ACCOUNTING FOR PRESSURE DEPENDENT AND ELONGATIONAL VISCOSITIES TO IMPROVE INJECTION PRESSURE PREDICTIONS IN MOLD FILLING ANALYSIS

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Abstract

The increasing demand for shorter product development timelines and more robust plastic part designs has made injection-molding simulation a critical tool for plastic part and mold designers. One of the most common objectives of injection-molding simulation is determining the pressure requirement to manufacture the part for a given resin and set of process parameters. The reliability of injection-pressure prediction is dependent on many factors including accurately modeling the part and mold geometries, and predicting the material behavior during this dynamic process. While advancements have been made with regards to improving the ability to properly represent the mold and plastic part geometries, the ability to adequately model the molten polymer behavior remains a difficult task. Of particular importance is the ability to properly characterize the material viscosity during the injection molding process. The ability to account for the effects of pressure and elongation deformation on the material viscosity is critical for providing reliable injection pressure predictions. This paper will present the results of an experimental validation study in which the effect of accounting for the pressure dependence and elongation deformation on the material viscosity influences the injection pressure predictions.

Introduction

Injection molding is used to efficiently mass produce high quality, tight tolerance parts. It is a pressure-driven process in which the hot molten polymer is injected from the injection unit into a cooler mold cavity to form the desired geometry. The amount of pressure required to form the part is dependent on many factors including: the part wall thickness, injection speed, melt temperature, and flow length. The industry trend of light-weighting plastic components and thinning the part wall thickness result in higher injection pressures required to fill the part, and are commonly approaching the injection pressure limit for the injection unit. Additionally, the compressed product development timeline restricts a designer’s ability to redesign a plastic part if the original design cannot be manufactured as a result of excessive injection pressures.

In response to these design pressures, injection-molding simulation has become a prevalent tool to help virtually validate plastic part designs before any physical parts are manufactured. From the author's experience, one of the common objectives of injection-molding simulation is to determine the pressure required to fill the mold. The ability to accurately predict the pressure required to fill the mold can help designers and molders make more informed decisions regarding the runner design, minimum clamp force requirements, and overall dimensional stability of the plastic part. While it is desired to accurately predict the maximum injection pressure, the ability to properly model the complex relationship between the variables that influence this pressure prediction often force analyst to remain conservative with their results.

The reliability of any simulation is dependent on the ability to properly input the correct data and boundary conditions to accurately represent the physical systems. When considering injection molding, the ability to accurately predict the injection pressure requires that the part and mold geometry, molten resin and mold temperatures, injection rate, and material viscosity be properly modeled [1]. With the increased access to high performance computers, many of the major injection-molding simulation providers have advanced the solver algorithms and mesh generation tools to better represent the part geometry, and heat transfer during the injection phase. Work performed by Okonski highlights that the reliability of the injection pressure predictions is strongly dependent on the quality of the polymer material characterization, and the ability to properly model the material viscosity [2]. However, that study was limited to analyzing a single material at a set melt and mold temperature. The only process parameter that was varied was the injection rate. Additionally, the construction of the test mold in that study only permitted the maximum injection pressure at the nozzle to be recorded, and did not allow the author to determine where the pressure discrepancy existed within the system.

The goal of this paper is to evaluate how the models used to characterize the resin viscosity during injection influence the overall pressure predictions for a given material. Additionally, the study evaluates how the different material models combine to represent the overall pressure profile during injection and the pressure drop throughout the mold.

Viscosity Models

Viscosity is defined as the property of a fluid that resists the force tending to cause the fluid to flow [3]. The injection molding process tends to exert two different types of forces on the molten polymer during injection. Shear stresses arising from the pressure driven flow through a narrow geometry tend to be the predominate deformation stresses in the molten resin in the mold cavity. However elongation stresses also exist at changes in thickness, for example, where resin flows from the runner into the cavity via a gate. Such rapid geometric changes result in the plastic molecules elongating as they flow and cause a higher pressure drop than would be expected by shear stresses alone. To account for both types of stresses commercial injection-molding simulation software packages implement multiple models, which help improve the injection pressure prediction.

Cross-WLF Model

The Cross-WLF viscosity model has been used extensively in injection-molding simulation, as it provides a good representation of viscosity over a wide range of processing conditions [4]. This model can calculate the molten polymer viscosity, η, as a function of melt temperature, T, shear rate, $\dot{\gamma}$, and melt pressure, p, Equations 1:

$$\eta(T,\dot{\gamma},p) = \frac{\eta_0}{1+\left(\frac{\eta_0}{\tau^*}\right)^{1-n}} \qquad (1)$$

Where:

- η is the melt viscosity, (Pa·s)
- η_0 is the zero shear viscosity,
- $\dot{\gamma}$ is the shear rate (s^{-1})
- τ^* is the critical shear stress at which the polymer starts to exhibit shear thinning behavior
- n is the power law index in the high shear rate regime

The zero shear viscosity, η_0, is described through a WLF representation (Eq. 2). This representation highlights that the zero shear viscosity is a function of both temperature and pressure. The coefficients in Equations 2-4 are all data-fitted from rheological measurements. The only coefficient in these equations that has a physical meaning is D_3, which represents the linear pressure dependence of the glass transition temperature for the resin, T*.

$$\eta_0(T,p) = D_1 exp\left[-\frac{A_1(T-T^*)}{A_2+(T-T^*)}\right] \qquad (2)$$

$$T^* = D_2 + D_3 p \qquad (3)$$

$$A_2 = \bar{A}_2 + D_3 p \qquad (4)$$

While the Cross-WLF model is capable of modeling the viscosity as a function of temperature, shear rate and melt pressure, it is often simplified to only account for the influence of temperature and shear rate. This simplification is commonly used because characterizing the pressure dependence can be difficult, and there are few testing laboratories who offer such a service.

Previous work conducted by Mahishi [5] has shown that pressure dependent data becomes important when one or more of the following conditions exist:

- Flow length to thickness ratios are greater than 100
- Part wall thickness is less than 2 mm
- Injection pressures are greater than 100-150 MPa

Additionally, some resins, like polycarbonate, exhibit a strong pressure influence on the viscosity of the material. In these cases, it is critical to account for the influence of pressure on the material viscosity.

Extensional Viscosity

While the Cross-WLF model does a good job of describing the viscosity of the molten resin in shear flows. It does not account for any changes in viscosity as a result of extensional flows. Extensional flow occurs when the molten material is stretched as it is flowing. This type of flow is common in the feed system (runner and/or manifold) where the flow channel cross-section reduces rapidly. The extension work done on the polymer melt at these transitions results in an additional pressure drop, $\mathbf{P_e}$. This additional pressure drop is particularly prevalent at the machine nozzle, and at the gate(s). In order to account for this additional pressure drop, additional material models have been developed.

One of the models used to help account for the additional pressure loss due to contraction in the flow path is the Juncture Loss Model, Equation 5. This model is used with the traditional 2.5D (shell-based) simulation solvers, or anytime the feed system is modeled using beam elements. The premise of this model is that the additional pressure loss generated as the polymer is stretched through the flow restriction can be related to the shear stress, τ_w, the molten polymer experiences in the restriction. The model consists of two coefficients, C_1 and C_2, which are fit based on capillary rheometer measurements where the length over diameter ratio of the die is varied. In the simulation, this additional pressure loss is then added to the pressure gradient determined by the solver arising from the shear deformation of the material.

$$\Delta P_e = C_1 {\tau_w}^{C_2} \qquad (5)$$

In a simulation where the mold geometry is represented using full 3D elements, the juncture loss model cannot be directly implemented. Therefore, an alternative extensional viscosity model was developed by Moldflow to help improve the pressure predictions in these models. This model is referred to as the extension viscosity model, and is shown in Equation 6. This auxiliary model is used to scale the viscosity of the molten material when extensional deformation or stretching forces are significant.

The model calculates an isotropic viscosity, $\overline{\eta}$, by scaling the shear viscosity generated from the Cross-WLF model and multiplying it by a scalar value. The scalar value is determined through a function, $f(\dot{\varepsilon})$, which calculates the scaling factor based on the extension rate the molten polymer experiences, $\dot{\varepsilon}$,

$$\overline{\eta}(T,p,\dot{\gamma},\dot{\varepsilon}) = f(\dot{\varepsilon})\eta_s(T,p,\dot{\gamma}) \quad (6)$$

$$f(\dot{\varepsilon}) = 1 + \frac{A\dot{\varepsilon}}{B+\dot{\varepsilon}} \quad (7)$$

Where:

- $\overline{\eta}$ is the isotropic viscosity (Pa-sec)
- η_s is the shear viscosity (Pa –sec)
- $\dot{\varepsilon}$ is the extension rate (sec^{-1})
- A, B are data-fit coefficients

Physical Experimental Equipment and Material

The first portion of the correlation study consisted of physical molding of 150 mm X 75 mm X 3 mm plaques. The mold consisted of a single-cavity that was fed by a cold runner system. A tunnel gate was used to manufacture the parts, which is representative of the cross-sectional change commonly designed in to cold feed systems. The mold was equipped with a total of five cavity pressure sensors, allowing for the pressures to be recorded through the feed system and cavity. Figure 1 shows a schematic of the feed system design, plaque geometry, and pressure sensor locations. There are two sensors in the feed system, and three sensors in the mold cavity.

The injection unit used for the experiment was an Arburg All-rounder 520 Selogica with a 40 mm diameter barrel. The injection unit is equipped with a custom nozzle adapter that incorporates a temperature and pressure, which allows for the injection pressure to be directly measured.

The correlation study uses a Moplen EP301K, a medium flow impact copolymer polypropylene resin. This resin has a Melt Mass-Flow Rate (MFR) of 4.0g/10 minutes (230°C/2.16 kg). This material is commonly used in cap and closure, and packaging applications where thin wall molding is common.

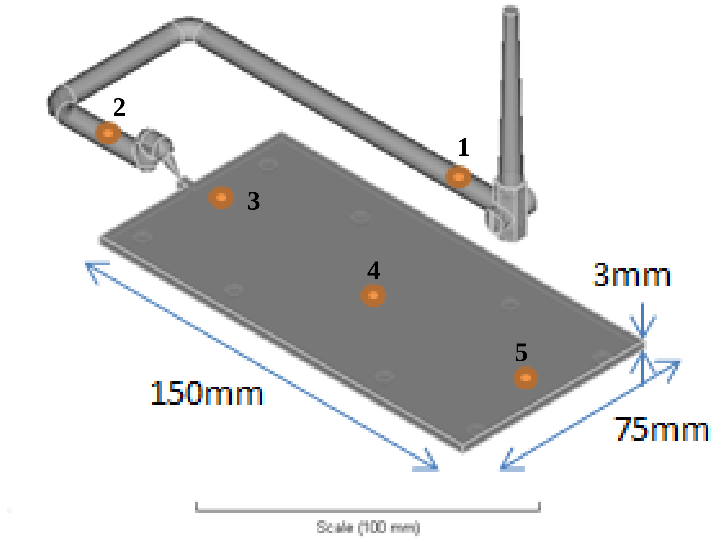

Figure 1 – Schematic showing the location of the pressure sensors within the plaque mold.

Physical Experiment

During the molding of the polypropylene plaques the melt temperature, mold temperature, and injection rate were varied with five replicates made to determine process robustness. The process parameter values used for the correlation study are highlighted in Table 1.

Table 1: Process Parameters Used In Correlation Study

Cycle Number	Melt Temperature	Mold Temperature	Flow Rate
105	230 °C	40 °C	40 cm^3/sec
237	230 °C	40 °C	80 cm^3/sec
385	230 °C	60 °C	40 cm^3/sec
570	200 °C	60 °C	40 cm^3/sec

Simulation Models and Evaluation

The second portion of the correlation study performed several injection-molding simulations for the plaque mold. Several variables were evaluated to determine the importance and sensitivity of the variable on the simulation results. Each simulation model included the custom nozzle adapter, cold runner system, cavity geometry, and cooling system. The simulations were performed using Autodesk Moldflow Simulation 2013 SP2, and performed a Cool+Fill+Pack analysis. A representative model of the simulation set up is shown in Figure 2.

The plaque geometry was modeled using both the midplane (shell) and full 3D tetrahedral elements. The cold runner and the custom nozzle adapter were modeled using beam elements for all midplane analyses. However, for the full 3D representation of the mold cavity, the feed system was modeled as either beams or with tetrahedral elements. Modeling the feed system in both ways allows for a comparison to be made between the juncture loss model and the extension viscosity model used in the two different solvers.

The Moplen resin was characterized at the Autodesk Plastics Lab located in Melbourne, Australia. The material was characterized at several different levels to allow for a comparison to be made between the different viscosity models. The first model, only characterized the shear viscosity of the resin without any extension viscosity effects or pressure dependence (i.e. D_3 = 0). The second model, characterized the shear viscosity of the resin without any pressured dependence, but did include the juncture loss or extensional viscosity models as appropriate. The third and final model characterized the shear viscosity of the resin *with* pressure dependence, and with the appropriate extensional viscosity models. While the coefficients of the models cannot be publically shared, it is worth noting that each model characterization of the polymer resulted in different coefficients. The change in the coefficient values is a direct result of the interrelated models.

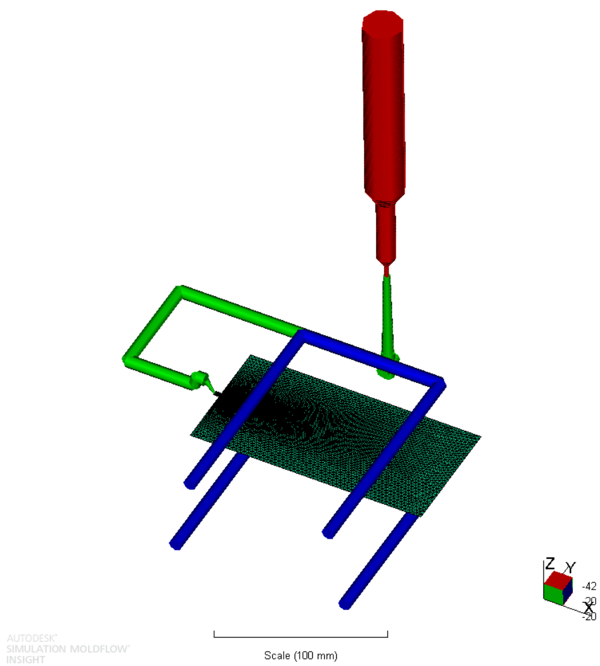

Figure 2– A representation of the midplane model used for the simulations, which modeled the entire mold design including the machine nozzle (red) and cooling circuits (blue).

Validation Study Comparison Results

Midplane

Figures 3 – 6 show the injection pressure comparisons for the four molding conditions when representing the molding process using the midplane solver. Reviewing the results of the midplane analyses show that the injection pressure prediction is greatly improved when the juncture loss model is incorporated into the simulation and slightly improved further when pressure dependence is also included. Three of the simulated cycles show very good correlation with the physical experimental data. Not only does the maximum pressure prediction improve, but the overall injection curve is better represented with the inclusion of the juncture loss model. The discrepancy in the injection pressure profile relative to time is likely a result of the inability for the simulation to account for the decompression of the melt in the injection unit prior to the beginning of injection.

The process parameters simulated in Cycle 570 under predicted the measured injection pressure with all material models. The material model that included the pressure dependent viscosity showed the best correlation, but still under predicted the injection pressure by 25%. From the three accurate simulations, it appears that the juncture loss coefficients had a more significant impact on increasing the injection pressure than the pressure dependent viscosity. However, this is not unexpected because the pressures remained low, and polypropylene is not a highly pressure sensitive material.

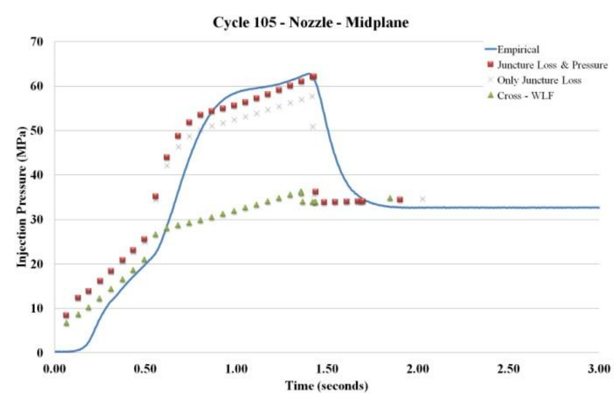

Figure 3– Injection pressure profile comparison for Cycle 105, using the midplane solver.

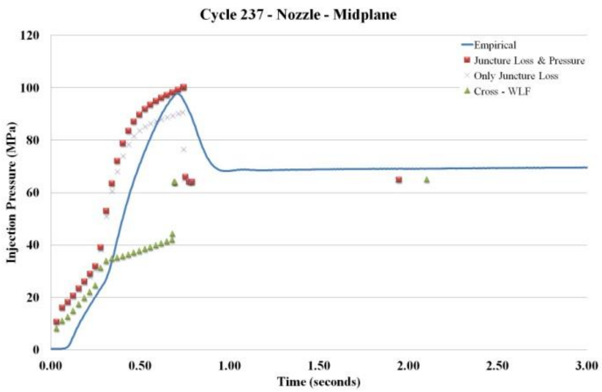

Figure 4 – Injection pressure profile comparison for Cycle 237, using the midplane solver.

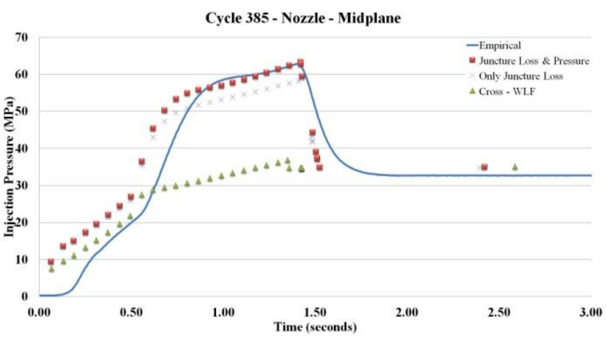

Figure 5– Injection pressure profile comparison for Cycle 385, using the midplane solver.

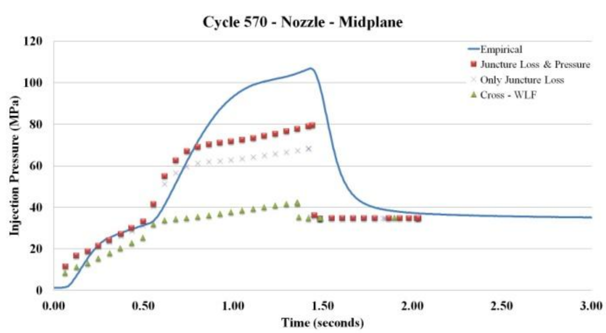

Figure 6– Injection pressure profile comparison for Cycle 570, using the midplane solver.

Full 3D

The analyses that modeled both the runners and the cavity with full 3D, tetrahedral, meshes reveal that the pressure was under predicted in two of the four cases, Figures 7 -10. Cycles 237 and 570 produce significantly lower predicted injection pressures, as compared to the measured pressure. The results of a mesh refinement study revealed that the discrepancy is not a result of insufficient mesh density. Additionally, while not shown, the results of modeling the runner with beams or tetrahedral elements did not appear to significantly influence the results. The incorporation of the extension effects did improve the pressure prediction, but in general the predicted pressures remain low. The full 3D solver appears to be more sensitive to changes in the injection rate or temperature than the midplane solver.

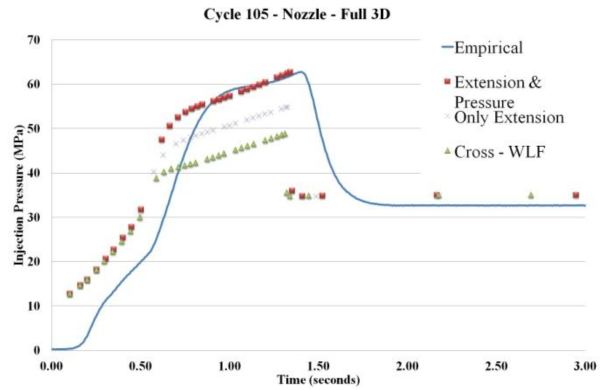

Figure 7 – Injection pressure profile comparison for Cycle 105, using the full 3D solver.

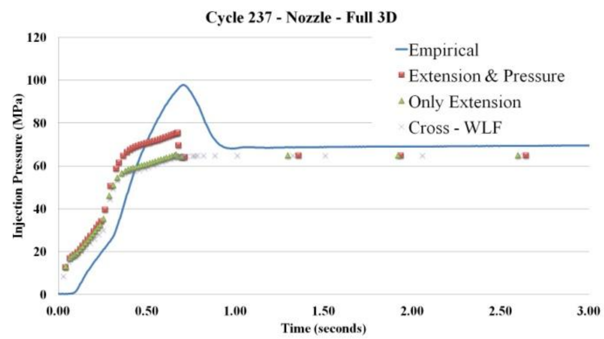

Figure 8 – Injection pressure profile comparison for Cycle 237, using the full 3D solver.

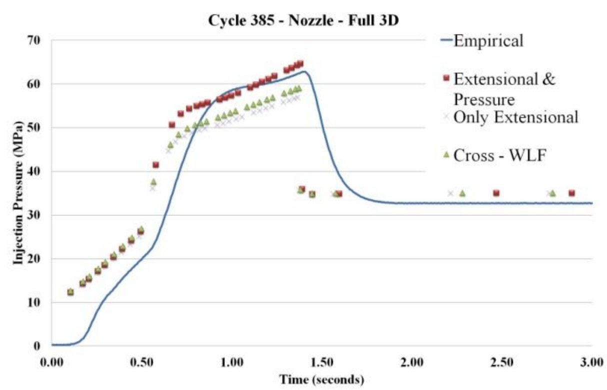

Figure 9 – Injection pressure profile comparison for Cycle 385, using the full 3D solver.

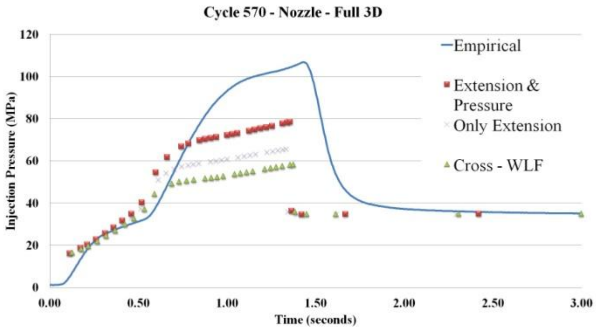

Figure 10 – Injection pressure profile comparison for Cycle 570, using the full 3D solver.

Runner and Cavity Pressure Correlation Study

While the common objective of injection-molding simulation is to predicted the total injection pressure it is also important that the pressure drop through the system is accurately captured. The highly instrumented mold allows for the comparison of pressures throughout the molding geometry. Cycle 385 was selected for this comparison since the total injection pressure profile during mold filling was well captured. The percentages shown in Table 2 represent the percentage difference between the maximum measured pressure at each sensor during molding filling, and those predicted using the pressure dependent and extensional viscosity models for various geometry model representations.

Examining the results of the runner and cavity pressure correlation study, suggests that the midplane model again shows the most robust performance. While all three models provide relatively accurate predicted injection pressures at the nozzle, the pressure drop through the runner system and in the cavity does not appear to be as good for the full 3D models.

Table 2: Pressure Error Throughout Mold Using the Different Model Solvers

Solver	Midplane	3D with Beam Runner	3D with 3D Runner
Nozzle	0.85%	2.71%	-0.68
Sensor 1	-4.86%	-1.66%	-5.97%
Sensor 3	-2.98%	8.53%	20.33%
Sensor 5	-0.71%	16.28%	29.09%

Summary

The results of this validation study show that injection molding simulation can provide accurate injection pressure predictions that can assist in product design. Additionally, it is important to account for both elongation deformation and shear deformation, particularly at any changes in cross-section in the feed system, to properly model the pressure drop through the mold. Finally, accounting for the role of pressure on the material viscosity can help further improve the injection molding simulation.

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References

1. J. Shoemaker, editor, "Moldflow Design Guide: A resource for Plastics Engineers", Hanser Gardner Publications (2006).
2. Okonski, “Moldflow 2012: A Material Validation Study,” proceedings of the ANTEC conference 2013 (2013).
3. Merriam-Webster Online Dictionary (http://www.merriam-webster.com/dictionary/viscosity)
4. Beaumont, J.P, “Runner and Gating Design Handbook,” Hanser Publishers (2004)
5. Hieber, C.A., in “Injection and Compression Molding Fundamentals”, Isayev, A.I., ed., 1-136, Marcel Dekker, Inc., New York (1987).
6. Mahishi, “Material Characterization for Thin Wall Molding Simulation”, proceedings of the ANTEC conference 1997