PRODUCTIVITY EVALUATION WITH A NEW STIFFNESS-BASED EJECTION CRITERION OF INJECTION MOLDING

Haoyu Xu, University of Massachusetts, Amherst
David Kazmer, University of Massachusetts, Amherst

Abstract

A stiffness-based ejection condition for injection molding is introduced and utilized for evaluation of different polymer materials. Comparison with industrial practice and other commonly used ejection criteria, such as molded part temperature, indicates that this approach not only can be an alternative when the ejection temperature of the polymer part is unavailable, but also is able to better model the complex behavior of polymeric materials. As such, the stiffness-based ejection criterion is effective in assisting the product development team to improve the design or reduce the cost by increasing the production rate while simultaneously ensuring injection molded part quality.

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.

The cooling time typically occupies more than one third of the whole molding cycle. As such, cooling time offers the largest opportunity for cycle time reduction and increased production rates. In addition, the quality of the final product, production efficiency, and manufacturing cost are significantly affected by the cooling stage. Therefore, estimating and optimizing cooling time play an important role in manufacturing operations. Although cooling time is dependent on many factors, such as resin properties, cooling system and processing conditions, the cooling time estimate is based on some assumed ejection condition.

The most common ejection condition is that the center-line or maximal temperature of the part is equal to or less than T_e, the ejection temperature. Ballman and Shusman presented a cooling time model to predict the cooling time of a given injection molded part [1]:

(1)

where CT is the cooling time in seconds; h is maximum cavity thickness, cm; α is the thermal diffusivity, cm^2/s; Ti is the injection temperature, ºC; Tm is the mold temperature, ºC; T_e is the ejection temperature, ºC.

Kwon and Opolski required average temperature of the given part to be equal or less than the ejection temperature, T_e as the criterion to estimate the cooling time by [2]:

(2)

Because the average temperature is used rather than the maximal, the cooling time will always be shorter than that predicted from equation 1. As such, Bush, Field and Rosato used both theoretical and statistical methods to derive the following equation to give a good estimation of cooling time [3]:

(3)

where W_p is part weight (grams) and N_{cav} is the number of cavities in the mold. While such a semi-empirical approach provides more accurate time estimation for parts representative of those used in the study, the resulting method may not be of much value beyond the investigated area.

Yu and Sunderland similarly developed relations to estimate the cooling time of a given part by experimental molding of many different material systems, thicknesses, and process conditions [4]. For instance,

, (4)

where . Equation 4 is for amorphous materials with thermal diffusivities greater than or equal to 0.001 cm^2/s. Different models were also developed for varying polymer morphologies and thermal diffusivities. However, the derived equations only apply to the specific part dimension, material properties, and process conditions inspected in this study.

In industrial practice, parts are ejected at the highest possible temperature that does not result in unacceptable sacrifices in quality. The process engineer will adjust the cooling time and/or other molding parameters until the molded part meets the quality specification. Often there is a significant trade-off between part quality and cycle time. As such, the design and process engineer must rely on available models and expertise to optimize the design and process. Recently, commercial computer aided engineering (CAE) softwares have been developed to relax many of the previous assumptions [5].

However, all of the previous approaches utilize some variant of T_e as the basis for ejection temperature. This specification of T_e is not well defined. Frequently the ejection temperature is set to some value less than the glass transition temperature – typically 10 ºC under T_g. Alternatively, the ejection temperature can be characterized by the heat deflection temperature which is not significantly more accurate. Thus, characterization of the solidification temperature severely limits the confidence in cooling time estimates.

Model Development

To develop better predictive capability, experimental and analytical methods are used to develop and validate different ejection criteria. The numerical treatment of heat transfer will first be developed for injection molding. Afterwards, the concept of part stiffness as a criterion for ejection will be explicitly defined and validated.

Heat Transfer

The typical heat path in the cooling stage of injection molding is that heat is conducted from hot polymer to the comparatively cold mold, then conducted through the mold to the cooling line, where it is convected away by the coolant. The heat equation for the cooling stage of a given control volume of the part is [6]:

. (5)

Assuming one dimensional cooling for illustrative purposes in this article, the governing equation for instantaneous heat transfer for a controlled volume in the part and mold is:

. (6)

At the interface between the mold and the coolant, we will assume that no gap arises between the polymer melt and the mold, so that the heat transfer is given by:

. (7)

Structural Integrity

Since the correct ejection temperature is not always known during application development, an alternative method for cooling time estimation is being proposed based on representative part stiffness. For all polymeric materials, the elastic modulus varies significantly with temperature as shown in Figure1 for two grades of ABS and one grade of an ABS/PC alloy. Such modulus information is widely available from material suppliers. For the remainder of this paper, all material grades and information are courtesy of GE Plastics (Pittsfield, MA).

As the polymer melt cools in the mold, the solidified layers increase in stiffness while continuing to propagate towards the core. Our premise is that ejection criteria based on temperature are misleading and inaccurate, and that an ejection criterion based on part stiffness would more closely approximate industrial practice. Thus, a molded part, if sufficiently stiff, could be ejected regardless of the core or average temperature.

The relation between the bending curvature, bending load, and stiffness is [7],

(8)

Equation 8 shows the inverse relation between bending curvature and stiffness. With increment of stiffness , the curvature and permanent deformation will decrease. The molded part stiffness must be sufficient to avoid plastic deformation upon ejection. It should be noted, however, that the bending curvature is also a function of the applied loading, which itself is a complex function of the evolving stress state and morphological history of the melt [8-10]. Research is currently on-going to utilize the described stiffness based approach with quantitative predictions of the residual stress to automate ejector layout design.

A fourth order divided-difference polynomial interpolation was utilized to develop the temperature dependence of elastic modulus as shown in Figure 1. The dynamic part stiffness can be evaluated at each instant in time by integrating the elastic modulus with the second moment of inertia [11],

(9)

The stiffness criterion will exhibit an asymptotic behavior as the frozen layers propagate towards the core and approach the coolant temperature. This asymptotic can be computed as:

. (10)

Thus, the stiffness can be evaluated in both absolute and relevant terms. The results of several different ejection criteria for cooling time estimation will now be discussed.

Results & Discussion

Stiffness was also chosen as a potential ejection criterion since it is a single aggregate value, derived from the elastic modulus that varies as a function of thickness and temperature. However, questions as to the approximate level of stiffness required for ejection remain unanswered. Towards this objective, the solution of the previous heat equations, Equations 8 through 10, were obtained utilizing an implicit numerical method with twenty four layers in the melt region and ten layers for the mold region. Cooling simulations were performed for a flat plaque molded of two grades of ABS, CYCOLAC® 4400 & 4320 and one grade of a PC/ABS alloy, CYCOLOY® MC 8002, with sample thicknesses of 0.5, 1, 2, 3 and 4 mm.

The dynamic temperature profile for the ABS (4400 grade) is shown in Figure 2 for a plaque of 4mm thickness. Initially the two mold halves are 50 ºC, with the melt at a uniform temperature of 250 ºC. Each of the inner curves shows the temperature change at an increment of 3 seconds. After 3 seconds, for instance, the core temperature has dropped only 2 ºC to 248 ºC while the mold wall has increased from 50 to 100 ºC. After 39 seconds, the core has dropped to 106 ºC while the mold wall has been cooled to 65 ºC.

Requiring the maximal part temperature to fall below Te is a conservative criterion, since it guarantees all temperatures in the part are less than Te. While a conservative criterion provides a “safe” basis for process costing, it will tend to provide an over-estimate of processing costs. A second commonly used criterion is that the mean part temperature be less than the ejection temperature. This is an aggressive assumption, since it does not guarantee that a large percentage of the part will have ejection temperatures less than T_e.

The estimated part stiffness can also be used as an ejection criterion. The propagation of increased modulus from the skin to the core will lead to asymptotic behavior in the stiffness of the part. To normalize the calculated stiffness, we divide the dynamic stiffness by the stiffness for material at a uniform mold temperature, i.e.:

. (11)

The resulting normalized stiffness as a function of time is shown in Figure 3. For parts with thin walls, the stiffness increases very quickly to the asymptotic value. As the wall thickness increases, the stiffness increases more slowly, indicating that a larger cooling time is required to obtain the same normalized stiffness. Note that the modulus quickly approaches the nominal value at the skin, but rises more slowly at the core of the part.

To assess a representative value of stiffness, a wall thickness of 3.0 mm was selected from industry cooling data for CYCOLAC® 4400. From this data, a cooling time of 18.5 seconds was specified in practice. Using Figure 3, it was observed that this cooling time corresponded to a stiffness of 70%. This normalized value of stiffness was then assumed as the ejection criterion for all wall thicknesses.

Figure 4 plots the estimated cooling time for all three ejection criteria as well as the cooling times from industry data. The correlation between industry data and predictions utilizing the stiffness criterion are very good. It should be noted, moreover, that adjusting the ejection temperatures for the other two criteria would result in a shift in the curves without any significant improvement in the global behavior.

Similar analysis was performed on the other materials, CYCOLAC® 4320 and CYCOLOY® MC 8002. The resulting normal stiffness requirements were 69% and 68%, respectively. These results indicate that a stiffness requirement of approximately 70% is representative of industry practice and may be used with cooling simulations to predict cooling time.

With this validation, we can now use the stiffness criterion for evaluating the molding productivity of different design and material candidates. As shown in Figure 1, each of the materials has similar room temperature properties but varying structural properties at processing temperatures. Let us consider the productivity via three scenarios.

Scenario 1:Material Selection

Since all these materials are processed at roughly the same temperatures, the normalized stiffness, , is defined utilizing CYCOLAC® 4400 at a mold temperature of 50 ºC. For a 3mm thickness, the normalized stiffness is 7.2 Nm. Performing a series of cooling analyses for each of the three materials, the results shown in Figure 5 use a relative stiffness of 70%, i.e. the part may be ejected when the stiffness exceeds 5 Nm.

From the figure, it is clear that at a given process condition, CYCOLOY® will permit a shorter cycle time since it becomes rigid at higher mold temperatures. Interestingly, the productivity change is non-linear as a function of wall thickness. With the increment of wall thickness, the cooling time discrepancies become larger. For instance, the 4400 and 4320 exhibit nearly identical cooling times for thin sections, but exhibit 15% variation above 3 mm thickness. Such material differentiation is critical to molding productivity. While these materials are quite similar, a similar approach is feasible with extremely different material properties even if processed at different temperatures.

Scenario 2: Process Robustness

The fundamental difficulty of the previous scenario, however, is precisely predicting the melt and mold temperatures that will be used in processing. CAE analyses have been successfully deployed in commercial application development to ensure moldability. However, simulation technology is not currently capable, and may never be capable, of precisely producing optimal machine settings in a reliable manner [12]. The simulation may not model some fundamental process phenomena such as three dimensional flow effects, complex material behavior, etc. Even assuming a perfect simulation, moreover, there are many physical aberrations that can induce error. Such instances may include unmodelled mold geometry, shut off and leakage of the check ring, tuning-dependent molding machine dynamics, etc.

Process optimization, in which melt and mold temperatures are reduced subject to injection pressure and part quality constraints, can only adequately be performed on the production floor. For instance, it is frequently necessary to vary process conditions to achieve unforeseen quality requirements. In this scenario, consider the need to increase mold temperature from 50 ºC to 100 ºC in order to reduce injection pressure or achieve improved surface quality. The stiffness-based ejection criterion can again be utilized to assess the cycle time for the three candidate materials as a function of mold temperature as shown in Figure 6.

The results indicate that at high mold temperatures, CYCOLAC® 4400 results in extremely poor molding productivity. This is due to the lower softening point of the material. However CYCOLOY® exhibits only a slight increase in cycle time to maintain equivalent ejection stiffness, with a productive efficiency approximately 70% higher than the 4400 grade. As such, the CYCOLOY® can be perceived as a more robust material solution since it provides a wider processing window. Moreover, the increased costs of materials with softening points at higher temperatures may be fully compensated through productivity gains.

Scenario 3: Product Design

Integration of the described cooling analysis with CAD (Computer Aided Design) has provided an easy – to – use software with potentially wide industrial and commercial application. Even with today’s fast computers, real-time design analysis is not possible without simplifying the assumptions or requiring lengthy computational intervals. As such, our approach analyzes each face on the part in thickness direction using a one-dimensional finite difference method (implicit Gauss – Seidel). To improve the accuracy of one-dimensional analysis of complex three-dimensional geometries, the analysis was developed to consider the thermal mass and heat flow from adjacent features at each numerical time step.

This approach represents a trade-off between the computing time and analysis accuracy, to provide a reasonable cooling time estimate without intensive computing time. Figure 7 shows the cooling time result display in SolidWorks® for a typical molded part. From the figure, it can be seen that although some features have the same thickness, the cooling times may vary significantly due to the additional thermal energy and limited heat conduction from adjacent features. For example, the bottom face of the part will be significant affected by the hot spot located between the two parallel side walls.

The implementation of this analysis is face – based, which allows the designer to access the cooling information of each face with a right – click. Moreover, summary information like analysis parameters, cooling time summary of mean, standard deviation, maximum, and minimum are shown on the feature tree as the attribute features to match the feature – based design of CAD packages. All the information can be saved with the CAD model. Another advantage of this program is that it can analyze not only the solid model created in Solidworks®, but also any other format, such as STL, STEP or ACIS etc., imported from other CAD packages, such as Pro/Engineer®, CATIA®, Unigraphics® etc.

Conclusion

This research has provided a new ejection criterion for injection molding. Utilizing part stiffness as an ejection criterion has been shown to provide more accurate estimation of cooling time than temperature based criteria. This stiffness criterion has two significant advantages (beyond accuracy) than other ejection criteria. First, it requires no ejection temperature of the user, though now modulus data must be supplied. However, such data is frequently available from material suppliers.

Second, the part stiffness criterion can be used for process improvement. Given a specific quality attribute, such as warpage, a process engineer can inspect stiffness as a function of time and infer what added stiffness may be achieved by increasing the ejection time, or reducing the melt or mold coolant temperature. It is important to note that the presented analyses have been oversimplified as flow, shrinkage requirements, and stress development also impact the ejection criterion and part design. Research is currently addressing these limitations.

The described methods have been incorporated into a Computer Aided Design (CAD) system, SolidWorks®. The cooling time is automatically calculated for arbitrarily complex geometries and utilized to estimate processing costs. Related research in integration engineering has developed an analysis server that is freely accessible through automated

CGI scripts at http://dpql.ecs.umass.edu. As such, development teams can assess the effect of process, material, or part design change on cooling time and molding costs.

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Nomenclature

h	convection heat transfer coefficient, W/m2.K
	density, kg/m^3
k	thermal conductivity, W/m.K
	rate of energy generation per unit volume, W/m^3
	specific heat, J/kg.K
A	area normal to heat transfer direction, m^2
T	temperature, °C
I	stiffness, m^4
E	shear modulus, Gpa
M	bending load, kN.m

	heat transfer rate, W
c	radius, m.
	differential unit in x direction
	differential unit in y direction
	differential unit in z direction
	controlled unit in x direction
	controlled unit in y direction
	controlled unit in z direction

	controlled time interval

Subscript:

	surrounding
i	node number
	mold
p	part

Superscript:

	time step

Greek:

	thermal diffusivity, m^2/s
	stress, N/m^2

strain, m

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Keywords

injection molding, part stiffness, cooling time, ejection

List of Figures

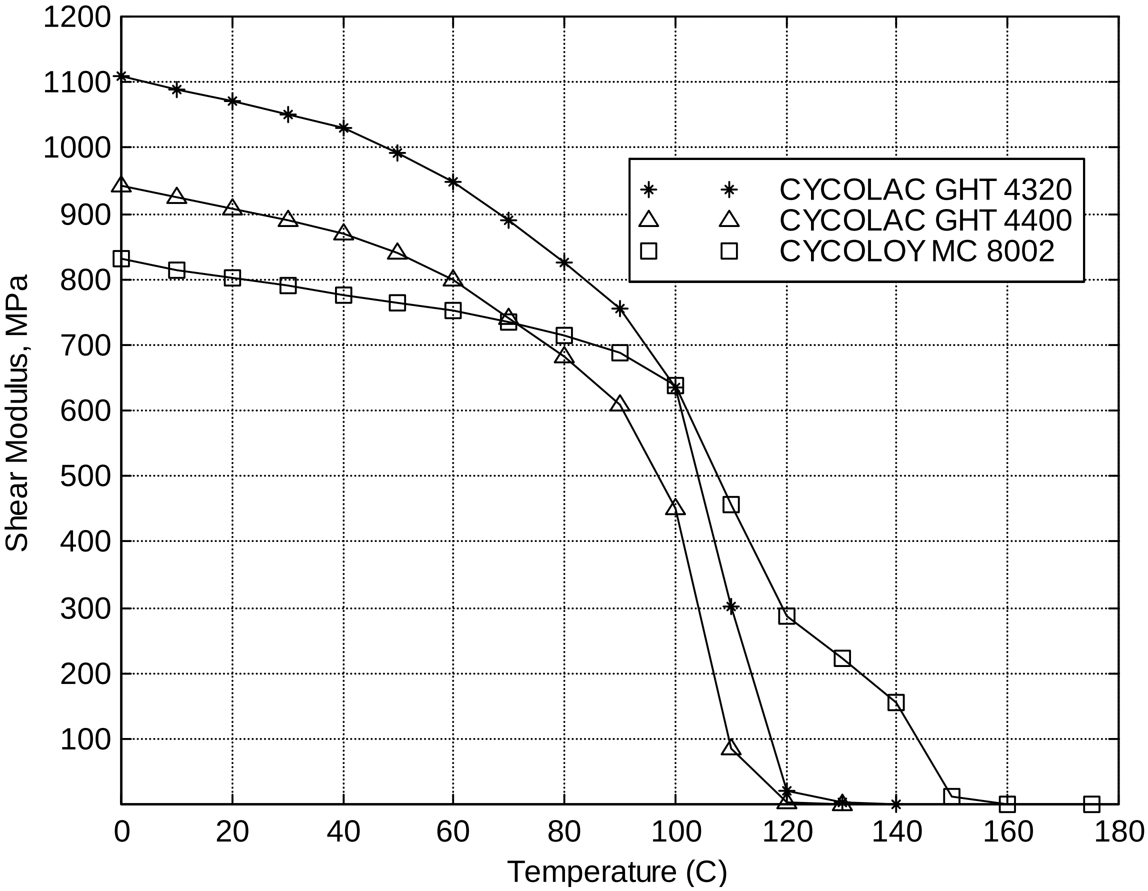

Figure 1: Shear modulus variation with temperature

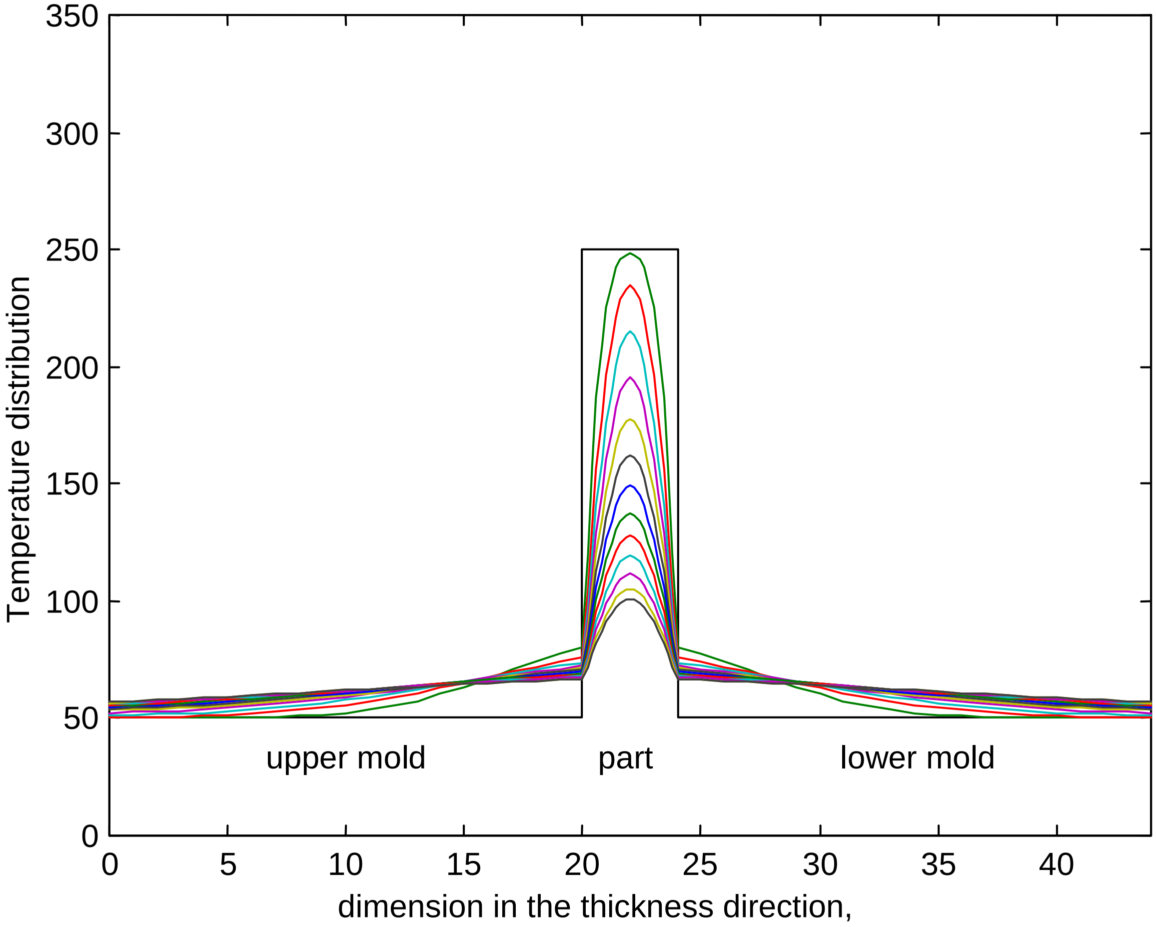

Figure 2: Temperature profile for part thickness of 4mm

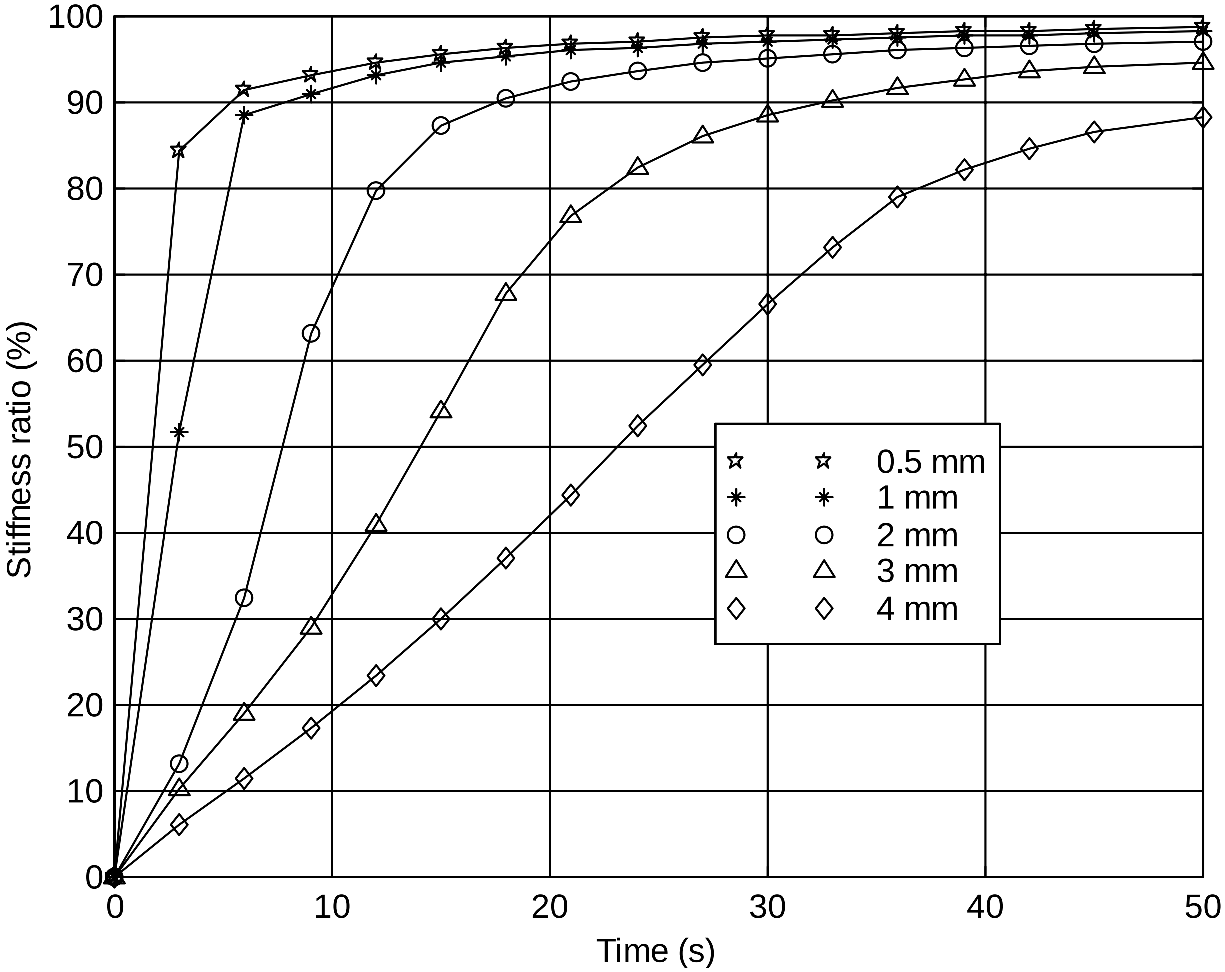

Figure 3: Stiffness variation as a function of time for different thickness

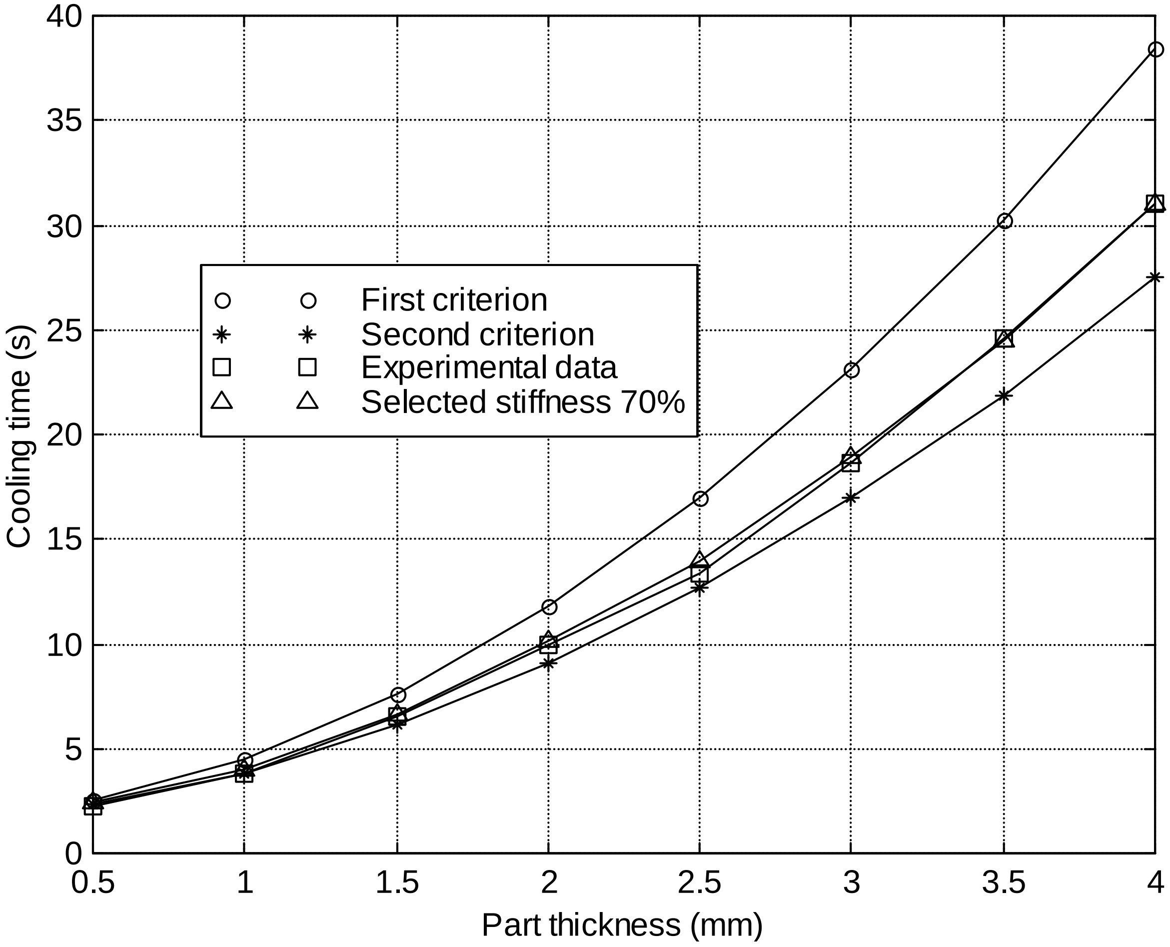

Figure 4: Cooling time comparison between different criteria and experiment

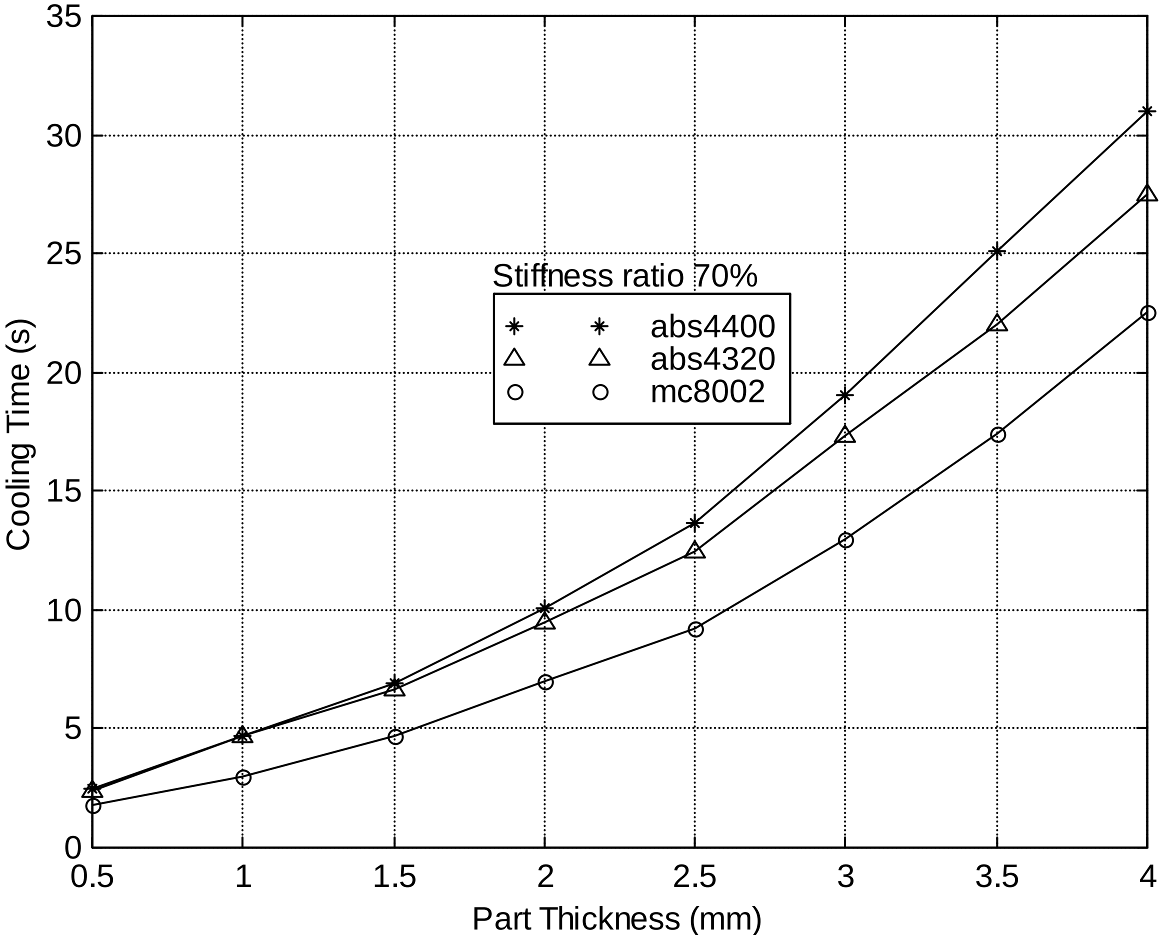

Figure 5: Cooling time predictions as a function of thickness

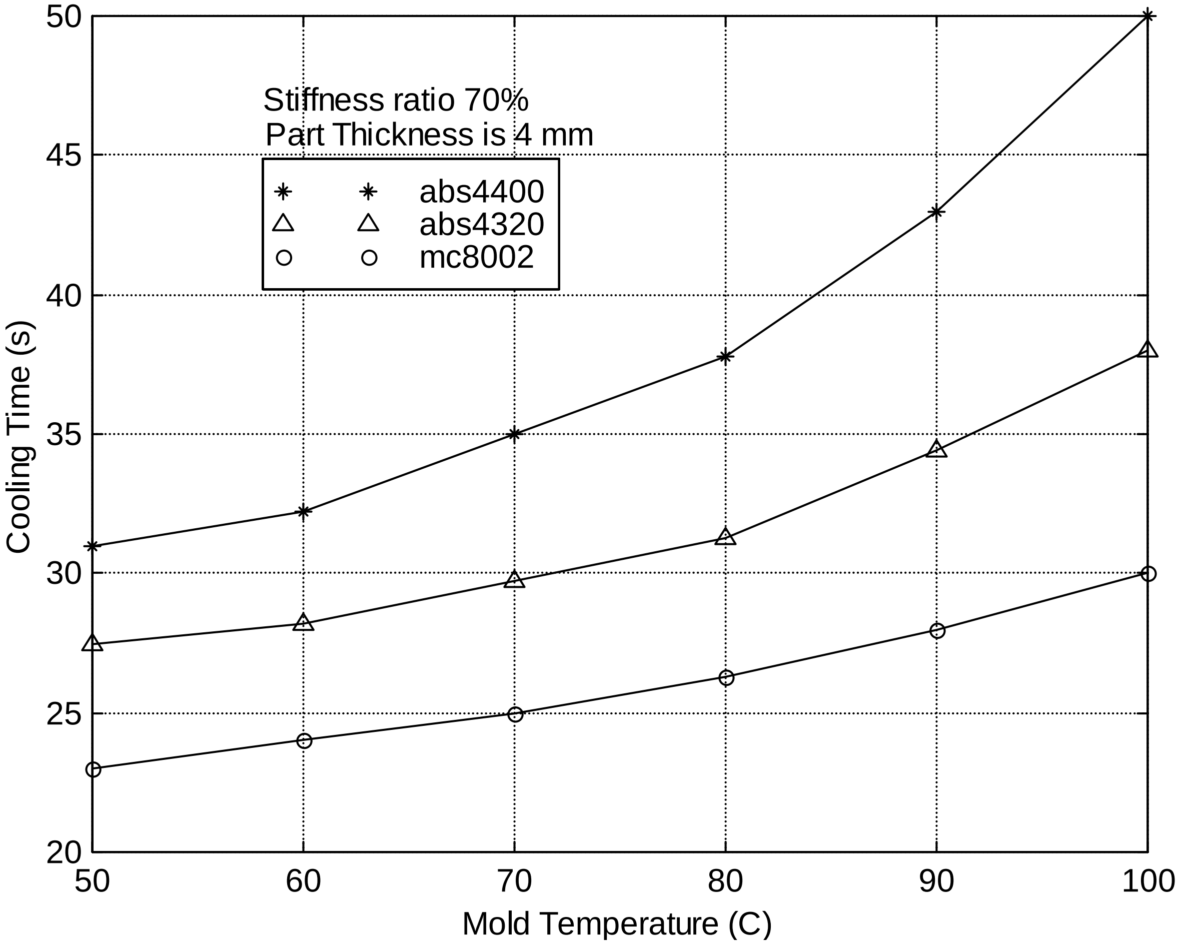

Figure 6: Cooling time predictions as a function of coolant temperature

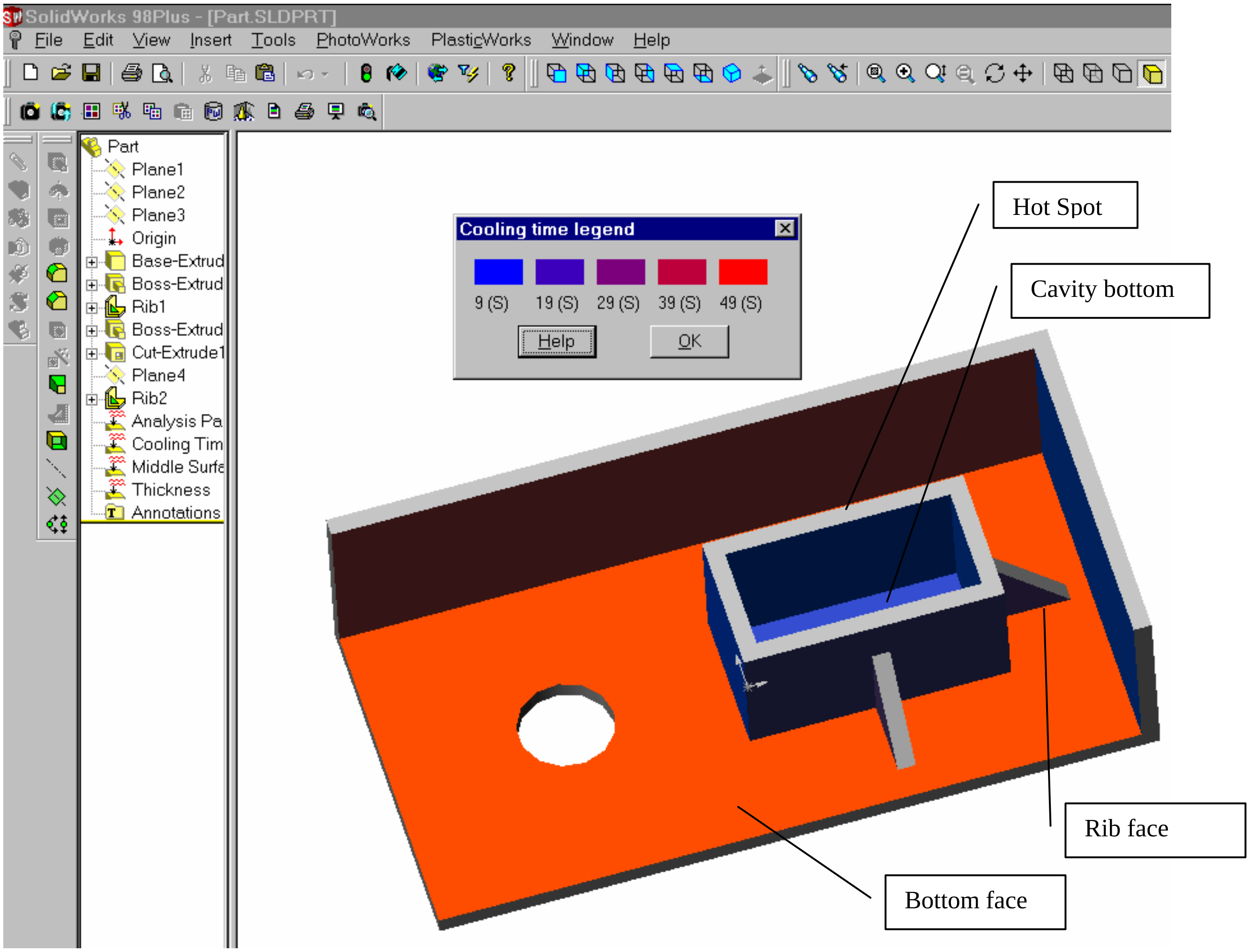

Figure 7: Cooling analysis of typical molded part