Simulation Methodology for Large Part Processing using 2-Shot Injection Compression molding (2K-ICM)

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Abstract

Large body panels, side air deflectors of trucks, panoramic sunroofs, rear quarter windows, TV back panels, housings, bumpers, backlights and tailgates are examples of large parts with higher surface area. If conventional injection molding (CIM or IM) is used to produce such parts, it requires very large pressure and clamp force, which may not be practically possible. In addition, part stress levels will be higher. To overcome these issues, 2-shot Injection-Compression molding (2K-ICM) an advanced molding technology is used, which results in lower residual stresses in the part and significant reduction in clamp forces while molding such large parts. A single-part solution is possible through the 2K-ICM process. With that said, for quicker adoption of this technology, it would be ideal to develop a fully validated simulation framework for 2K-ICM process so as to enable machine and grade selection, mold design, as well as optimization of processing parameters in a reliable manner, while minimizing or eliminating experimental trial and error. The specific objective of this work is to demonstrate the novel simulation framework for 2K-ICM developed using Moldex3D® software, and capture the key phenomenological aspects of the process in the context of a model ribbed geometry. In the simulation study, the thermal history of the first shot is interlinked with the second shot by Multi-Component Molding (MCM). This interlinking of results effectively captures the thermal gradients and differential cooling rates at cross section of rib area; such information would be critical to understand the impact of processing and geometry on development of defects on surface. This framework will aid in optimization of the design for 2K-ICM parts and evaluation of its performance in a realistic manner.

Introduction

Typically, large body panels – e.g., for automotive and transportation solutions, hoods, fenders, housings, bumpers and side-air-deflectors of heavy trucks are produced from thermoset plastic materials through sheet molding compound (SMC) processes. Replacement of existing SMC with engineering thermoplastics can have several benefits such as greater design flexibility, weight reduction, and functional integration of two or more parts into a single structural part, while also meeting stringent surface appearance requirements. Use of thermoplastics would enable single-piece solutions for large parts, which would further help to minimize secondary operations, incorporate increased part complexity, reduce production costs, consolidate parts and improve impact characteristics.

If conventional injection molding [1] or sequential hot runner system were to be used to produce large parts with surface area of about 1m² or more, it would require very large clamp forces and pressures that may not be practically possible. In addition, part stress levels will be higher. To overcome these issues, advanced molding technology like 2-shot injection compression molding (2K-ICM) is used. This results in lower residual stresses in the part and significant reduction in pressure and clamp forces while molding such large parts [2-3].

While employing multi-component injection molding technologies, such as 2K-ICM, the various shots provide different attributes to the part - either structural, or aesthetic, or both [4]. While employing 2K-ICM specifically in case of large part molding, the conventional injection molding (CIM) shot is employed for molding the “carrier” which contains the design features for structural integrity and mounting details, while the injection compression molding (ICM) shot is employed for the aesthetic “A class” surface.

Generally speaking, in 2K-ICM it is theoretically possible to have either the CIM step or the ICM step as the first shot (see, e.g., Ref. [4]. But the choice of molding sequence is finally governed by the nature of final use of the part. Specifically, for large parts in structural or semi-structural applications, the carrier component may be required to cover a significant portion below the aesthetic surface to offer sufficient structural integrity of the part. In such scenarios, based on empirical observations, it is preferred to have the CIM step (for the structural carrier) as the first shot. Over-molding the aesthetic surface on the carrier using ICM as the second shot has been noted to result in better surface aesthetics. The optimal sequence of shots in large part molding qualitatively assessed from experiments, have not been systematically evaluated either through a design of experiments or through simulations. It may be argued that such sequence (CIM first-shot) is necessitated for large part molding because of significant disparity in molding temperatures and viscosities of the two shots (with the structural CIM shot requiring higher molding temperatures for reinforced resins).
This is in contrast to glazing scenarios [5-7] where the sequence of 2K-ICM reversed whereby the class A part (ICM) is molded in the first shot [7]. This difference in sequencing may be explained based on the fact that the CIM second shot in glazing scenario is typically a lower melting resin which does not completely cover the aesthetic surface.

**Motivation and Objective:** CIM has been widely employed, studied and researched over the last few decades. Processing simulation software packages such as Autodesk Moldflow† and Moldex3D† [8-9] have incorporated state of the art research in this area to arrive at simulation methodologies for CIM that allow accurate design of molds as well as reliable estimates of parameters such as flow rate, pressure, tonnage, warpage fiber orientation etc. CIM simulations with Autodesk Moldflow† and Moldex3D† are now routinely employed for machine selection and process-parameter optimization, taking into account the part dimensions, resin rheology and compressibility. On the other hand, ICM is gaining popularity and an evolving technology; injection molding machine manufacturers are continually improving and modifying this process. The ICM process, while having great potential, is still not widely adopted due to the additional hardware costs and the requirements of better process control compared to CIM. Further, the optimization of processing parameters for ICM are still carried out mainly using trial and error approach in real world. Experimental trial and error results in additional time and effort to prove out parts. This situation is further complicated when 2-shot or 2K-ICM is employed due to the significantly higher complexities associated with mold, process design and optimization. The establishment of a fully validated ICM or 2K-ICM simulation framework is therefore not only expected to reduce the costs associated with trial and error approach, but also lead to faster adoption of this promising technology in plastic manufacturing industry. It needs to be noted here that the simulation methodologies for ICM are still evolving [10-17], even more so for 2K-ICM, compared to the relatively mature framework for CIM.

The overall objective of this work is to develop a fully validated simulation framework for 2K-ICM so as to enable machine and grade selection, 2K-ICM mold design, as well as optimization of processing parameters in a reliable manner while minimizing or eliminating experimental trial and error. The specific objective addressed in the remainder of this paper is to demonstrate the novel simulation framework for 2K-ICM developed using the Moldex3D† software, and capture the key phenomenological aspects of the process in the context of a model rib geometry. A full-fledged validation of the simulations using comparison with experimental molding trials is out of scope of the current paper and will be detailed in subsequent reports. A representative design is developed and is used for the study. During the study, the thermal history of the first shot CIM is interlinked with the second shot in ICM via Multi-Component Molding (MCM). By interlinking, complete molding temperature data of first shot is captured while solving for second shot. It helps to understand interfacial temperature behavior between both shots and differential cooling rate at that area. Further effect of these variations on aesthetic surface are studied in this paper.

This paper focuses on developing a simulation framework for 2K-ICM process specifically for large part moldings (with specific focus on CIM first shot and ICM second shot), which can capture the key phenomenological aspects of the process. Prior to defining the specific objectives, we briefly outline the key aspects of the various injection molding processes and compare and contrast conventional injection molding with 2K-ICM.

**Brief Description of CIM, ICM, and 2K-ICM**

**CIM or IM:** The CIM or IM process [1], which is used extensively for producing molded parts, has an inherent limitation of higher shrinkage variation across a part. In this process there will be Filling, packing and cooling phase. The packing phase is limited by the available gate freeze time and regions away from the gate do not get packed-out effectively. Sometimes very high pack pressure is needed to better control shrinkage variation in the part. which can lead to higher clamp force, flash and other molding problems. Due to all these reasons, the molded part will have high in-mold residual stresses, warpage and lack of dimensional stability. Figure 1 below shows the schematic view of the CIM process, where \( F_{\text{Pack}} \) is the pack pressure exerted from the injection screw just after the filling phase.

![Fig.1: Schematic representation of the Conventional Injection Molding (CIM) process](image)

**ICM:** In the ICM process, which is an extended form of the conventional molding process, consists of two phases: the “injection” phase and the “compression” phase. In this process there is no packing phase during molding. In the injection phase, the resin is injected into a gap that is initially set higher than the required part thickness.
Subsequently, during the compression phase, using the available clamp force, the mold closes to obtain the final desired part thickness and shape. In this manner, as the injected melt is compressed using the entire projected surface, there is a uniform distribution of pack pressure across the part, resulting in effective compensation of shrinkage throughout the part. This leads to molded parts with better control on dimensional stability, lower molded-in stresses, reduced warpage and excellent surface replication [2,3,7,15,16].

It is basically a technique of integrating two molds into one big machine and therefore one may identify two distinct molding stations in such large machines. At the first station, as the mold closes, the resin is injected- it is filled, packed, and the part is cooled. After this, the mold opens at both the stations large enough to allow the rotation of the central unit (refer Figure 3). The central unit carrying the part from first station rotates and gets indexed with the other half of a mold at second station. Now at the second station, onto the earlier molded part, the resin for second shot is injected from another injection unit as an over-molding process. Here it is to be noted that the process used for large parts involves the use of Conventional Injection Molding (CIM) for the structural first shot and Injection-Compression Molding (ICM) for the aesthetic surface second shot, thus forming a 2-Shot Injection Compression Molding process. During the startup of the process, no molding takes place in the second station, awaiting the indexing of first shot molded part. After the first shot is molded, molding may be carried out at both the stations simultaneously. Even otherwise, there are enough controls and resolutions in these sophisticated molding machines, that the two stations can be made to function either independently or in tandem.

Advantages of the ICM Process vs. CIM

There are several advantages of ICM compared to CIM [2,3,7,15,16], both in terms of processing and part quality are shown in table 1.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process advantages</td>
<td>Compared to CIM, the molding process is more complicated</td>
</tr>
<tr>
<td>Reduction in clamping force</td>
<td>Investment requirement will be higher</td>
</tr>
<tr>
<td>Reduction in injection pressure</td>
<td>Increased mold and machine costs</td>
</tr>
<tr>
<td>Improved venting, as there is sufficient time for the air to escape out additionally at the compression frame regions. This is in contrast to CIM where the mold is already closed and venting can happen only from specified regions in the mold</td>
<td>Higher precision machine controls required to ensure process repeatability</td>
</tr>
<tr>
<td>Part design compatibility – 3D profile or depth in parts can be difficult to achieve</td>
<td></td>
</tr>
<tr>
<td>Part quality improvements</td>
<td>Compression motion has less effect on angular surfaces (not normal to compression movement)</td>
</tr>
<tr>
<td>Lower residual stresses</td>
<td>Reduced tool life - more relative motion between mold inserts</td>
</tr>
<tr>
<td>Part warpage reduction</td>
<td></td>
</tr>
<tr>
<td>Reduced material shear</td>
<td></td>
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</table>

Simulation Model Setup

Part details: The part employed to simulate and validate the 2K-ICM process is shown in Figure 4a. As shown, the full part is obtained in two shots: the top ribbed portion (colored sky blue, shown separately in Figure 4b) is formed as the first shot using conventional injection molding (CIM) process, while the bottom flat portion (colored purple, shown separately in Figure 4c) is achieved as the second shot using injection compression molding (ICM) process.
The overall dimensions of the 2K-ICM part is 104x64x10mm and the volume of the part is 40cc. The top portion of the part obtained in the first shot CIM is designed to have ribs of different thickness so as to study the combined impact of rib size and processing conditions on thermal gradients and volumetric shrinkage on the part surface. As shown in Figure 4b, rib thickness varies from 1mm to 3mm and nominal thickness of the CIM part is 2.5mm. The bottom portion of the part obtained in the second shot ICM (refer to Figure 4c) is a flat part, with uniform thickness of 2.5mm.

Feed system, mold and material details:
The feed systems employed for the CIM and ICM shots are shown in Figure 5a and 5b respectively. As shown in Figure 5a, for the CIM shot, a direct hot drop on the part is employed, while for the ICM shot (Figure 5b), a hot drop with cold runner and edge gate is employed.

The material used for the first CIM shot is polycarbonate (LEXAN™ 4701R resin) and ABS (CYCOLAC™ MG94 resin) is employed for the second ICM shot. Both grades are from SABIC [18].

Results of first shot (CIM)
The process settings employed for the first shot CIM simulation are shown in Table 2.

Table 2: CIM process parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Mold Temperature</td>
<td>100 °C</td>
</tr>
<tr>
<td>Melt Temperature</td>
<td>360 °C</td>
</tr>
<tr>
<td>Fill time</td>
<td>1 sec</td>
</tr>
<tr>
<td>V/P switch-over</td>
<td>98%</td>
</tr>
<tr>
<td>Packing time</td>
<td>5 sec</td>
</tr>
<tr>
<td>Packing pressure</td>
<td>80% filling pressure</td>
</tr>
<tr>
<td>Cooling time</td>
<td>20 sec</td>
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</table>

The key insights from the CIM shot simulation with respect to filling are captured in Figure 7 (a-d). Fill time of about 1 second (Figure 7a) and peak pressure required to fill of 32MPa (Figure 7c) were observed from the simulations.
Filling is balanced within the acceptable limits with a center hot drop (Figure 7b). As seen from an inspection of Figure 7d, sink marks are estimated to become progressively more prominent as the rib thickness is increased from 1mm to 3mm. With increasing rib thickness, heat accumulation at the T-intersection (its rib and part intersectional area) area will progressively increase due to the thermal mass in the T-region associated with the rib; the increased thermal mass would induce more prominent thermal gradients, which in turn would lead to differential cooling and volumetric shrinkage, thereby making the sink-marks more prominent.

In Figure 8(a-d), further trends from the CIM simulation, particularly with respect to volumetric shrinkage and cooling time, are presented. An inspection of the contours of volumetric shrinkage along a cross-sectional plane across thickness of the part (Figure 8a) clearly highlights the higher volumetric shrinkage observed at thicker cross-sectional areas in the part. The highest shrinkages are observed in the T-junction associated with the thickest rib of 3mm (Figure 8b). As explained earlier, and as further highlighted in the hot-spot area (the last area to cool within the part) associated with the 3mm rib (refer to Figure 8c-d), the higher shrinkage at the 3mm rib is caused due to the higher thermal mass, which results in longer cooling times, and consequently the higher thermal gradients.

Fig.8: CIM volumetric shrinkage and cooling results

After solving for the first shot, while running the second shot which is ICM process, in the simulation tool the first shot was added as part insert. By doing this the temperature history from the first shot is seamlessly interlinked to the second shot ICM molding calculations. In Moldex3D this interlinking between the two shots is enabled in the solver by MCM (Multi Component Molding).

**Results of second shot (2K-ICM)**

The process settings for the second shot ICM are shown in Table 3.

<table>
<thead>
<tr>
<th>Table 3: 2K-ICM process parameters</th>
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<tbody>
<tr>
<td><strong>Filling setting</strong></td>
</tr>
<tr>
<td>Mold Temperature</td>
</tr>
<tr>
<td>Melt Temperature</td>
</tr>
<tr>
<td>Fill time</td>
</tr>
<tr>
<td>% of volume filled</td>
</tr>
<tr>
<td>V/P switchover</td>
</tr>
<tr>
<td>Cooling time</td>
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<td></td>
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</table>

Second shot ICM component is over-molded on the first shot CIM component as described earlier. The part thickness of ICM is 2.5mm. To provide for the compression phase in the ICM process, an additional 1mm “compression gap” is provided. Thus, the melt is injected into a cavity that has an initial gap of 3.5mm. Of course, the entire volume is not filled during the injection phase. Therefore, as seen in Table 2, the fill volume % for V/P switchover is set at 74%; i.e., only 74% of the total initial cavity volume is filled with melt (which translates to 100% of the final desired cavity volume at a 2.5mm gap at the end of the compression phase). Further, it needs to be noted that simultaneous ICM is employed; therefore, the compression phase starts when 69% of the initial cavity volume is injected. In the compression phase, the compression half of the mold closes the 1mm compression gap at a velocity of 1mm/s, i.e., within duration of 1 second using a compression force of 150 tonnes.

The trends observed from the simulation of the second shot ICM over-molding on the first shot are shown in Figure 9(a-d).

As shown in Figure 9a, the compression stage overlaps with the injection stage when the mold is partly (69%) filled. At the onset of compression phase, the injection peak pressure observed about 26MPa (see Figure 9c). Pressure variation with time is shown in Figure 9d in pressure XY...
plot. Figure 9b shows the combined fill time for the second shot ICM process; an injection phase of 9a (onset of compression phase) and 9b (end of fill) implies an additional duration of about 1 second is required for the compression phase. The unfilled area in figure 9c (or 9a) will fill during the compression stage of molding.

In the CIM process, significant cavity pressure drops are expected going from areas close to the gate to those further away. But as evident from an inspection of estimated pressure transients (Figure 10) recorded at seven points within the mold cavity (see inset in Figure 10), in the ICM phase the pressure gradients are significantly lower more importantly, uniform compared to the CIM phase.

Fig.10: Cavity pressure at different locations

In the 2K-ICM process, the compression speed and force are two important parameters that need particular attention. The settings for these parameters are further governed by volume injected into the cavity (relative to the initial enlarged cavity volume) and the switchover point at which compression phase is started. An optimal combination of settings of all these parameters is critical; otherwise, the compression phase will be force limited and the ram will not move at the desired speed. It will result in a different part thickness than the designed CAD part thickness.

In this study, the process is optimized for 1 mm gap; from Figure 11, it is clear that the set compression speed of 1 mm/s is maintained for the entire duration of the compression (Figure 11a) while the peak compression force is 21 tonnes (Figure 11b), which is well below the setting of 150 tonnes maximum compression force.

Figure 12 shows the temperature contours within a cross section of the cavity at the end of the compression phase of the second shot ICM process. The upper flat portion is processed as second shot ICM while the lower ribbed portion is processed in the first shot CIM step. As expected, the upper second shot portion shows higher temperatures compared to the previously molded first shot CIM portion. In the upper portion, the regions of the melt in contact with the mold are at lower temperatures than those in contact with the first shot. At the interface with the first shot resin, the highest temperatures of about 170°C are observed. An inspection of the ribbed portion achieved in the first shot show significant rise in the temperatures, indicating reheating of the solidified portion in contact with the fresh melt from the second shot. With continuity of heat flux and equality of temperature imposed at the interface, it is safe to consider that the temperatures of the resin at the first shot also reach up to 170°C at the interface. Since the glass transition temperature of the first shot PC resin is 140°C and freeze temperature is 164°C, it may be concluded that the first shot resin re-melts at the interface area that ensure good interlayer bonding.

Fig.11: Compression speed (a) and Compression force (b) results

Fig.12: Contours of resin temperature within the cross section of the cavity
When considering more details on temperature distribution between parts, a cross-section detail is taken at different location to show how the temperature is varying across the thickness. In Figure 13a, the temperature variation shows at a nominal area of the 2K-ICM part. The blue curve (pointed using the black arrow) in graph is at the interface of first and second shot. The temperature at the interface is around 170°C, which is well above the freeze temperature of first shot. As shown in Figure 13b, temperature across the thickness of both the parts is monitored at these five regions termed as probe points. The first probe point is at top side of ICM part which is at mold temperature (in contact with mold steel), the second probe point is at center of the ICM part and it’ll be at its melt temperature, the third probe point is at the interface of the two parts and is critical in understanding the re-melt behavior. The fourth probe point is at the center of the first (CIM) part, the fifth probe point is at the bottom surface of the CIM part which is at mold temperature of second shot. (and in contact with mold steel)

These temperature profiles are checked at different regions in the part to study the re-melt zone temperature. The cross-section in Figure 14a is shown for 1mm rib and Figure 14b is shown for 3mm rib thickness to capture temperature variation across the thickness. A quick comparison of temperature transients at the rib-junction (cf. the curve of the black arrow, it’s probe point 5 in fig13b) for the 1mm rib (Fig. 14a) and 3mm rib (Fig 14b) shows the significantly lower rate at which the melt cools within the thicker rib. This is expected to drive larger thermal gradients (differential cooling rates) around the rib and also result in local variations in volumetric shrinkage; such effects are precursors for aesthetic defects on the top surface. While the model is presently not fully resolved to capture sink marks in the ICM step (due to limitations within the software), the underlying phenomenology is captured accurately. Therefore, the process simulation may be employed to mitigate these factors through optimization of processing and geometry.

**Fig.13: Temperature profile across the thickness of 2K-ICM part**

**Fig.14: Temperature profile at 1mm (a) and 3mm rib thickness (b) of 2K-ICM part**

**Conclusions**

A validated simulation framework for complex molding operations such as 2K-ICM for large part moldings is expected to not only reduce the costs associated with trial and error during tool design, but also lead to faster adoption of this promising technology in manufacturing scenarios.
This study is the first step in developing such methodology using the commercially available simulation tool Moldex3D †. In this study involving 2K-ICM ribbed part, it is established that the key phenomenological aspects of 2K-ICM process may be realistically captured using simulation. The detailed thermal history from first shot CIM molding process have been seamlessly linked to the second shot CIM process using the Multi-Component Molding(MCM) module in Moldex3D †. Several complex phenomena such as local variations in thermal gradients and volumetric shrinkage governed by geometrical design aspects (e.g., rib thickness) have been captured in detail for the second shot CIM.

With the basic capability developed, this simulation framework will now be extended to address the effect of molding sequence (CIM first-shot vs. ICM first-shot) for similar or dissimilar material pairs on the factors governing surface aesthetics. Going forward, the results will be validated with molding experiments on the rib tool, and more detailed aspects of the process such as time lag between shots will be accounted for in the simulation. This framework is expected to enable better selection of machine, material grade selection, 2K-ICM mold design, as well as optimization of processing parameters in a reliable fashion while minimizing or eliminating experimental trial and error.

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