotic structures in a single molding shot. To illustrate this, we manufactured a prototype of a 9 degree of freedom articulating structure for a robot with potential application in neurosurgery. The design of this articulating structure consists of 10 independent parts which are connected by metallic mold inserts of 1.58 mm diameter. The articulating structure was manufactured in a single injection shot using the insert molding method described in this paper. Owing to the small joint sizes, the radial stress at the joint interface were sufficiently low. Hence, no sleeve was required for successful articulation of the joints. Figure 14 shows the manufacturing steps for fabricating the 9 DOF articulating structure in a single injection shot.

The robot fabricated using the insert molding approach can be actuated using shape memory alloy based actuation. Bejgerowski

Table 3 Designed thickness ratio and resulting dimensions for macroscale in-mold assembled revolute joint

k	0.8	r	3.175 mm
k_s	0.2	r'	3.81 mm
k_h	0.5	R	5.715 mm

Fig. 14 9 degree of freedom robot structure manufactured using insert molding

et al. [26] have discussed a method to optimally embed actuators in injection molded parts. Additionally, Pappafotis et al. [27] demonstrated the use of shape memory alloys for actuating an MRI compatible miniature robot. Their robot prototype is fabricated using machining and assembly. As part of this work, we have also demonstrated the use of shape memory alloys for actuating the 9 degree of freedom robot that we have manufactured using insert molding methods. Figure 14 also illustrates the 9 degree of freedom robot wired with shape memory alloys. The shape memory

Table 4 Production time estimate in minutes for 9 DOF robot using different manufacturing strategies

	Machining and assembly	In-mold assembly	In-mold assembly using insert molding
Mold manufacturing time per link	N.A.	40	180
Part manufacturing time for 9 link robot	240	10	1.5
Mold insert fabrication time	N.A.	N.A.	30
Assembly time	60	30	N.A.

Fig. 15 Cost comparison based on production time estimate for fabricating a 9 DOF robot structure using different manufacturing strategies

alloy based actuation strategy provides a low weight solution for independent control of each degree of freedom of the robot.

One of the most noteworthy benefits to using an injection molding based approach to manufacturing robots is its advantage in mass production. To illustrate this, we compared the cost of fabricating the 9 degree of freedom robot structure using the following three strategies (1) Machining and assembly [27], (2) In-mold assembly [10], and (3) In-mold assembly using insert molding (this work). For the purpose of this comparison, we consider the production time as a direct indication of the production cost. Considering that labor cost is one of the most prominent factors contributing to the overall production cost, the authors feel, this is a reasonable assumption. Table 4 shows an estimate of the time required to complete different aspects of the production using the different approaches. Figure 15 illustrates the comparison of the cost of fabricating upto 30 prototypes of a 9 degree of freedom robot structure using the different manufacturing approaches outlined above. The graph clearly demonstrates the advantage of using an in-mold assembly approach to fabricating robots over machining and assembly. This advantage is increasingly prominent with increasing number of robots that need to be fabricated. The graph also illustrates that using the in-mold assembly approach with insert molding is significantly more advantageous than using the conventional in-mold assembly approach to manufacturing. This is because use of the insert molding approach eliminates the post fabrication assembly step completely. This is because, use of this approach allows manufacturers to fabricate the complete 9 DOF robot in a single injection shot.

8 Conclusions

This paper presents the first successful demonstration of the insert molding method for manufacturing in-mold assembled mechanical assemblies. We have presented two distinct strategies which can be used at the miniature size scale and the macroscale, respectively, to fabricate mechanical assemblies. Cylindrical mold inserts made of Aluminum/Brass are used as the articulating members of the in-mold assembled joints. Results reported in this paper show that the shrinkage of the polymer around the cylindrical mold inserts leads to the development of radial stresses at the joint interface. These radial stresses are responsible for the joint friction which leads to jamming. We have presented a theoretical framework to predict the radial stresses that appear at the joint interface due to the in-mold assembly process. At the miniature size scale, the frictional torque resulting from the radial stresses are sufficiently low. Therefore, it does not interfere with the functionality of the joint.

The modeling results presented in this paper reveal that the strength of the weld-line formed at the joint interface significantly impact the overall strength of the robotic assembly. However, this

can be overcome by choosing the right dimensional parameters while accounting for the structural shortcoming resulting from the appearance of the weld-line. We have presented an analytical model to compute the minimum allowable joint thickness in in-mold assembled revolute joints. Increase in the size of the joint results in appearance of higher frictional torque at the joint interface. We have developed a method to control the radial stresses at the joint interface by using a soft polymer at the joint interface. We have also presented a rigorous theoretical framework to predict the radial stresses at the joint interface due to the presence of the soft polymer at the interface. These results can be used to select the optimum dimensional parameters for fabricating functional in-mold assembled robotic structures at any size scale.

We have used the methods presented in this paper to successfully prototype a 9 degree of freedom articulating structure for a medical robot with applications in neurosurgery. This articulating structure is envisioned to be actuated and controlled using shape memory alloys.

Acknowledgment

This research has been supported by NIH Grant No. 1R21EB008796. Opinions expressed in this paper are those of the authors and do not necessarily reflect opinions of the sponsors.

References

- [1] Ananthanarayanan, A., Gupta, S. K., and Bruck, H. A., 2010, "Characterization of a Reverse Molding Sequence at the Mesoscale for In-Mold Assembly of Revolute Joints," *Polym. Eng. Sci.*, **50**(9), pp. 1843–1852.
- [2] Moon, S. I., Monson, L. L., and Extrand, C. W., 2006, "Insert-Molded Poly (Ether Imide)/Carbon Fiber Poly(Ether Ether Ketone) Bimaterial Composites: Fracture and Interfacial Analysis," *J. Appl. Polym. Sci.*, **102**(3), pp. 2362–2371.
- [3] Teh, N. J., Conway, P. P., Palmer, P. J., Prosser, S., and Kioul, A., 2000, "Statistical Optimisation of Thermoplastic Injection Moulding Process for the Encapsulation of Electronic Subassembly," *J. Electron. Manuf.*, **10**, p. 171–179.
- [4] Webb, D. P., Hutt, D. A., Hopkinson, N., Conway, P. P., and Palmer, P. J., 2009, "Packaging of Microfluidic Devices for Fluid Interconnection Using Thermoplastics," *J. Microelectromech. Syst.*, **18**(2), pp. 354–362.
- [5] Grujicic, M., Sellappan, V., Pandurangan, B., Li, G., Vahidi, A., Seyr, N., Erdmann, M., and Holzleitner, J., 2008, "Computational Analysis of Injection-Molding Residual-Stress Development in Direct-Adhesion Polymer-to-Metal Hybrid Body-in-White Components," *J. Mater. Process. Technol.*, **203**(1–3), pp. 19–36.
- [6] Ramani, K., and Zhao, W., 1997, "The Evolution of Residual Stresses in Thermoplastic Bonding to Metals," *Int. J. Adhes. Adhes.*, **17**(4), pp. 353–357.
- [7] Priyadarshi, A., Gupta, S., Gouker, R., Krebs, F., Schroeder, M., and Warth, S., 2007, "Manufacturing Multi-Material Articulated Plastic Products Using in-Mold Assembly," *Int. J. Adv. Manuf. Technol.*, **32**(3–4), pp. 350–365.
- [8] Ananthanarayanan, A., Gupta, S., and Bruck, H., 2008, "Characterization and Control of Plastic Deformation in Premolded Components in In-Mold Assembled Mesoscale Revolute Joints Using Bi-Directional Filling Strategy," All India Manufacturing Technology and Development Research.
- [9] Ananthanarayanan, A., Gupta, S., and Bruck, H., 2009, "Characterization and Control of Pin Diameter During In-Mold Assembly of Mesoscale Revolute Joints," North American Manufacturing Research Institute, Vol. 37.
- [10] Ananthanarayanan, A., Gupta, S., and Bruck, H., 2009, "Characterization and Control of Plastic Deformation in Mesoscale Premolded Components to Realize In-Mold Assembled Mesoscale Revolute Joints," *Polym. Eng. Sci.*, **49**(2), pp. 293–304.
- [11] Ananthanarayanan, A., Thamire, C., and Gupta, S., 2007, "Investigation of Revolute Joint Clearances Created by an In-Mold Assembly Process," International Symposium on Assembly and Manufacturing, IEEE.
- [12] Chen, Z. B., Giacomini, A. J., and Turmg, L. S., 2006, "Flash," *Polym. Eng. Sci.*, **46**(3), pp. 241–247.
- [13] Kwon, K., Isayev, A. I., and Kim, K. H., 2006, "Theoretical and Experimental Studies of Anisotropic Shrinkage in Injection Moldings of Various Polyesters," *J. Appl. Polym. Sci.*, **102**(4), pp. 3526–3544.
- [14] Kwon, K., Isayev, A. I., Kim, K. H., and van Sweden, C., 2006, "Theoretical and Experimental Studies of Anisotropic Shrinkage in Injection Moldings of Semicrystalline Polymers," *Polym. Eng. Sci.*, **46**(6), pp. 712–728.
- [15] Hamrock, B. J., Schmid, S. R., and Jacobson, B. O., 2007, *Fundamentals of Machine Elements*, 2nd ed., McGraw-Hill Science/Engineering/Math, New York, NY.
- [16] Wu, C., and Liang, W., 2005, "Effects of Geometry and Injection-Molding Parameters on Weld-Line Strength," *Polym. Eng. Sci.*, **45**(7), pp. 1021–1030.
- [17] Selden, R., 1997, "Effect of Processing on Weld-Line Strength in Five Thermoplastics," *Polym. Eng. Sci.*, **37**(1), pp. 205–218.
- [18] Gouker, R., Gupta, S., Bruck, H., and Holzschuh, T., 2006, "Manufacturing of Multi-Material Compliant Mechanisms Using Multi-Material Molding," *Int. J. Adv. Manuf. Technol.*, **30**(11–12), pp. 1049–1075.

- [19] Ananthanarayanan, A., Gupta, S., and Bruck, H., 2008, "Mechanical Characterization of Cold Weld-Lines and Meld Lines in Mesoscopic Revolute Joints for Bioinspired Structures," SEM Annual Conference and Exposition.
- [20] Davies, B., 2000, "A Review of Robotics in Surgery," *Proc. Inst. Mech. Eng., Part H: J. Eng. Med.*, **214**(H1), pp. 129–140.
- [21] Camarillo, D. B., Krummel, T. M., and Salisbury, J. K., 2004, "Robotic Technology in Surgery: Past, Present, and Future," *Am. J. Surg.*, **188**(4A), pp. 2S–15S.
- [22] Louw, D. F., Fielding, T., McBeth, P. B., Gregoris, D., Newhook, P., and Sutherland, G. R., 2004, "Surgical Robotics: A Review and Neurosurgical Prototype Development," *Neurosurgery*, **54**(3), pp. 525–536.
- [23] Cutkosky, M. R., and Kim, S., 2009, "Design and Fabrication of Multi-Material Structures for Bioinspired Robots," *Philos. Trans. R. Soc. London*, **367**(1894), pp. 1799–1813.
- [24] Walsh, C. J., Hanumara, N. C., Slocum, A. H., Shepard, J.-A., and Gupta, R., 2008, "A Patient-Mounted, Telerobotic Tool for CT-Guided Percutaneous Interventions," *J. Med. Devices*, **2**(1), p. 011007.
- [25] Bejgerowski, W., Ananthanarayanan, A., Mueller, D., and Gupta, S. K., 2009, "Integrated Product and Process Design for a Flapping Wing Drive Mechanism," *J. Mech. Des.*, **131**(6), p. 061006.
- [26] Bejgerowski, W., Gupta, S. K., and Bruck, H. A., 2009, "A Systematic Approach for Designing Multifunctional Thermally Conducting Polymer Structures With Embedded Actuators," *J. Mech. Des.*, **131**(11), 111009.
- [27] Pappafotis, N., Bejgerowski, W., Gullapalli, R., Simard, J., Gupta, S., and Desai, J., 2008, "Towards Design and Fabrication of a Miniature MRI-Compatible Robot for Applications in Neurosurgery," ASME 2008 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE).