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Research Paper

Simulating And Validating The Pressure Profile During The Filling And Packing Phases of Injection Molding

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ABSTRACT

Autodesk Moldflow Insight (AMI) is a Computer-Aided Engineering (CAE) tool used to predict many molding phenomena such as pressure, filling pattern, cooling pattern, and deflection of injection molded parts. The purpose of this study is to validate AMI for use with plastic connector housings and determine the key factors in improving simulation accuracy. To validate AMI, a 3D Computer-Aided Design (CAD) model of a hypothetical, simplified connector housing with round circuit holes was created in Creo software. Then, a test mold was built using the simplified connector housing geometry with round core pins for the part circuit holes. The mold was outfitted with pressure sensors to monitor the exact pressures achieved in both the runner system and cavity. Using this mold, the validation part was manufactured more than fifteen times using an identical combination of material and processing conditions. Pressure sensors placed in the mold capture the exact pressures achieved in the part and runner system during molding. The averaged pressure profiles for each sensor are later compared against results from the simulation software to determine accuracy of the simulation program. Computer simulation models of the validation part were created with a mesh density of eight layers through the thickness of the model, which is appropriate for connector housings. The averaged values of the fifteen identically molded parts are then compared to the simulation results. This study results in an improved method for simulating the pressure profiles during plastic injection molding using refined process parameter definitions.

Keywords: Injection molding Machine; Cavity pressure; 3D Modeling; Finite element analysis.

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1 INTRODUCTION

INJECTION molding is a common manufacturing process for producing high volume plastic products. Injection Molding Machines (IMM) consist of a hopper, barrel, reciprocating screw, nozzle, platens, tie bars, heater bands, and mold. A high-level overview of IMM describes the process in this manner: solid plastic pellets residing in the hopper are released into the barrel where they are heated and progressed forward via the reciprocating screw. More details about the injection process can be found in [1][2]. Chen et al., [3] attempted to increase accuracy of plastic IMM simulation results by varying data input into the simulation. These authors validated the use of Corrected Residual In-Mold Stress (CRIMS) data to better predict warpage in injection molded parts when using a 2.5D mesh [3]. The conclusion of this work was that a 2.5D mesh with CRIMS data resulted in simulation results that were statistically like 3D mesh. However, the "Dual Domain Solver, without CRIMS material data, was found to differ from the 3D solver by up to 29% in predicting the warpage of parts molded from the unfilled crystalline material used in the study" [4].

Many industry leaders use simulation to increase the likelihood of successful molding, or to optimize products to shorten either the development cycle of new product design and/or the troubleshooting cycle of part failures [5][6]. Additional experiments have attempted to use simulation to optimize a new product design by making efficient use of the gating location, cooling system, and injection molding process conditions [7]. Simulation is used to optimize mold design and process parameters and to reduce manufacturing cycle time and the number of mold trials to improve work efficiency [9][8].

Other research has proven the effectiveness of using IMM simulation software for predicting residual stresses in injection molded parts [**Error! Reference source not found.**]. These studies concluded that when the thickness of the product is between ($0.0045 \leq x \leq 0.01$) mm, both flow and thermal-induced stresses should be considered to improve the accuracy of numerical analysis [11]. This additional experiment has taken part thickness into account, but not material or processing conditions as was done in the focused experiment. Calculating thickness-dependent stresses is a step in the right direction, but it is only a portion of the journey toward improving simulation accuracy [12]. More research has been done to simulate filling to optimize the filling balance; varying gate location algorithms, or combinations of them depending upon whether speed or accuracy is most important [13]. Additional experiments such as these also use a method of optimization using plastic IMM simulation software like the one discussed in this paper.

Some research focused on simulating the melt flow behavior in Ultra High-speed injection molding. The Heat Transfer Coefficient (HTC) value relative to the thickness needs to be considered, as does the length to thickness ratio relative to injection speed and wall slip effect [14][15]. Some items such as the HTC value and wall slip effect will significantly influence pressure predictions. Typical CAE injection molding simulation output data of interest include, but are not limited to, the following: filling pattern, weld lines, pressure profiles, shrinkage, and deflection [14]. An experiment that has attempted to verify simulated cavity pressure predictions discusses the importance of the HTC value when molding liquid crystal polymers [14]. It was determined that an overestimate of the HTC value would result in an overestimate of the pressure prediction. The simulation work was conducted using a Dual Domain mesh (also referred to as "2.5D") [15]; unlike the experiment that will be discussed later, which uses a 3D mesh. Using this 2.5D mesh, it is stated that an "HTC value of 5000 W/m^2 x °C for the filling stage of the injection molding simulation resulted in the most accurate prediction of both fill pattern and injection pressure" [16].

This paper focuses exclusively on the pressure profiles experienced during the filling and packing phases of injection molding. The pressure data output from the actual pressure sensors are the experimental data and the pressure data output from AMI simulation are the *simulation data*. This study compares experimental data to simulation data and determines key factors in reducing the difference between these two sets of data. Additionally, the focus of this paper is to simulate the pressure profiles of the molten plastic in the runner and cavity during molding phase using CAE software and to compare it with the actual sensor data. The injection molding trials were done using the validation part and thermoplastic resins which are the plastics used in injection molding that can be repeatedly melted, cooled, and re-melted. The validation part was injection molded using four distinct thermoplastic resins, individually. For simplicity, only one thermoplastic will be highlighted in this investigation.

In this research, CAD software was used to create the geometry of the validation part which is used in AMI CAE simulation. The accuracy of AMI is directly dependent on model meshing techniques, meshing algorithms, material characterization data, and process parameter definitions. The use of accurate injection molding simulation reduces time and cost to market by shortening mold conditioning times and demonstrating the effects of design changes without steel re-work, thus allowing costly changes to be made on a computer model, rather than expensive tool steel.

2 OBJECTIVES

To validate the use of AMI in simulating the pressure profiles associated with IMM of the validation part and determine the key factors in achieving, or at least improving, simulation accuracy, a 3D CAD model of the validation part was first created as shown in Figure 1. The 3D CAD model was then imported into AMI and a mesh was created on the part. AMI allows the user to specify certain mesh controls such as chord height, edge length, minimum number of elements through the thickness, etc. Initially, a surface mesh, consisting of triangles, was created on the part. Then, that mesh was repaired from any defects and then converted into 3D tetrahedral elements.

From that 3D CAD model, a mold was built as shown in Figure 2. Pressure sensors were strategically placed in the mold to capture the exact pressures achieved so that this data could then later be compared to the data output from CAE simulation. Five pressure sensors and a pressure monitoring tool were used for data collection. Figure 3 shows the locations of the pressure sensors in AMI simulation:

- Pressure sensor 1 is in the feed system close to the base of the sprue to measure the bulk of the molding pressure (referenced as "P1").
- Pressure sensors 2 and 4 are symmetric sensors located near the gate to measure part pressure and to help detect asymmetry in the cavity ("P2" and "P4")
- Pressure sensors 3 and 5 are located near the end of the part to capture the end of filling information and to help detect asymmetry in the cavity ("P3" and "P5").

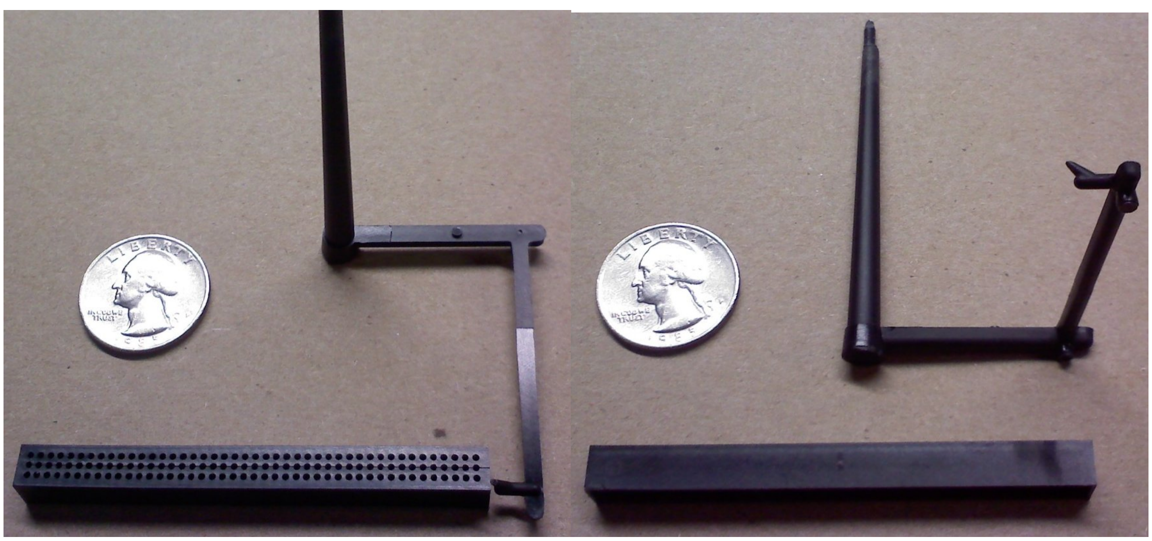

Fig. 1
Top-down (left) and side (right) of the validation part and feed system.

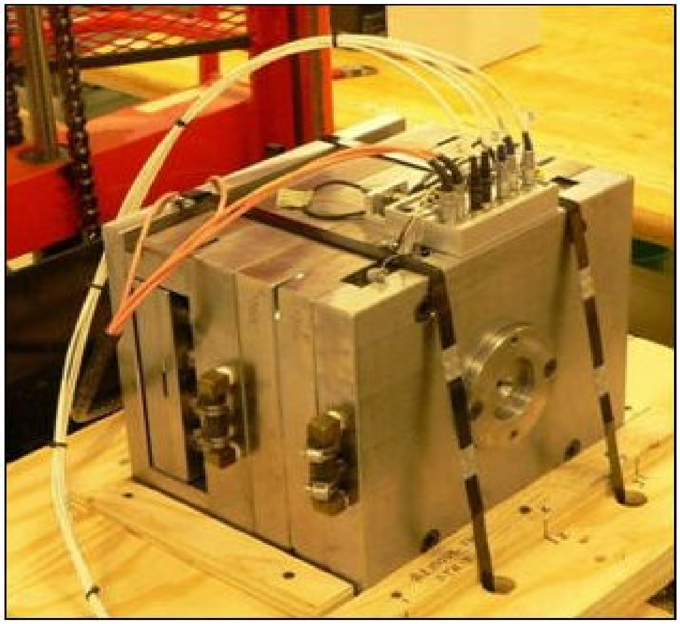

Fig. 2
Mold used to make the validation part and feed system.

3 INITIAL CONSIDERATIONS

AMI simulations that accurately represent an injection molding process require many parameters and measurements. The graphical user interface of the AMI program that was used in this study is shown in Figure 3. According to Autodesk Moldflow, the basic steps to accurately duplicating an actual molding process include verifying the following:

1. The dimensions of the 3D CAD model of the geometry represented in AMI simulation are identical to the dimensions of the mold geometry used in the experiment,
2. The runner system modeled AMI simulation is the same as what is used in the experiment,
3. The correct material data is used,
4. The filling and packing parameters are the same,
5. The warpage process settings are correct,
6. The IMM and the process are stable when the parts are molded.

In aligning with these steps, validation parts were molded in the IMM and measured to make sure that the dimensions were accurately reflected within the 3D CAD model used in AMI simulation; the same was done for the runner system. The materials chosen for use in the experiment were materials that were tested and characterized for use in AMI simulation. The materials used in the experiment are part of the Autodesk Moldflow material database and ranked well in accuracy of material characterization. This high level of material characterization fidelity helped to reduce, if not eliminate, variability in duplicating an injection molding process due to inaccuracy in material characterization data. This paper focuses on different ways to input the filling and packing parameters into AMI simulation and the resulting change in accuracy of replicating the pressure predictions. The warpage process settings, IMM data, and process were all verified and stable.

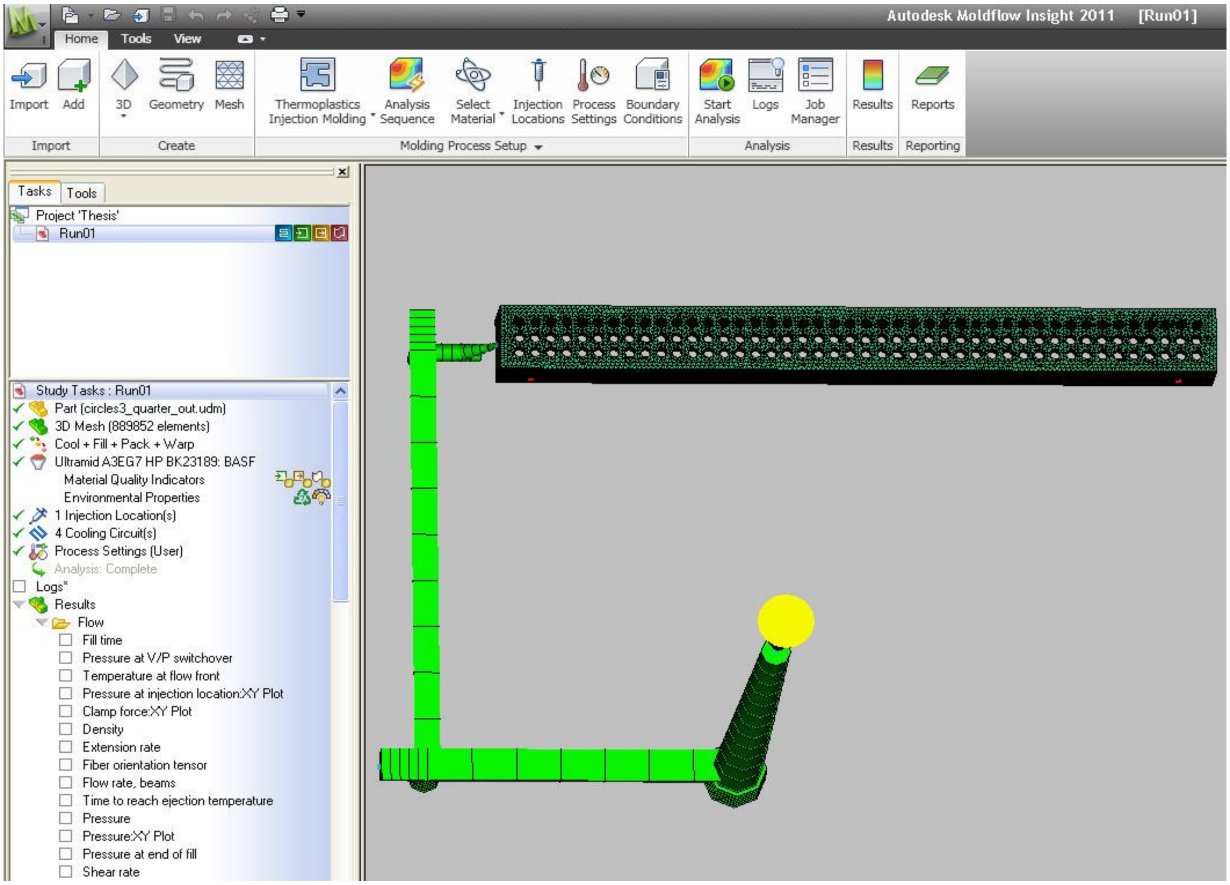

Fig. 3
AMI graphical user interface, and meshed validation part and feed system.

In addition to the need for accuracy with respect to the 3D part model, feed system, cooling system, and process parameters, there is a great need for an appropriately meshed model. In simulation, there are several meshing options, one of which we will discuss here. All results discussed here will be results using a 3D mesh. A 3D mesh contains nodes and elements not only on the exterior part surfaces, but nodes and elements also throughout the part thickness. The elements used in these 3D meshes are 4-noded tetrahedral elements which graphically represent the validation part geometry. The 3D models used for analyses contain 8 layers of tetrahedral elements throughout the thickness of the model. At every node, multiple calculations are performed including, but not limited to, fill time, shear rate, temperature, and pressure. This paper will focus exclusively on pressure predictions.

4 MOLDING TECHNIQUES

The validation part was manufactured using two distinct materials, and ten sets of processing condition combinations for each material. The material on which the research will be centered is a polyamide manufactured by BASF with the trade name Ultramid A3EG7. More details about this polymer can be found in [17]. Another polymer was used in this test with a trade name Volox 420. At least fifteen parts were produced using each material and set of processing condition combinations. For simplicity, only one material and one primary set of processing conditions will be discussed in this paper and used for comparison purposes as shown in Table 1.

Table 1
Example of a set of processing conditions used.

Simulation/Experimental Parameters	Unit
Coolant Flow Rate	2.8 gpm
Mold Open Time	3 sec
Screw Position	0.72 in
Peak Pressure	22,391 psi
Cushion	0.131 in
V/P Transfer Position	21,888 psi
Injection Time	0.13 sec
Injection Speed	6.0 in/sec
Recovery Time	1.36 sec
Cycle Time	15.16 sec
Cool Time	7 sec
Decompression	0.2 in
Transfer	0.28 in
Shot Size	0.52 in
Screw Rotate	200 rpm
Back Pressure	500 psi
Pack Pressure	3000 psi
Pack Time	4.5 sec

For each of the 15 parts produced, pressure sensors placed in the mold at various locations (Figure 4) captured the exact pressures achieved in both the runner system and cavity during experiment and relayed that data to sensor monitoring equipment. This data was then compiled and compared against the corresponding simulation prediction data.

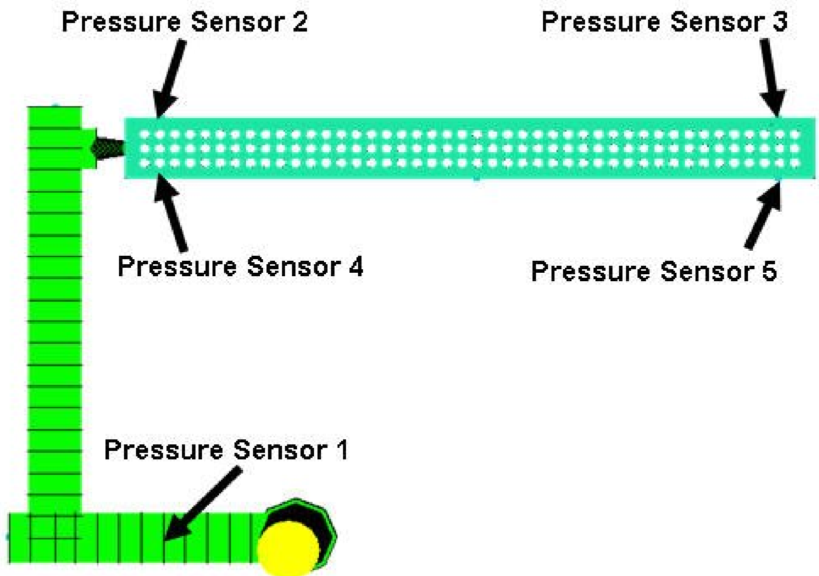

Fig. 4
Feed system, validation part, and sensor placement.

5 RESULTS

Several variables were included in this experiment, including the first variable discussed—material. When the material varied but simulation conditions remained representative of experimental conditions, pressure profiles differed significantly from experiment, proving that the inaccuracy is not solely material dependent (Figures 5 & 6). With the knowledge that the discrepancy is not dependent on material, we focus the research using one material from this point forward. After the discrepancy between experimental data and simulation data was discovered, the processing conditions were intentionally modified in simulation to achieve greater simulation accuracy. The details of such modifications are discussed below.

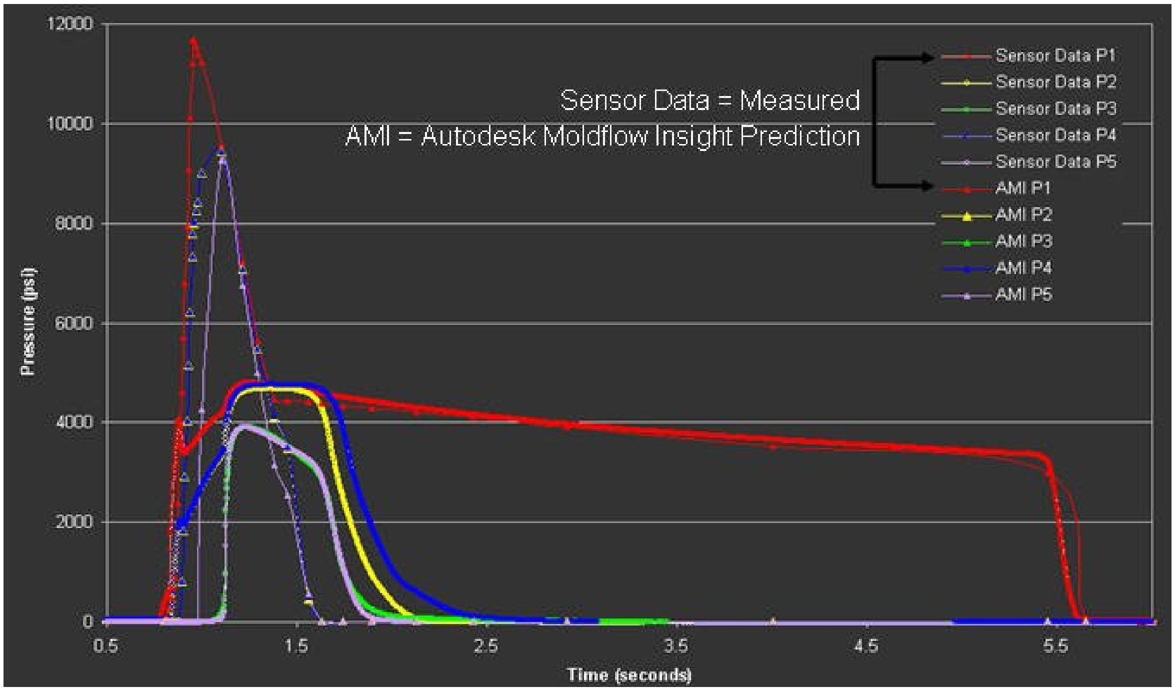

Fig. 5
Pressure profile output: Experiment versus Simulation using Ultramid A3EG7.

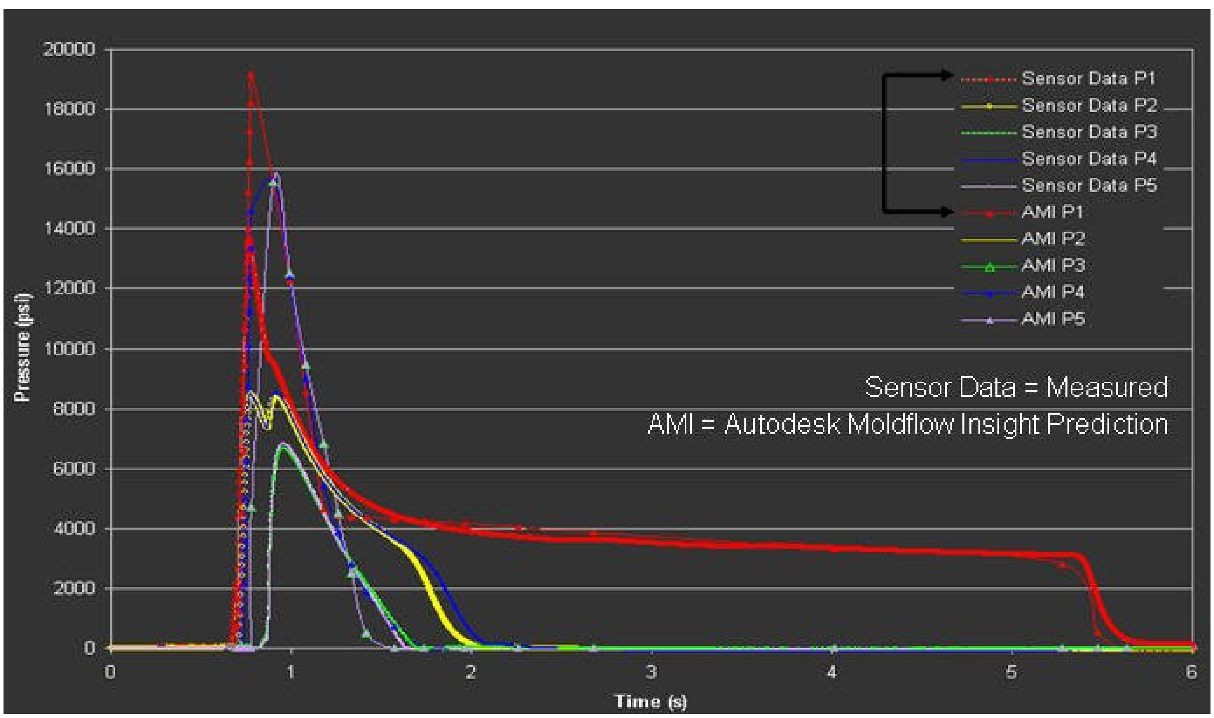

Fig. 6
Pressure profile output: Experiment versus Simulation using Valox 420.

The main processing condition modifications that were intentionally introduced into simulation are components of the filling and packing parameters. Filling control was analyzed using filling control by ram speed versus time. However, two different degrees of accuracy were used in estimating the ram speed versus time increments. One method used the constant ram speed that was an input on the IMM at 6 in/s, while the second method used very granular time steps for the actual ram speed that was captured as an output from the IMM during experiment (Table 2).

Table 2
Filling control profile granular time steps vs. experimental ram speed.

Filling Control Profile Settings

Ram speed vs time

	Time s [0:300]	Ram speed in/s [0:196.8]
1	0.03	0.2599
2	0.037	0.8315
3	0.044	1.403
4	0.0515	1.888
5	0.058	2.492
6	0.065	2.934
7	0.0744	3.505
8	0.0833	4.067
9	0.0907	4.539
10	0.0935	4.724
11	0.1062	5.071
12	0.1165	5.295
13	0.1259	5.531
14	0.1325	5.331
15	0.1419	5.047
16	0.1489	4.791
17	0.1579	4.567
18	0.1602	4.209
19	0.1636	3.778
20	0.1674	3.272
21	0.1702	2.852
22	0.1735	2.367
23	0.1783	1.796
24	0.1825	1.117
25	0.1868	0.6539
26	0.1916	0

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The ram speed profile that was captured as an output from the IMM was a static image of the IMM's screen which displayed ram speed versus time. This image of the profile was then input into a program to estimate the points on the curve and extract approximate numerical values for each point. This new, more finely estimated ram speed profile is the second option for the profile that was input into simulation (Figure 12). Packing control was analyzed using packing pressure versus packing time. However, as was done with filling control, two different degrees of accuracy were used in estimating the packing pressure versus time increments. One method used, as the input, the pressure that was a set point on the IMM was 3000 psi., while the second method used very granular time steps for the actual pressures that were recorded as an output from the pressure sensors during experiment as shown in Table 3.

Table 3
Packing control profile granular time steps vs. experimental pressure results.

Pack/Holding Control Profile Settings

Packing pressure vs time

	Duration s [0:300]	Packing pressure psi [0:72520]
1	0.0001	23116
2	0.0289	16584.7
3	0.0043	15582.7
4	0.0043	14525
5	0.0052	13495.3
6	0.0057	12326.4
7	0.0047	11213.1
8	0.0052	10211.2
9	0.0075	9237.39
10	0.009	8208.1
11	0.0085	7317.91
12	0.0071	6427.61
13	0.0155	5733.1
14	0.0202	4899.9
15	0.0211	4373
16	0.0254	3874.5
17	0.0277	3515.41
18	0.0272	3295.5
19	0.0315	3103.8
20	0.0286	3023.3
21	0.0301	2887.2
22	0.3502	2895.9
23	3.861	2895.9

The packing pressure profile that was captured as an output from the IMM was a static image of the IMM's screen which displayed packing pressure versus time. As was done for the injection profile, this image of the profile was then input into a program to estimate the approximate numerical values for each point on the curve. This new, more finely estimated packing pressure profile is the second option for the profile that was input into simulation. Therefore, all four sets of data are estimates, but the theory is that the higher refinement profile for each increase's accuracy. This paper precisely proves that theory.

In some situations, as was seen in experiment, the IMM controls can be set to specific values, but the IMM may never reach the set point values (Figure 7a-b). In molding situations such as this, the set point data should not be used as an input into the simulations.

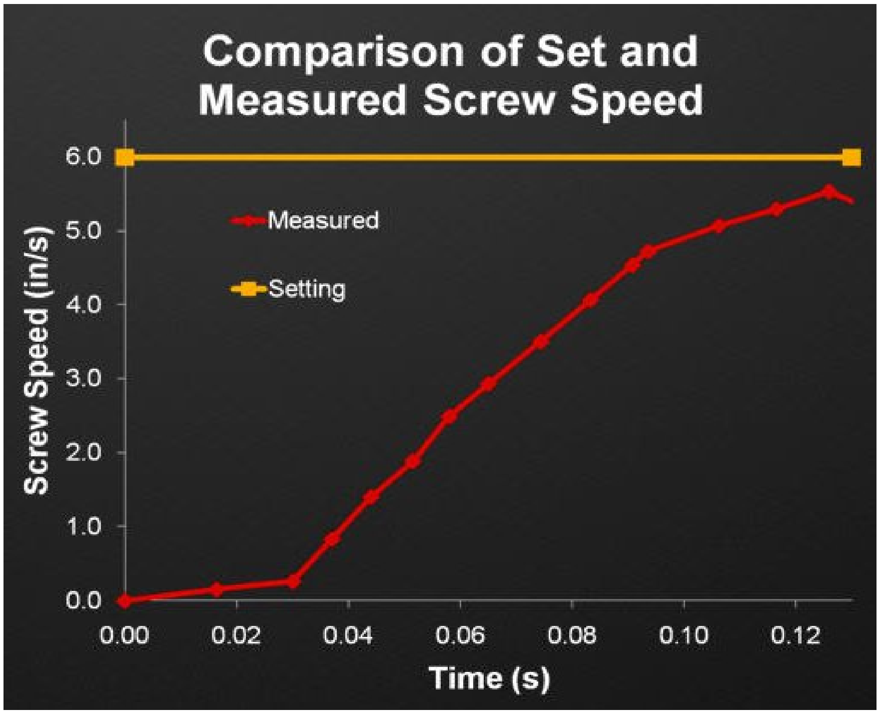

Fig. 7a
Screw speed: IMM set point versus experimental.

Fig. 7b
Packing profile input: IMM set points versus experimental.

When the data is available, the actual IMM readouts, for example, injection velocity vs. time as shown in Figure 8, should be used as the input into the simulation to best reflect experiment and obtain a higher level of accuracy in simulation predictions.

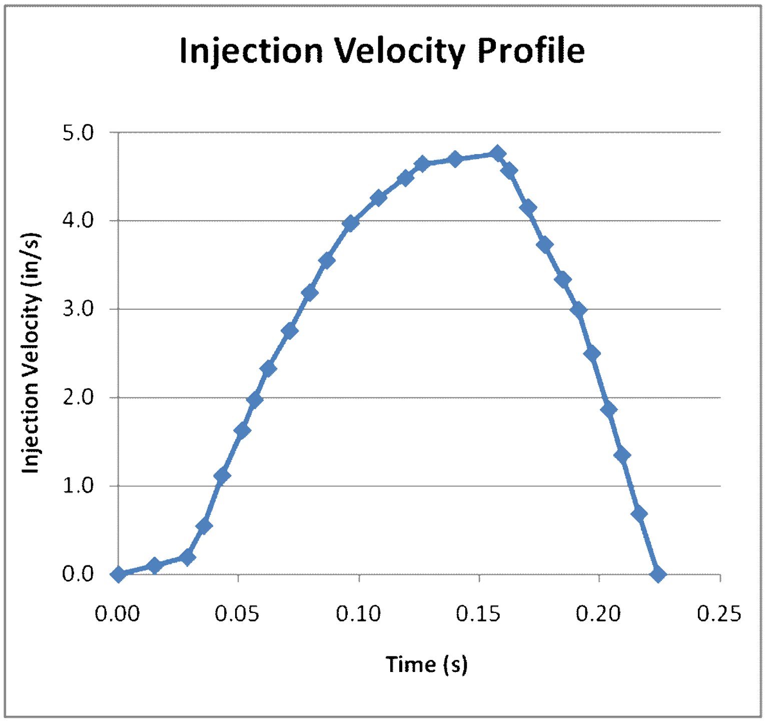

Fig. 8
Example of velocity profile from experimental data.

Figure 9 shows the result comparisons of the pressures experienced at sensor #1 in the runner while Figure 10 shows the result comparisons of the pressures experienced at sensor #2 which is located at the post gate, near the gate.

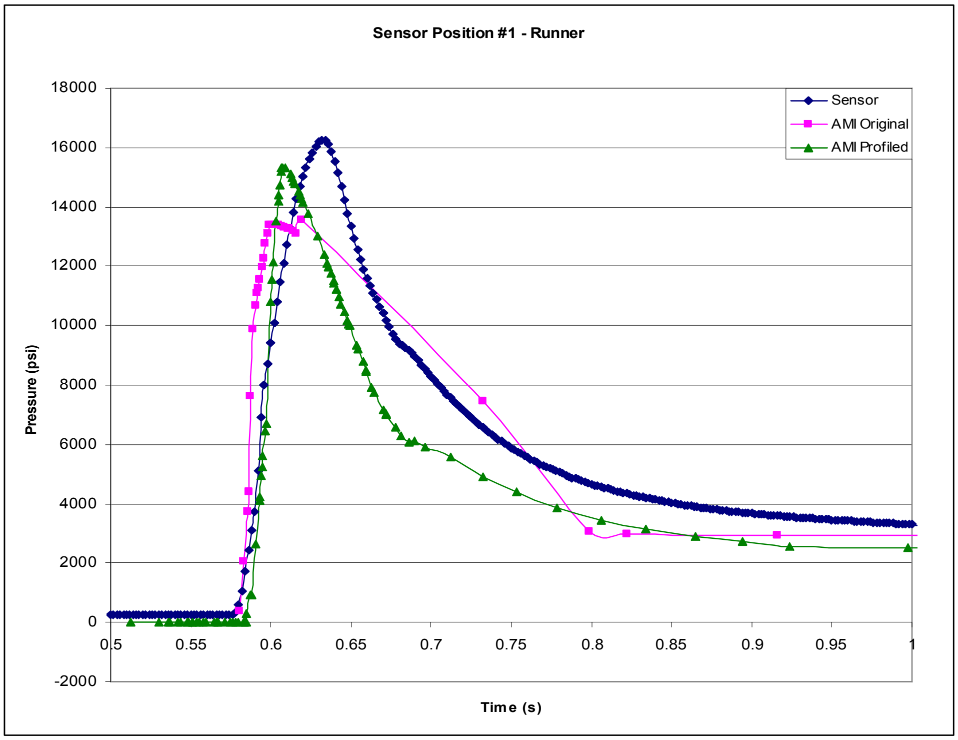

Fig. 9
Sensor #1 Results: Sensor versus AMI Original versus AMI Profiled.

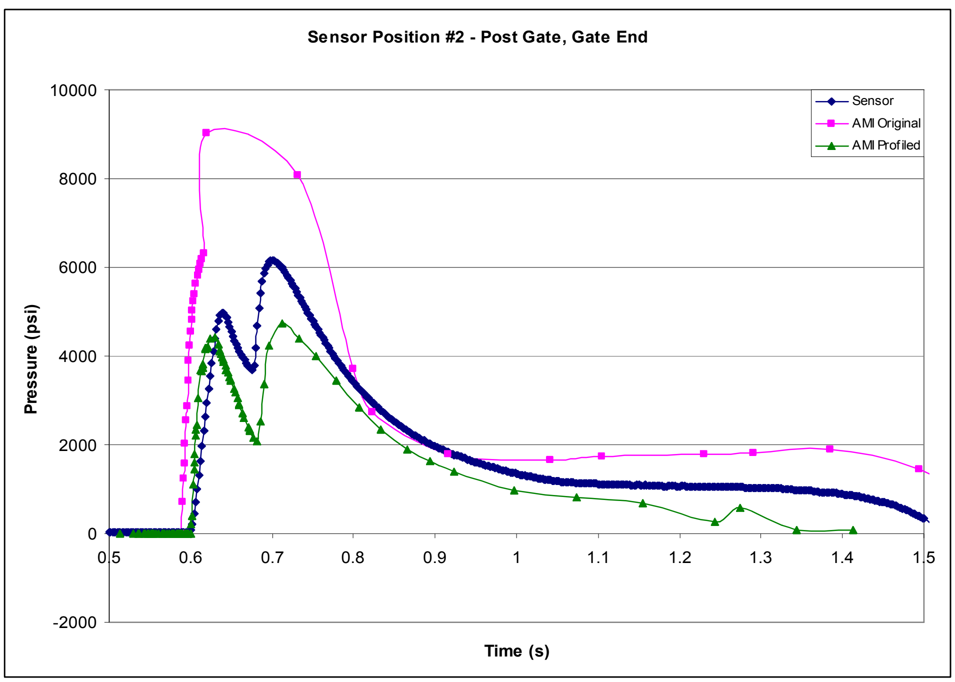

Fig. 10
Sensor #2 Results: Sensor versus AMI Original versus AMI Profiled.

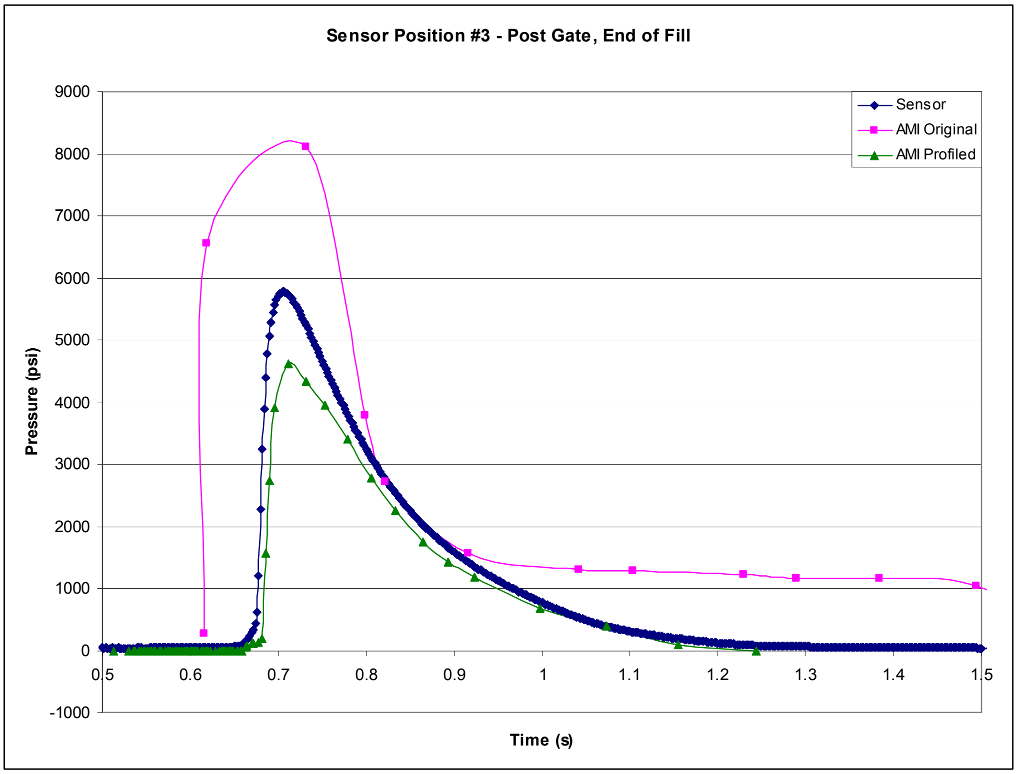

Fig. 11
Sensor #3 Results: Sensor versus AMI Original versus AMI Profiled.

Figure 11 shows the result comparisons of the pressures experienced at sensor #3 which is located post gate, at the end of fill. For reference, all sensor locations can be seen again in Figure 3. In all three figures, the "AMI Profiled" curves more closely follow the "Sensor" curves, the experimental data. The values for the ram speed profiles and the pressure profiles that were set points on the IMM are not representative of what is experienced during molding, and the results reflect the inaccuracies in the pressure profile predictions. Since the result curves, that use this machine set point values do not follow the sensor curves in magnitude or shape, we can conclude that the use of the granular time steps, when used for the actual ram speed and actual pressures, produce the most realistic results. This is because input data for "AMI Profiled" uses the granular time steps for the ram speed profile and the granular time steps for the packing pressure profile, which are both the more realistic way of representing those profiles and accurately reproducing the experiment in simulation.

One goal is to be able to observe enough combinations of materials, conditions, and part geometries to formulate a trend. Then, those trends can be used when actual data is not available. When/If actual data is available when the part is already being manufactured in production, that actual data will allow us to troubleshoot failures more efficiently and accurately. For instance, if a part in production is experiencing an area of no-fill, we can input all data to reproduce that no-fill condition and then change things such as part geometry or material in simulation instead of wasting costly material, time, etc. on the production equipment. This will streamline new product development along with troubleshooting and resolving failures.

6 CONCLUSIONS

The use of granular time steps for the actual ram speed and actual pressures produced the most realistic results. Since it is advantageous to run CAE software like AMI before building a mold and before producing parts, the challenge will lie in determining what values to use in simulation for filling control and packing control profiles since we will not have the actual values to input into simulation. Research and results from the validation study featured in this paper combined with results from some of the potential research efforts described subsequently may be used to create a "Best Practices Guide" to use for simulating many different product geometries and materials without ever having had to first manufacture such geometries. This would serve as a very valuable tool in the optimization of product designs early in the concept phases by shortening mold conditioning times and demonstrating the effects of design changes without expensive steel re-work; thus, reducing time and cost to market.

7 FUTURE WORK

Future research in this field could be to use temperature sensors that can detect not only the time at which the melt front reaches the sensor, but also the true temperature of the molten polymer at that sensor. This investigation was attempted during this study, but the temperature sensors used were only able to detect the approximate mold temperature and not the true value of the polymer melt. Therefore, the only real value of the temperature sensors in this study was to detect the time at which the molten polymer melt front reached the temperature sensor. Another possibility for research is to determine the sensitivity of inputs on specific results of interest for a variety of geometries and materials. This will probably become a rather large research effort but may be of high value.

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