AN ASSESSMENT OF DYNAMIC FEED CONTROL IN MODULAR TOOLING

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ABSTRACT

Modular tooling provides an approach for molders to manufacture multiple different plastic parts during one molding cycle, and to quickly exchange mold cavities according to dynamic production needs. However, the capability of modular and family tooling to mold parts of very different geometries to tight specifications has been limited by the inability to individually control the flow rate and pressure of the melt in each of the cavities. Axiomatic design principles were applied to the injection molding process to add control parameters that enable the spatial and dynamic decoupling of multiple quality attributes in the molded part. The developed system, Dynamic Feed, enables the direct controllability of the melt at different locations in a mold.

An experimental investigation of the inter-cavity dependencies of a modular tool using Dynamic Feed control is presented. The results show that part weight and overall part dimension are controlled by the individual command pressure to each cavity and the material's melt temperature. The weight and dimensions of a particular cavity appear independent of the control pressures set to fill the other cavity inserts. This was demonstrated to the extent that weight and dimension showed independence from a deliberate short shot condition in the hardest to fill part. There may be a minor synergistic effect of adjacent cavity pressure and the intentional shorting of alternate parts, but this would need to be confirmed with additional experimentation. Once initially stabilized, both traditional machine velocity control and Dynamic Feed weight variations were in the range of +/- 0.025% or less.

KEYWORDS

Injection molding process, dynamic feed, modular tooling, flexibility, controllability

1 INTRODUCTION

Injection molding is capable of producing very complex components to tight specifications. The process consists of several stages: plastication, injection, packing, cooling, and ejection. In injection molding and its variants (coinjection, injection compression, gas assist molding, etc.), thermoplastic pellets are fed into a rotating screw and melted. With a homogeneous melt collected in front of the screw, the screw is moved forward axially at a controlled, time-varying velocity to drive the melt into an evacuated cavity. Once the melt is solidified and the molded component is sufficiently rigid to be removed, the mold is opened and the part is ejected while the next cycle's thermoplastic melt is plasticized by the screw. Cycle times range from less than four seconds for compact discs to more than three minutes for automotive components.

Injection molded components are consistently designed to minimize the total system cost of the aggregate product or assembly. As such, it is common for a single product or assembly to be composed of multiple components that are molded of the same material. In such cases, a modular and/or family tool may provide a very economical method for producing all the components in a single cycle, yet also provide significant tooling and production flexibility for exchanging mold inserts to manufacture slightly different part geometries thereby facilitating management of product platforms and architectures [1].

However, the manufacture of different components in a modular tool to tight specifications has been challenging. The quality of the manufactured product is determined by the dynamics of the injection molding process. Unfortunately, the controllability of injection molding has been limited by the nonlinear behavior of the polymeric materials, dynamic and coupled process physics, and convoluted interactions between the mold geometry and final product quality attributes. A system's view (updated from Ma's view [2]) of the modern conventional injection molding process is presented in Fig. 1. The machine parameters are indicated on the left side of the figure, and some common quality attributes are listed on the right. In this figure, the process is decomposed into five distinct but coupled stages. The output of each stage not only directly determines the initial conditions of the next stage, but also influences some of the final qualities of the molded part.

Independence of the quality attributes for different mold cavities in a modular tool is not achievable with conventional injection molding. Specifically, the dimensions, weight, and other part properties for one cavity can not be changed without similarly effecting other cavities in the mold or re-tooling the mod geometry. However, a new molding process has been developed that fundamentally alters the dynamics of the molding physics. These added control parameters allow the spatial and/or dynamical decoupling of multiple quality attributes in the molded part.

2 DYNAMIC FEED DEVELOPMENT

The complex nature of the injection molding process necessitated the development of sophisticated, numerical process simulations to estimate the progressing melt fronts, pressure distribution, and temperature dynamics of the process. Design decisions that are supported may include number of gates, location of gates, pressure drop through gates, wall thickness, process input parameters, shrinkage compensation, and others. These process simulations have been widely adopted, and have enabled the development of extremely advanced molding applications. This infrastructure is necessary since the molding process is not capable of significantly altering the molded part quality attributes once a mold is manufactured. Thus, significant effort must be expended during product development to ensure the mold tooling delivers the desired product before the tooling enters production.

The polymer state (pressure, temperature, and morphology) directly determines the molded part quality [3]. Thin cavity filling of polymer melt corresponds to creeping flow (Re<<1) which is coupled to a temperature field characterized by a thin cold layer (Pe>>1) surrounding a hot core region [4]. As an example, consider a reference velocity of 10 cm/sec, reference thickness of 3 mm, and a viscosity of 100 Pa Seconds. The Reynolds number based on this case is very small, ϑ(10-3), indicating the validity of the highly viscous creeping flow assumption. Furthermore, the flow regions are considered fully developed, and both the unsteady and the gravitational force effects can be ignored due to negligible local acceleration. On the other hand, the thermal diffusivity, $\alpha=k/\rho Cp$, of typical polymer melts is $\vartheta(10^{-3})$ cm^3/sec, and the kinematic viscosity, $\nu=\eta/\rho=10^3$ cm^2/sec; hence, the Prandtl number is about ϑ (10^6) and Peclet number, $Pe= Re*Pr$, is ϑ (10^3). Using these assumptions, the molding process physics can be modeled as shown in Figure 3.

While it is not possible to change these physical laws, it is possible to significantly alter the initial and boundary conditions such that the process is dominated by different dynamics and exhibits very different behaviors. Consider, for example, some of the differences between the injection molding and extrusion processes. Both processes utilize a polymer melt in a similar temperature, pressure, and shear rate range. Both processes utilize a mold wall as an impermeable boundary condition to shape the polymer melt into a useful solid form. However, the extrusion process does not have an impermeable boundary at the end of the extrusion length. This simple difference allows the extrusion process to be continuous, with process models and dynamics to be approximated as steady state with no initial conditions. By comparison, the injection molding process must maintain many additional initial and boundary conditions to control the dynamic filling and cooling of the polymer melt.

The controllability of the process' pressures and temperatures has been investigated [5]. Melt temperature was quickly discarded due to slow thermal diffusion and poor spatial localization. Closed-loop control of cavity pressure had recently been implemented and shown to achieve a consistent process and uniform set of product attributes [6-8]. Adaptive control and learning methods had been developed to track cavity pressure profile, though at only one location in the mold [9-11].

Several placement locations and actuator designs were considered. The current embodiment is shown in Figure 3, in which the valves meter the flow of melt from the runners into the mold cavity. The pressure drop and flow rate of the melt is dynamically varied by the axial movement of each valve stem which controls the gap between the valve stem and the mold wall. By de-coupling the control of the melt at different valve stem positions, melt control at each gate can override the effects of the molding machine and provide better time response and differential control of the melt. Each valve acts as an individual injection unit, lessening dependency on machine dynamics. For closed loop control, manifold pressure transducers were used in the runner drops instead of in the cavity. This implementation not only provides lower cost and greater reliability, but also renders a conventional appearance for the system.

The resulting controllability of the injection molding process is demonstrated in Fig. 4 where multiple pressure profiles can be maintained in the mold cavity of a single part. In the same cycle, three different magnitudes of melt pressure were exerted at different gates for the part shown in Figure 5. The control pressures for the holding stage at Gate 1 and 2 are 41.4 MPa (6000 psi.) while Gate 3 is 20.7 MPa (3000 psi.) and Gate 4 is 62.1 MPa (9000 psi.). In conventional injection molding, the melt pressure would be the same at all gates. This level of process control has not previously been achieved by any molding technology thus far. Each gate can exert a unique holding pressure.

The decoupled process physics are shown in Figure 5. There are two major benefits of the process redesign effort. First, closed loop pressure control has enabled tight coupling between the mass and momentum equations. This tight coupling allows the direct input and controllability of the melt pressure. Second, the use of multiple melt actuators provides for the decoupling of melt pressures between different locations in the mold cavity. Such decoupling can then be used to maintain functional independence of multiple quality attributes.

3 DYNAMIC FEED IN A MULTI-GATED APPLICATION

The controllability of three part dimensions was investigated for a typical multi-gated application shown in Figure 6 [12]. Eight different run conditions were performed for the conventional injection molding process according to a half-factorial design of experiments [13]. The resulting relationship between the three critical part dimensions and injection pressure, injection velocity, melt temperature, and screw rotation speed was:

$$\begin{bmatrix} L1 \\ L2 \\ L3 \end{bmatrix} = \begin{bmatrix} 0.57 & -0.10 & 0.43 & 0.02 \\ 0.51 & -0.18 & 0.29 & 0.00 \\ 0.23 & -0.05 & 0.18 & 0.10 \end{bmatrix} \begin{bmatrix} Pressure \\ Velocity \\ Temperature \\ ScrewSpeed \end{bmatrix} \tag{1}$$

In this equation, the machine parameters have been scaled to the range of 0 to 1, indicative of the maximum feasible processing range for this application. The resulting coefficients of the linear model are actual change in part dimensions (measured in mm) for the printer output tray shown in Figure 6. It should be noted that once tooling is completed, the dimensional changes available through processing are quite limited though functionally significant.

There are two significant conclusions that can be drawn from eq. (1). First, all three of the dimensions react similarly to changes in the process settings. Thus, the molding process behaves as a one degree of freedom process in which only one quality attribute is controllable. Second, the equation shows the relative effect that each of the processing variables can have on the product quality attributes. Pressure was the most significant process variable, followed by temperature, velocity, and others.

The mold was refitted with Dynamic Feed to control the pressure at each of the four gates. The material shrinkage and dimensions change at differing locations in the part based on the pressure contours and histories around the gates. A Taguchi L9 design of experiments was conducted with different levels of pack pressure at each of the gates. The parts were then measured, and a linear model developed. It is possible to augment eq. (2) with the additional degrees of freedom and re-examine the controllability of the three part dimensions:

$$\begin{bmatrix} L1 \\ L2 \\ L3 \end{bmatrix} = \begin{bmatrix} -0.02 & -0.05 & 0.08 & -0.01 \\ -0.03 & -0.09 & 0.05 & 0.00 \\ -0.01 & -0.02 & 0.03 & 0.01 \end{bmatrix} \begin{bmatrix} Pressure \\ Velocity \\ Temperature \\ ScrewSpeed \end{bmatrix} + \begin{bmatrix} 0.00 & 0.31 & 0.60 & 0.00 \\ 0.10 & 0.17 & 0.00 & 0.16 \\ 0.00 & 0.02 & 0.00 & 0.21 \end{bmatrix} \begin{bmatrix} P1 \\ P2 \\ P3 \\ P4 \end{bmatrix} \tag{2}$$

There are two significant implications of this result. First, the closed loop control of cavity pressures has significantly reduced the dependence of part dimensions on machine settings, as evidenced by the reduction in the magnitude of coefficients for the primary machine settings. This effect has also been evidenced by reductions in the standard deviations of multiple part dimensions by an average factor of five, resulting in an increase in the process capability index, *Cp*, from less than 1 to greater than 2.

The second matrix in eq. (2) is also evidence of the improved dimensional controllability provided by the dynamic regulation of the cavity pressure distribution. In general, changing the cavity pressure at the gate closest to a dimension provides the major effect on part dimensions.

Additionally, independent control of the valve stems provides the capability to vary dimensions at one location without altering the dimensions at another location. This flexibility does not exist in conventional molding because hold pressure changes intended to influence one area of the part can be transmitted to other areas of the part through the static feed system. It should be noted, however, that the total magnitude of dimensional change available with dynamic pressure regulation is approximately the same as for conventional molding.

4 DYNAMIC FEED IN A MULTI-CAVITY MODULAR APPLICATION

Watkins and Hume have previously discussed the application of Dynamic Feed in modular tooling [14]. While it is clear from the mechanics that Dynamic Feed operates with individual valve controls for each zone of operation, it is not clear that this results in independent functionality of each zone. For example, the shorting of one part in an adjacent cavity or the sudden filling of another might be anticipated to have a deleterious effect on neighboring cavities.

To investigate the capability of Dynamic Feed in a modular tooling application, a four cavity modular tool was retrofitted with the technology. Four different mold insert geometries were then utilized that corresponded to the molded parts shown in Figure 7. **(* Some text on the different parts, sizes, and requirements. *)** The material used was an ABS GPM5500-4500 Lot AZ4124. The material was dried under manufacturer recommended conditions. The quality metrics of part weight and the largest part dimension were chosen to assess the process capability of Dynamic Feed. A visual quality ranking was also suggested but was later dropped as all parts appeared indistinguishably good.

Preliminary runs focused on establishing upper and lower pressure limits for each of the cavities in the tool. Table 1 shows these experimentally determined upper and lower limits for the melt pressure in each cavity insert. Generally, the upper pressure limit was constrained by the occurrence of flashed and/or sticking parts. The lower pressure limit was constrained by excessive sink and part warpage. A short shot series was also performed to see the order in which cavities filled.

Next, a sixteen run, half-factional design of experiments was conducted to investigate the effect of five control variables, which consisted of the four control pressures plus melt temperature. The left side of Table 2 shows the experimental design factors and levels for the study implemented. The pressures explored in the design were well inside the limiting pressures, except for the column labeled “Pressure Multi” this column refers to the pressure for the multi-cavity part. At the high-pressure level, a full multi-part is produced while at the lower pressure a significantly short part is intentionally produced. In this way, the influence of a part shorting could be established. Pressure profiles were then established for each cavity with a rectangular shape. The pressure setting shown in Table 2 is indicative of the largest plateau region of the command pressure profile.

Data was collected using a Netshal 200 ton injection-molding machine with a Roundmate modular tool having 4 distinct cavity insert. A Dynisco Hot Runner plate manifold, naturally balanced with HTP10 (10mm diameter), 2 hole cone nozzles CV21 tip style and quick couple actuators were used. The actuators were driven by a dynamic feed PC controller system that implemented a closed loop pressure control scheme incorporating Dynisco PT4676XL pressure transducers in each zone. Inlet and manifold runner size were 10 and 12mm respectively. PDC temperature controllers maintained the process at a nominal 243 C. The injection molding machine was velocity controlled with maximum inject pressures of 220 Mpa, and a pack/hold pressure of 124 Mpa. Front and back mold temperatures were controlled to 32 and 38 C respectively.

All parts where created while at Nypro Inc. in Clinton, Ma. Weight and dimensional measurements were taken for twenty consecutive molding cycles. These moldings were collected after having established steady state experimental conditions in fully automatic cycling with at least 20 shots discarded. Weight measurements were made using an AND FX300 precision balance with readability to +/- 0.1mg. All part weight measurements were made about 20 minutes after part production. Dimensions were measured by a video dimensional measurement system and confirmed using a Starret height gage. Dimensional measurements were also made approximately one week after the experiment. Melt temperatures were verified via a hand held pyrometer measured from injection unit puddles. The last experiment run was a run chart of “normal” machine velocity control on all the parts and the Dynamic Feed version of the same using middle of the range (Table 1) pressures profiles. Approximately every 4th shot was collected during these runs.

Short shot sequencing showed that the MULTI-PART was the hardest to fill (shorted first), next hardest was the BATTERY case, after that the FRONT and easiest to fill was the BACK. Analyses were done using standard Yates, ANOVA and surface methods techniques [15]. Figures 8 to 10 show Pareto charts of the main effects and second order interactions. The primary factor of influence for both weight and dimension is the pressure command for the each cavity in every case.

Only in the FRONT cavity dimension does the temperature fail to be the second most important factor influencing the weight and dimensions. The ANOVA technique indicates that only the first two effects in the Paretos charts are significant at the alpha=0.10 level. For the investigated pressure ranges, part weights varied from 0.8-2% while dimensional changes were more than an order of magnitude smaller being 0.05-0.1%. These magnitudes correspond to the results obtained with Dynamic Feed in the multi-gated application.

Figure 5 shows that once established, the velocity controlled machine had slightly lower variance than the dynamic feed run data under the given test conditions. **(*Need more discussion on this: 1) for what parts, 2) what are the Cp values, 3) why? *)**

5 DISCUSSION OF RESULTS

Significant molding experience generally indicates that dimension and weight measures are typically correlated. The results of this study are inline with these expectations, as shown by the Pareto summaries of length and weight measurements. Response surface methods, not shown, were also utilized in addition to the ANOVA. It should be noted that the dimensional results were analyzed using raw data with two measurement replicates instead of averages, thus allowing for some indication of system noise and variation. This provides an analytical error estimate and the real variation would be expected larger allowing less discernment. Nevertheless the RSM indicates that using just the main effects and ignoring interactions provides consistently good models with correlation coefficients above 0.97 for both weight and dimensions. Adding interaction effects does not significantly improve the adjusted correlation coefficient.

The results presented in this article may have a significant impact on the product and tooling development process. Currently, numerical mold filling simulations and expert judgments are combined to estimate the process behavior and make critical design decisions. If these decisions are incorrect, then tooling modifications may be required. Improved controllability of the injection molding process with Dynamic Feed permits correction for many design inaccuracies during the mold commissioning stage without retooling. Such a change in the development process could substantially reduce the tool development costs and hasten time to market.

The described process is also significant in that it moves polymer control from the molding machine to the mold itself. This reduces the molding machine to a ‘polymeric pump.’ Variations in injection pressure, flow rates, pack pressures, or pack times are all compensated through dynamic pressure and temperature control. The market repercussions could be significant, as 1) an old machine without closed loop control can provide consistency equal to modern machines, and 2) a mold commissioned on a molding machine in the United States is ensured to produce consistent parts on a molding machine overseas. The mold becomes its own self-contained quality control mechanism, resulting in substantial productivity and quality gains.

6 CONCLUSIONS

The development of the Dynamic Feed system was presented with applications to a multi-gated part and modular tooling. The extensive investigation with the modular tooling application has shown that the Dynamic Feed system demonstrates robust and independent control for each cavity in an interchangeable insert mold. This was indicated by both part weight and dimension using an ABS material. It is significant that this independence occurred over substantial pressure profile changes. The ranges covered during the experiment were 53 Mpa (7,800 psi) for the communicator back, 28 Mpa (4000 psi) for the communicator front, and 17 Mpa (2,500 psi) for the battery case. Even while an adjacent part was intentionally shorting, dimensions and weight had no substantial change in other cavities.

Pressure effects easily dominate the temperature effect of 11 C (20 F) over the ranges studied. This illustrates that pressure could be used to compensate for the effects of changing temperature if this is desired. This enhanced process control should allows molders more flexibility in the temperature and pressure processing window for their applications.

7 ACKNOWLEDGMENTS

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LIST OF FIGURES

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Table 1: Pressure Limits

Cavity Insert Name	**Maximum Pressure (Part sticks)**	**Minimum Pressure (Part shorts)**
	MPA	MPA
Front	103	34
Back	131	36
Battery	83	28
Multi	165	41

Table 2: Implemented Design of Experiments

Std Order	Controlled Factors					Results					
	Pressure Front MPa	Pressure Back MPa	Pressure Battery MPa	Melt Temp C	Pressure Multi MPa	Part Weights			Part Dimensions		
						Front g	Back g	Battery g	Front mm	Back mm	Battery mm
1	55	57	45	243	124	9.942	6.973	34.033	75.64	75.46	109.11
2	83	57	45	243	28	10.023	6.978	33.987	75.67	75.49	109.09
3	55	110	45	243	28	9.939	7.137	34.017	75.64	75.78	109.11
4	83	110	45	243	124	10.020	7.140	34.045	75.64	75.77	109.13
5	55	57	62	243	28	9.940	6.975	34.383	75.59	75.46	109.22
6	83	57	62	243	124	10.020	6.973	34.375	75.67	75.48	109.22
7	55	110	62	243	124	9.939	7.138	34.391	75.65	75.74	109.19
8	83	110	62	243	28	10.017	7.140	34.378	75.67	75.76	109.22
9	55	57	45	254	28	9.968	6.984	34.105	75.59	75.49	109.12
10	83	57	45	254	124	10.071	6.984	34.068	75.67	75.49	109.17
11	55	110	45	254	124	9.951	7.148	34.081	75.59	75.76	109.12
12	83	110	45	254	28	10.065	7.145	34.046	75.65	75.77	109.11
13	55	57	62	254	124	9.983	6.989	34.456	75.67	75.49	109.26
14	83	57	62	254	28	10.068	6.985	34.427	75.70	75.50	109.25
15	55	110	62	254	28	9.986	7.147	34.430	75.65	75.76	109.26
16	83	110	62	254	124	10.066	7.152	34.468	75.69	75.78	109.25

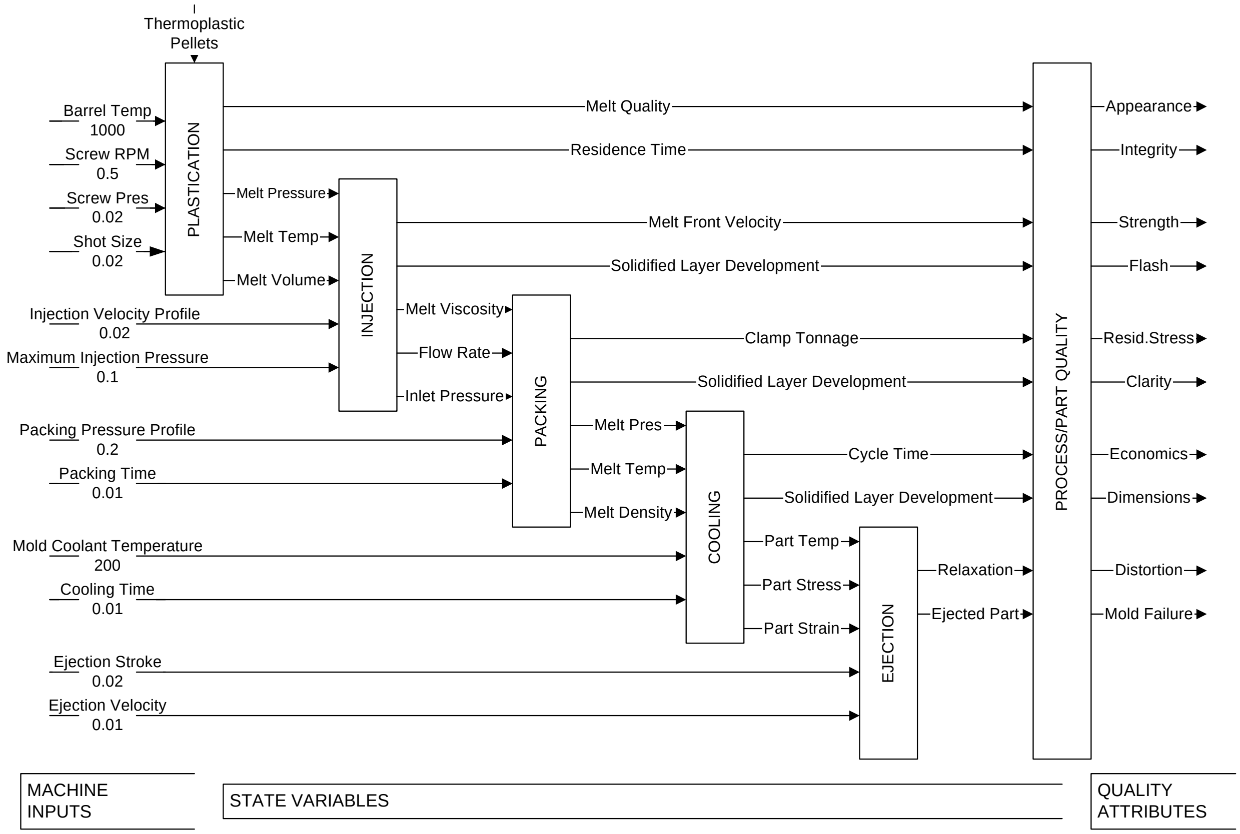


Figure 1: System view of the injection molding process

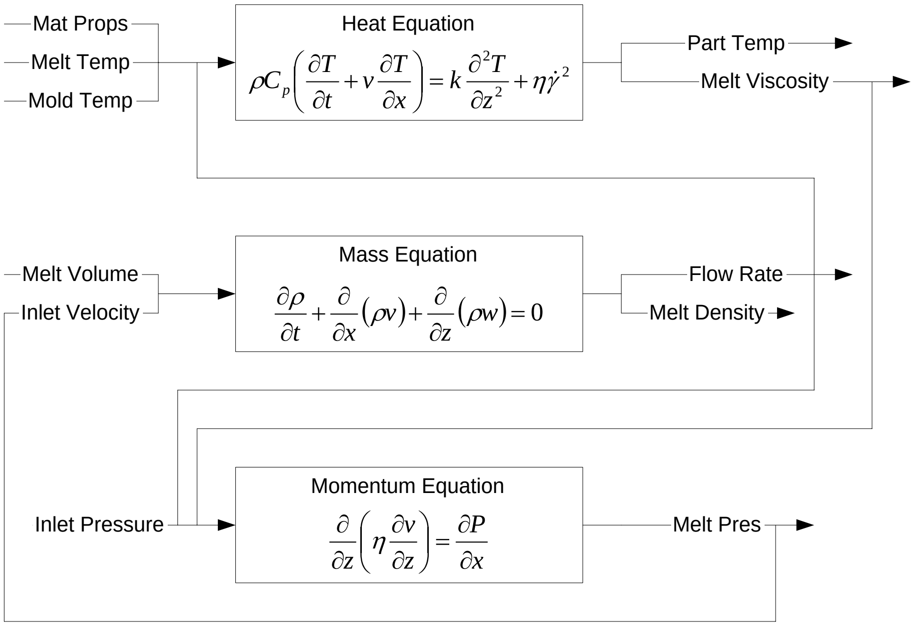


Figure 2: Coupled process physics

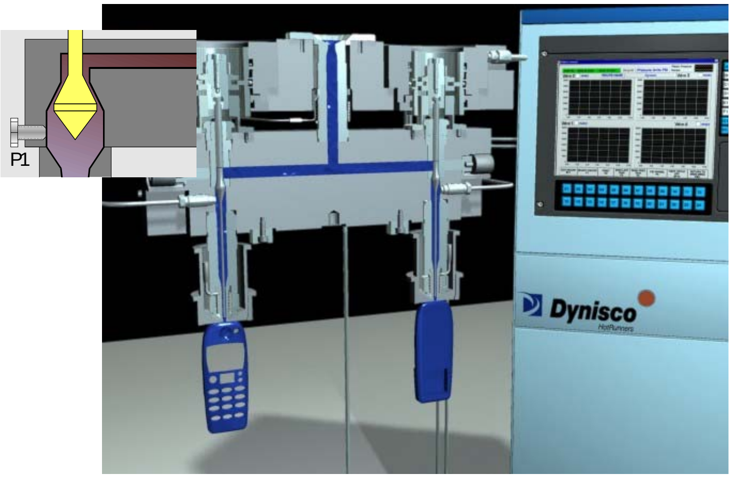
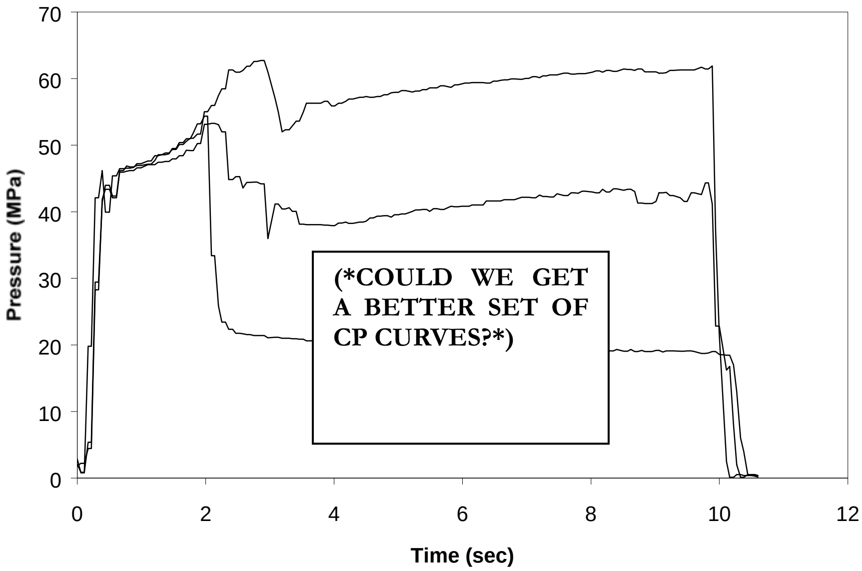


Figure 3: Dynisco's Dynamic Feed™ System



(*COULD WE GET A BETTER SET OF CP CURVES?*)

Figure 4: Dynamic pressure regulation

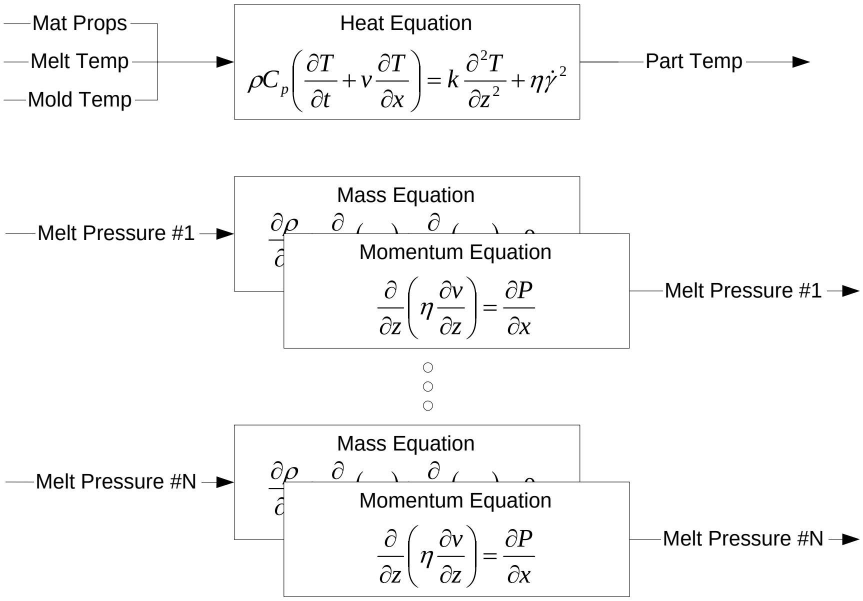


Figure 5: Modified process physics

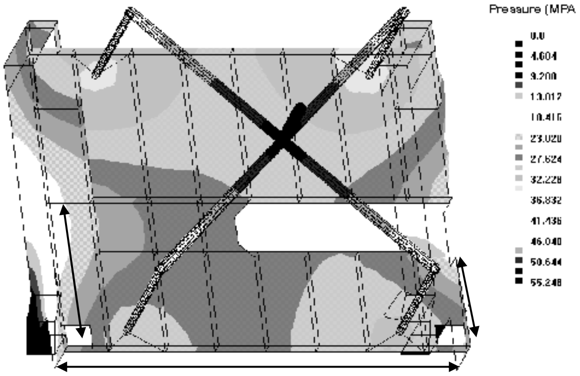


Figure 6: Geometry and packing pressure distribution

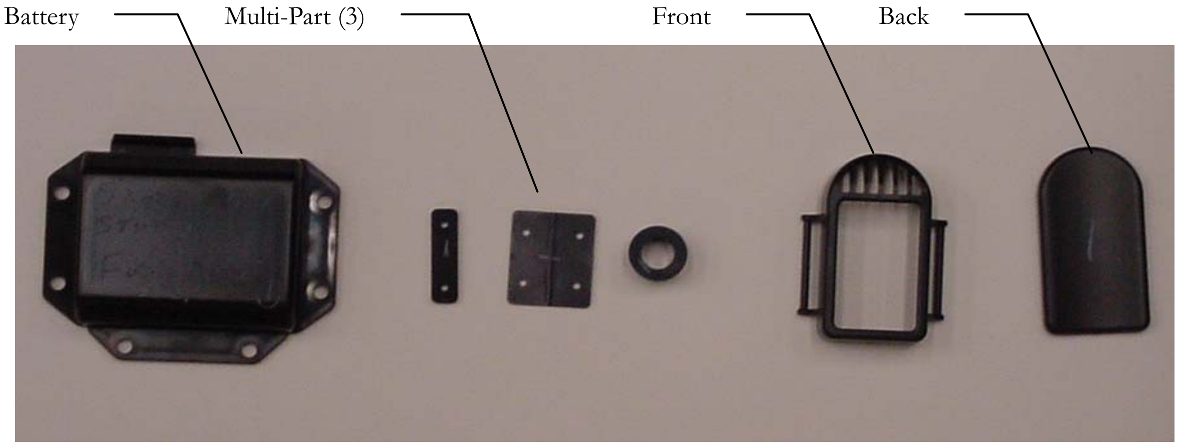


Figure 7: Parts molded from modular tooling with Dynamic Feed

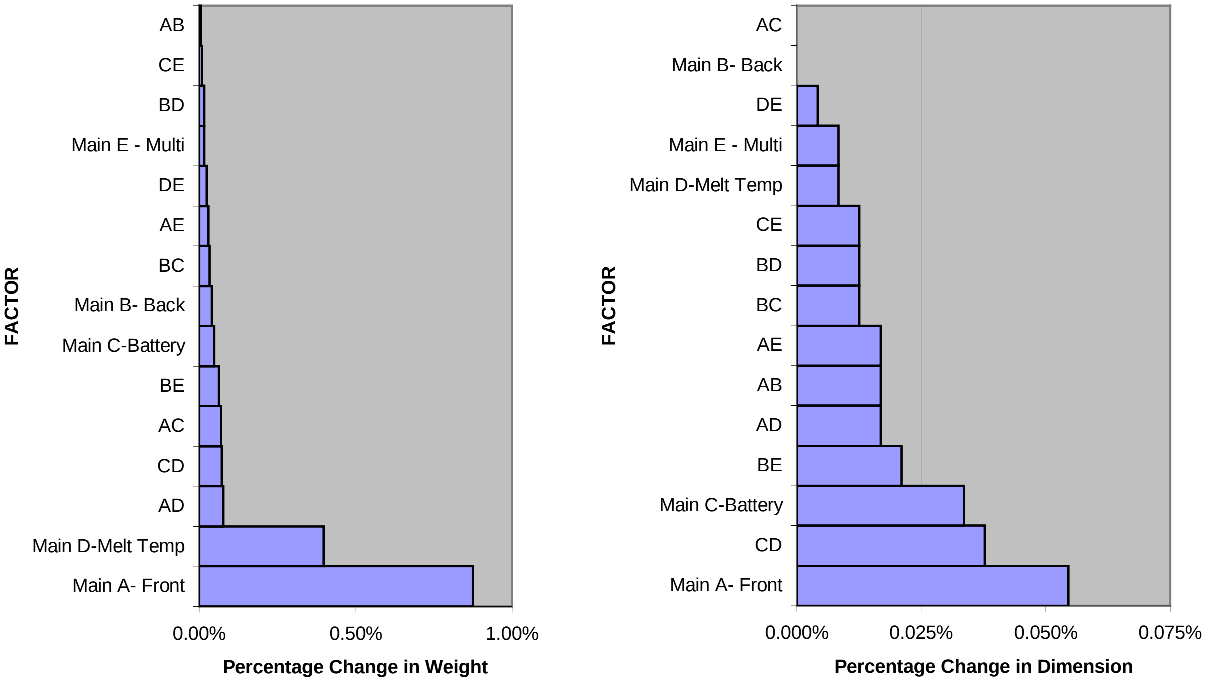


Figure 8: Pareto effects plot for front cavity

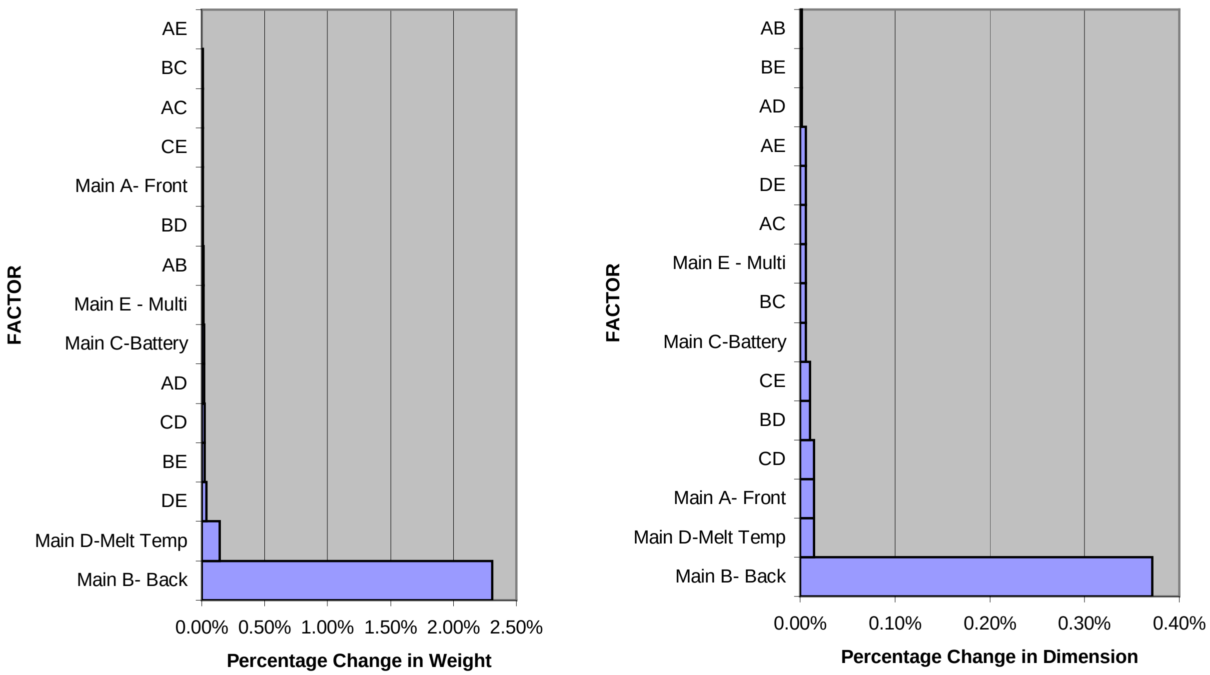


Figure 9: Pareto effects plot for back cavity

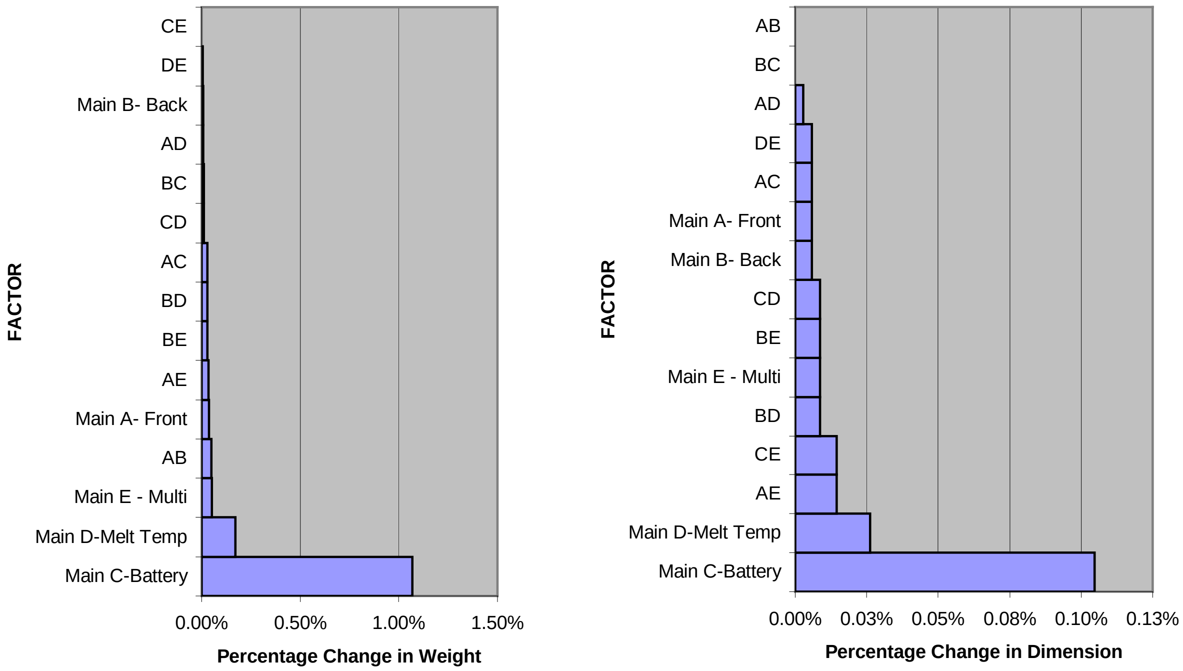


Figure 10: Pareto effects plot for battery cavity

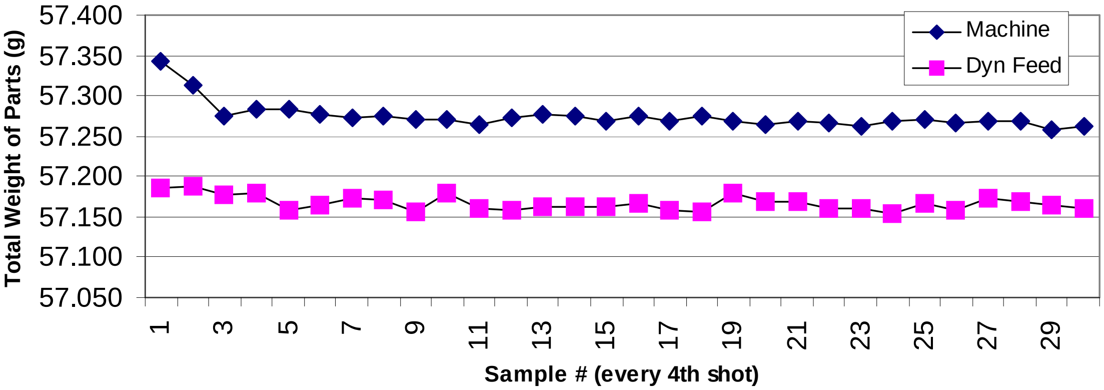


Figure 11: Run chart data