AN EJECTION MECHANISM DESIGN METHOD FOR AIM TOOLS

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ABSTRACT

One of the key advantages of AIM tooling is time savings when producing small batch production quality parts. However, designing suitable ejection mechanisms is becoming a bottleneck. There are two goals of this paper. First, a model is presented that effectively characterizes the stresses on the mold core and part during injection molding. Second, a method is described for ejection system design. Our approach consists of a combination of analytical, computational, and physical experiments. The ejection system design method will first determine the feasibility of ejection for a particular part geometry, then will determine the number, sizes, and locations of ejector pins. Each phase of the method will be formulated into a Compromise Decision Support Problem, a multi-objective optimization problem formulation. An example will be presented to provide an idea of the robustness and the limitations of the method. Preliminary results indicate that this methodology is sound for a simple geometry.

1. INTRODUCTION

Rapid Prototyping (RP) is fast becoming the preferred method for hastening the product realization timeframe. The deficiency in this field is the lack of the ability to perform functional tests on the produced parts. Hence the development of the field of Rapid Tooling (RT) which entails creating an injection molding tool capable of producing small batch parts, from an RP technology. RT combines the speed of RP technologies with the realistic test specimens from injection molding. For this work we will consider AIM tooling which uses the StereoLithography Apparatus (SLA) as the RP technology to create the molding tool. There are three phases to the injection molding process; filling, cooling, and ejection. While all three of the phases present issues not considered when using traditional tooling, the final phase, ejection, has become the bottleneck for the RT process. As such, the ejection phase will be considered in this work.

The practice of injection molding has always been based on heuristics. Hence the area needs some form of standardization to ensure good parts are produced independent of the manufacturer. The most glaring area where this is true is the ejection of the parts. The material properties of the SLA resin are much closer to the injected material than those of the steel tools. Thus, the user must be more wary of the mold tool being damaged and even failing during the ejection of the part. We believe that the system that has been created will help to address these concerns.

The first step in the system is to determine whether or not the part can be ejected successfully. This step is carried out before any tools have been created. Therefore there is immediate timesaving. The second step in the system is to determine the actual ejection layout. This layout consists of the number, diameter, and locations of the ejector pins. This information will be invaluable to the user since there is less need for the incorporation of a highly skilled manufacturer in the early testing phase of product development.

2. BACKGROUND

2.1 Ejection Literature

There has been quite a bit of research on ejection for traditional injection molds. This literature ranges from papers dealing with studies of the forces associated with part ejection [1-3], to sections from books describing the process in detail [4-7], to potential improvements to the ejection process [8]. However, until recently, very little work has been done with respect to RT molds. Clearly, the theory related to the forces associated with ejection would apply. Yet, the rules developed would not due to the material property differences between RT and steel tools. The difference in material properties is significant enough that it is necessary to redevelop ejection rules. Palmer [9], has established a foundation for these new rules. Her work entailed an investigation into the failure mechanisms for AIM tooling. During the course of this investigation she conducted extensive physical experiments the results of which were categorized into design rules. At the same time, CeDorge [10] has conducted research that investigates the thermal effects on the AIM molding process, and how that affects the life and productivity of the tool.

The work that has been done in the area of ejection in rapid tooling has mainly been in the area of evolving design rules for traditional tools into usable rules for RT. Dickens [11] has made strides towards this end by measuring the ejection force characteristics for both pin and stripper plate ejection systems. At the same time, there are other areas that must be considered.

2.2 Compromise Decision Support Problem

The compromise DSP is a general framework for solving multi-objective, non-linear, optimization problems [12]. Mathematically, the compromise DSP is a multi-objective decision model which is a hybrid formulation based on Mathematical Programming and Goal Programming [12]. The compromise DSP is used to determine the values of the design variables, which satisfy a set of constraints and bounds and achieve as closely as possible a set of conflicting goals. The structure of the cDSP is as follows:

Given:	A feasible alternative, assumptions, parameter values and goals.
Find:	Values of design and deviation variables.
Satisfy:	System constraints, system goals, and bounds on variables
Minimize:	Deviation variable that measures distance between goal targets and design point

The alternative in this case is a part configuration. The goals of this system are to minimize the stress experienced by the part during ejection, and to minimize the number of pins to be used. The goals are often weighted depending on the intent of the designer. The design variables to be investigated will be the number of pins, the pin diameters and the location of the pins. The orientation of the part and the location of the part with respect to the mold will also be considered but they are not design variables. The constraints to be satisfied in this system are the ejection rules discussed earlier.

A solution to the compromise DSP is called a satisficing solution, because it is a feasible point that achieves the system goals to the "best" extent that is possible [13]. This notion of satisficing solutions is in philosophical harmony with the notion of developing a broad and robust set of top-level design specifications. The compromise DSP will be at the heart of the ejection system design methodology.

2.3 Ejection Force Determination

The ejection force (the force required to remove the part from the mold) is the primary consideration in the ejection process from a mechanics standpoint. The base equation for this force is as follows:

$$F_E = \mu * P * A \qquad (1)$$

Where μ is the coefficient of friction, P is the contact pressure, and A is the contact area. Glanvill [5] developed a more advanced formulation that considers an equivalent diameter:

$$F_e = \frac{\Delta\phi * E * A * \mu}{\phi\left[\frac{\phi}{2t} - \left(\frac{\phi}{4t}\nu\right)\right]} \qquad (2)$$

where:

$$\Delta\phi = \alpha(T_m - T_e)\phi \qquad (3)$$

$\Delta\phi$ = "restrained" thermal contraction of plastic material across the equivalent diameter (m)
ϕ = diameter of circle with a circumference equal to the length of perimeter of molding surrounding the male core (m)
E = plastic modulus at the temperature of ejection (Pa)
A = contact area (m^2)
μ = coefficient of friction
α = plastic coefficient of thermal expansion (m/m/°C)
ν = Poisson's Ratio
T_m = "melt" temperature/softening point (°C)
T_e = part temperature at time of ejection (°C)

This formulation is more robust than the base equation, yet it still has limitations. The most glaring of these limitations are the lack of consideration of internal geometry and of draft. The ejection mechanism design method reported here is capable of dealing with both issues.

3. EJECTION MECHANISM FORMULATION

3.1 Approach

There are two main areas that have to be dealt with in order to reduce the amount of time required to develop an ejection system. The first area to be understood is the nature of the force that results from ejecting the part with respect to both the mold and the part. The second area to be understood is the effect that each ejector pin has on the entire system. This will allow for the addition or removal of pins as necessary. The overall approach to designing the ejection mechanism will be based on the Compromise Decision Support Problem (cDSP). The word formulation for the cDSP is represented in Figure 1.

Given
- Assumptions
- Injection Molding Parameters
- Ejection Relations
- Material Properties

Find
- System Variables
  - *Pin Diameter*
  - *Number of Pins*
- Values of Deviation Variables

Satisfy
- System Constraints
  - *Pins must not buckle*
  - *Pins must not pierce part*
  - *Mold core must not fail*
  - *Required force must not exceed machine capacity*
- System Goals
  - *Minimize Stress produced in part*
  - *Minimize number of pins*
- Bounds on System Variables
  - *1/64" ≤ Pin Diameter ≤ Part wall thickness*
  - *2 ≤ Number of pins ≤ 16*

Minimize • Deviation Function

Figure 1 cDSP Word Formulation

The design process for the ejection mechanism is depicted in Figure 2. The first step in designing the mechanism is to conduct a shrinkage analysis using an Finite Element Analysis (FEA). This analysis will dictate the amount of pressure that shrinkage due to the part's solidification will produce on the mold core. The second step is to formulate and solve the cDSP. The formulation of the cDSP requires only the addition of the part-specific information (part geometry, material properties). Once formulated the cDSP is solved using a computer algorithm. The output from this algorithm will be the number of ejector pins and their diameter. The next step will be to input the number of pins and their diameter into the algorithm that will be used to determine the potential ejector pin configurations. These configurations will then each be analyzed using an FEA. From these configurations the final layout will be selected, completing the design of the ejector mechanism.

In order to facilitate the determination of part shrinkage, a two stage FEA is performed. The first stage simulates the solidification of the part via a thermal analysis. The second stage simulates the shrinkage of the part during cooling via a structural analysis that uses the results from the thermal analysis as loading conditions. After determining the injection molding parameters, the user is required to input the parameters along with the part geometry into the Finite Element Model (FEM). With this information, the FEA is run and the result is the contact pressure between the part and mold core.

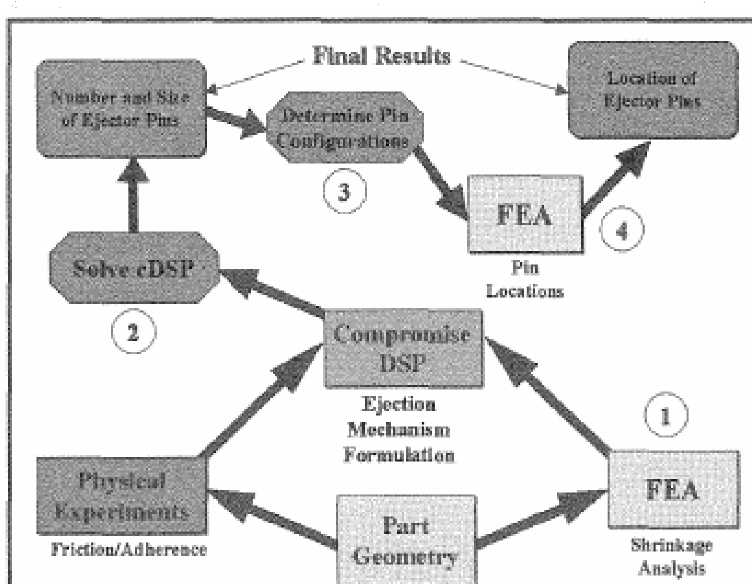

Figure 2 Process Flowchart

Once the contact pressure is known, the cDSP can be solved. The cDSP has already been formulated into a generalized form. Like the shrinkage analysis, the completion of the formulation of the cDSP requires the user to input problem specific information (part geometry, part material properties, and injection molding parameters). The formulated cDSP is solved using a computer code written in FORTRAN. The algorithm conducts an exhaustive search of the design space. In this case the deviation function is composed of deviation variables representing the number of pins and the stress produced in the part. The more pins that are used the less the amount of localized stress. At the same time, the fewer the number of ejector pins required, the less expensive the process is with respect to both time and money. Hence the combination of design variables (number of pins, Pin Diameter) that produces the minimum value for the deviation function as a whole is the desired satisficing solution. This solution is the first half of the ejector mechanism. The variable values from this solution are input into a separate algorithm to determine the other half of the ejector mechanism specifications, the pin locations.

The algorithm that has been created to determine the pin locations requires the information that is output from the solution of the cDSP. The user will have to specify certain information about the part. This includes the number of features that are to be ejected directly and the number of pins per feature. Based on the ejector pattern for the mold base, the algorithm considers a range of part orientations and the resulting pin locations. From this range the best set of pin locations is based on the desire to centrally locate the pins within the feature. Hence, for each angle, there is a part origin and a set of pin locations. The output from this algorithm will be a list of all of the different part configurations (orientations and the associated pin locations). Each one of these configurations will then be analyzed using an FEA to determine the configuration that produces the least amount of stress. This configuration will be the one selected. At this point, the specifications for the ejection mechanism are complete.

3.2 Constraints

In this work, constraints take two forms. On one hand there are boundary conditions that must be considered during the development of the ejection mechanism. On the other hand there are the design rules for injection molding and part design that must be taken into account. Both of these are depicted in the word formulation of the cDSP in Figure 1.

For the mold base used in this work, as is common with RT molds, there is an ejector plate with a set pattern of ejector holes. There is a hole at the center of the plate for the sprue. From the center of that hole, there are two sets of intervals. One set is spaced at ½". The second set is offset by ¼" and again spaced at ½" intervals. As such, the mechanism design system must account for the ejector plate. This compensation takes place in the computer algorithm that determines the feasible configurations.

Four design rule constraints have been derived from well-known theory. First, the ejector pins must not buckle. The equation used to enforce this constraint is Euler's column buckling formulation [14]. Second, the mold core must not fail, meaning that the tensile stress resulting from the ejection of the part can not exceed the tensile strength of the mold material. Third, the ejector pins can not pierce the part. The force acting on each pin will create a localized stress. This stress can not exceed the compressive strength of the part material. Finally, the Ejection force can not exceed the capabilities of the machine. There is a set amount of force that the machine can generate in the assembly that ejects the part. The required ejection force can not exceed that amount of force. These constraints are addressed within the cDSP.

In some of these cases, these constraints will never be violated. The concern is for the cases where that is not true. Hence, the system has been designed such that the constraints are either met, or that particular combination of variable values is no longer considered.

3.3 System Goals

The two objectives for this system are to minimize the stress produced in the part due to ejection, and to minimize the number of pins. It is clear that these goals are in conflict with one another. However, that is what the cDSP was designed to handle.

The minimization of stress within the part is crucial for "good" parts. There are a myriad of things that too much force could conceivably do to a part in an injection mold. Hence to avoid any potential difficulty, the system has been designed to minimize the stress produced in the part. This is accomplished via the second FEA. The computer algorithm dictates the potential configurations. Each configuration is then analyzed and the configuration that produces the lowest stress is the one that is selected. The natural reaction would be to add ejector pins so as to avoid stress concentrations. However, the addition of ejector pins is also an addition in both cost and time. Any increase in either one of these areas is undesirable. Hence the minimization of the number of ejector pins.

4. RESULTS

4.1 An Example Problem

To demonstrate the implementation of the ejector mechanism design system, an example problem will be presented. Due to space limitations, all of the steps will not be described in detail. The part that will be used for this example is a box-shaped part (see Figure 3). The dimensions of the part depicted in Figure 3 are 5.08cm x 5.08cm x 1.27cm (2in x 2in x 0.5in).

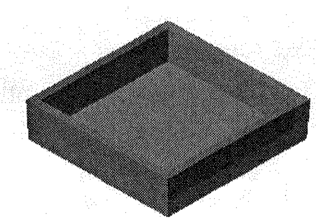

Figure 3 Box-Shaped part

The first calculation step, denoted step 1 in Figure 2 is the shrinkage analysis of the part and the mold. This two stage FEA is used to determine the amount of contact pressure between the part and mold. From the contact pressure, it can be deemed whether or not the mold core will fail when the part is ejected. The result of the shrinkage analysis is shown in Figure 4. As shown in the figure, the part is shrinking on to the mold core with a magnitude of between 40 and 50 MPa. This is well within the strength range of the mold material. This value, along with the experimentally derived value for the coefficient of friction (0.29) is incorporated into the

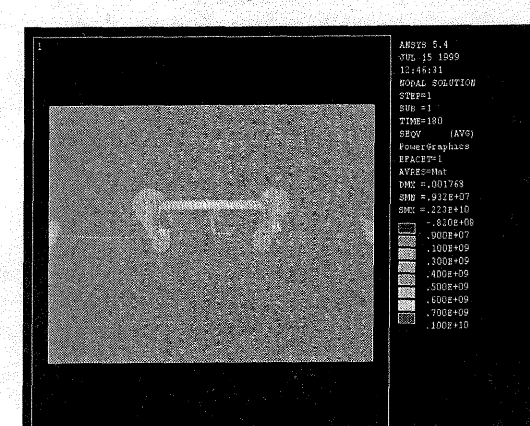

Figure 4 Structural Contact Pressure Results (von Mises stress)

algorithm that will be used to solve the cDSP. The cDSP is to be solved as described in section 3.2.

Part Orientation			Pin Displacement		Pin Locations							
Angle	Origin				Pin 1		Pin 2		Pin 3		Pin 4	
	X	Y	d1	d2	X	Y	X	Y	X	Y	X	Y
-45.0000	0.25	0.75	1.011	0.7571	0.9649	0.0351	2.1996	-0.1289	2.3791	1.4493	0.7854	1.2854
0.0000	0	0	1	1	1.0000	0.0000	2.0000	1.0000	1.0000	2.0000	0.0000	1.0000
45.0000	1.5	0.5	-0.7571	1.111	0.9646	-0.0354	3.6998	2.6998	2.3789	1.3789	2.2856	1.2856

Table 1 Abbreviated Output from Pin Configurations

The formulated cDSP is solved by exhaustively searching the design space. The two system variables and the system variable bounds determine the design space as depicted in step 2 of Figure 2. The solution algorithm outputs a number of pins and the pin diameters. Since the example part has four features to be ejected and the wall thickness is 0.1 in, the results from the cDSP solution algorithm is four pins and a pin diameter of 0.093875in. (3/32"). This is to be expected due to the nature of the trade-off between number of pins and stress in the part. In order to minimize the stress produced in the part, the ejector pin diameters should be maximized to minimize the local stress. One of the geometric constraints is that the pin diameters not exceed the wall thickness of the part. The value output from the system is the largest standard pin diameter that will fit within the wall thickness. The next step is to determine the final configuration of the ejector mechanism.

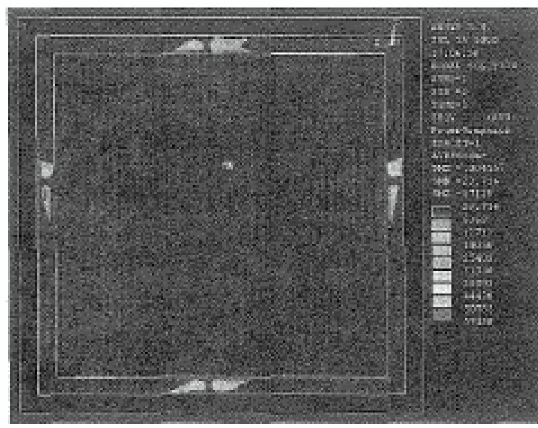

Figure 5 Resultant Stress Due to Pins Due to Ejection

The output from step 3 of the flowchart in Figure 2 is a set of feasible pin configurations. This set ranges throughout the feasible range of part angles with one feasible configuration emerging for each angle. Table 1 is an abbreviated listing of the output.

These alternative configurations are run through an FEA to determine the configuration that yields the minimum stress in the part. This is solution step 4 in Figure 2. In this example the configuration that emerged was at 45 degrees. The stress in the part produced by this configuration is illustrated in Figure 5. The maximum stress in the part is between 50 and 58 kPa. This is well under the compressive strength of the material, which is 100 MPa. At this point the ejection mechanism is complete. The final layout is configuration 3 (45-degree orientation) in Table 1. The final layout with respect to the ejector plate is depicted in Figure 6.

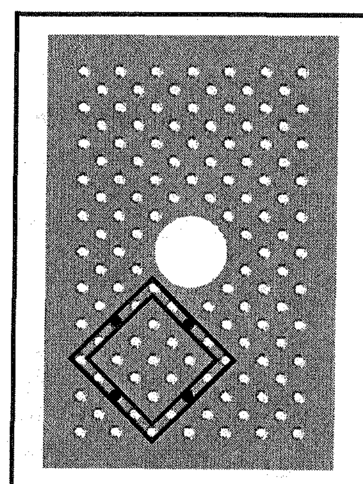

Figure 6 Ejector plate with final part configuration

5. CONCLUSIONS

An ejection mechanism design method was developed that creates a mechanism while accounting for both the part geometry and the injection molding parameters involved with the product. The goals of the design system for this mechanism are to minimize the number of pins, and the stress induced in the part due to ejection. The intent of this system is to allow the user to hasten the realization of a product by shifting the production of prototype parts that can be functionally tested to earlier in the design process. This is accomplished by the system in that it removes a bottleneck from the rapid tooling arena, and as such improves the ability of the user to achieve high quality parts relatively quickly and with a minimal amount of effort. By using the methods outlined in this paper, the ejection mechanism can be designed successfully and with little cost to the user in time. This design system will help to keep the "rapid" in rapid tooling.

While the ejection mechanism design system will significantly impact the field of rapid tooling, it is not without limitations. The reliance on the part having a fairly simple geometry is a limitation. The system is also limited in its ability to handle parts that require multiple pins per feature. Finally, as complexity is added to the requirements, (increased number of parts, number of features, etc…) the system becomes computationally expensive. Efforts are being made to further enhance the capabilities and eradicate the limitations of both the system and the underlying design methodology.

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