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Intelligent Process Development of Foam Molding for the Thermal Protection System (TPS) of the Space Shuttle External Tank

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ABSTRACT

Martin Marietta has designed a knowledge-based system to assist process engineers and technicians in evaluating the processability and moldability of poly-isocyanurate (PIR) formulations for the thermal protection system of the Space Shuttle external tank (ET). The Reaction Injection Molding - Process Development Advisor (RIM-PDA) is a "coupled system" which takes advantage of both symbolic and numeric processing techniques. Process knowledge, consisting of heuristic knowledge acquired from domain experts, such as case histories of chemical formulations and their moldability in test mold configurations, and the knowledge of causal relationships derived from the empirical data will aid the process engineer in 1) identifying a startup set of mold schedules, and 2) refining the mold schedules to remedy specific process problems diagnosed by the system.

INTRODUCTION

Research in expert systems and their application to machine and process control and diagnostics has received much attention in recent years. However, relatively little has been done to provide the application experts with any intelligent, generic tools for organizing and representing their discoveries and knowledge of novel processes. In particular, little attention has been given to exploratory processes whose feasibility must be confirmed by significant experimentation.

A wide array of process management tools is available for modeling and design of both discrete and continuous processes. At one end of the spectrum are commercially available algorithms for numerical simulation of chemical and fluid flow processes. These algorithms are useful only for modeling processes which are relatively well understood and hence amenable to rigorous mathematical treatment. At the other end are tools for symbolic representation that are well suited for describing process domains which are too complex to be modeled numerically, yet represent a significant body of experiential process knowledge. The knowledge acquired from those in the field (also referred to as domain experts) is usually available in the form of process heuristics or "rules of thumb" which have been developed and refined through a combination of intuition and trial and error over an extended period. Such knowledge, represented in the form of condition-action pairs, can be called upon by a novice to help with local process problems.

A major drawback of the symbolic reasoning systems (also called expert systems) developed thus far is their lack of mechanisms for guiding the process engineer in exploring the causal relationships between process parameters and their effects on process performance. That is, they provide no capabilities for generic process development, such as deriving and representing parameter interactions between successive stages of a multi-stage process, which is crucial for model development and/or refinement. This paper highlights the characteristics of intelligent information processing technology that would most appropriately address the important issues in process development. Our discussion is based on our experience with the design of a process development advisor to assist process engineers in developing a complex foam Reaction Injection Molding (RIM) process. Both the advisor and the process are currently under development as a joint effort between Martin Marietta Corporation and NASA at NASA's Productivity Enhancement Center.

In the following, process development tasks common to a large class of process and manufacturing domains are identified, followed by a description of the RIM process and the design of a system to address the development tasks that are relevant to the RIM domain.

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PROCESS DEVELOPMENT TASK: A PERSPECTIVE

How generic can a process development task be? Although the problem domain of immediate interest to us is the manufacture of poly-isocyanurate (PIR) moldings with RIM technology, our principal concern is developing tools and techniques that are useful for generic process development tasks. Hence, the system design we propose for this purpose is equally applicable to development activities in composites, metals, and semiconductor fabrication.

In a polymer molding operation, a process is considered developed if the molded parts consistently meet the functional requirements of the intended application. For our domain, these requirements would be in the form of mechanical and physical properties and thermal protection criteria for the external tank (ET), as stated in the design specifications. In this case, process development also includes process problem diagnosis and solution, as well as process optimization for greater consistency, higher quality, and improved efficiency.

Expert process engineers are very successful at diagnosing process problems because they can envision a process as a continuum as well as a construct of discrete major functional components. This duality allows them to track major process events and relate them to the relevant interactions between the parameters of the components. The interactions of specific interest are later characterized by modeling the parameter relationships empirically through carefully designed sets of experiments. The experience so gained is then used for qualitative analysis of the relative importance of the control parameters and quantitative manipulations of the functional relationships to produce a desired improvement in the properties and thus quality of the molded parts. The experience described above is believed to be quite generic and common to all process development domains.

To perform these representation and reasoning tasks, an engineer needs a system that will allow construction of a causal model for simulation of the process behavior at a high level of abstraction. This model can be refined as more information is obtained about the precise quantitative relationships from the experimental data, and knowledge of these relationships can then be reasoned with to determine the tolerance windows on all material and equipment controls for optimum performance. A schematic describing the three-layered process development scheme applicable to the RIM process is shown in Figure 1. The schemes for knowledge acquisition, knowledge representation, and reasoning are distinctly different at each layer.

A system that embodies a hybrid representation comprising the three layers discussed above should be able to answer a wide variety of process-related questions, ranging from very general to very specific. For example, a process engineer may want to understand the role of a catalyst in PIR polymer formulation. Catalysts come in many varieties, ranging from those that accelerate reaction rates to those that promote selective precipitation. A process engineer should be able to ask the following types of questions of such a system:

Causal Level: How does the catalyst concentration impact the flowability of PIR formulations?

Empirical Level: If the catalyst concentration is increased by 10%, how will the gelation time of the polymer change?

Heuristic Level: Do catalysts usually affect flowability?

Here, the concerns addressed are primarily those of knowledge acquisition, knowledge representation, and reasoning at the second layer. Issues pertaining to causal modeling, causal simulation, and integration of all three layers for efficient reasoning will be a subject of future study.

Systematic and efficient acquisition of process knowledge derives from the application of appropriate experimental methods and analysis tools to identify the process-critical variables and determine their impact on the processability of the polymeric material. Such tools must couple numeric processing algorithms for analysis with symbolic processing schemas for reasoning and interpretation of the analytical results [Kitzmiller]. Hence, our approach is to design a coupled system with the following features:

1. Computationally efficient numeric algorithms for statistics, analysis, and graphics, which exist as separate modules and are callable by the system as needed

2. Symbolic processes to guide the user in identifying the right selection of numeric routines to extract the empirical relationships and in interpreting the results.

Additionally, the knowledge acquired has to be represented in a manner natural for reasoning within the process development environment, i.e., for dealing with process problem diagnosis and corrective actions. Within the RIM-PIR domain, the reasoning tasks rely heavily on the explicit representation of parameter effects on the characteristic properties of the process. A detailed description of the RIM process and its requirements follows.

The RIM Process

Reaction injection molding is a process in which polymeric products are formed from highly reactive chemicals in high-pressure impingement mixing machines. Obtaining the desired functional properties of the molded part requires control of a wide variety of process variables associated with four major process areas:

1. The chemical systems which produce the urethane and PIR polymers
2. The RIM machine itself, including at least two metering pumps, a self-cleaning impingement mixer, a set of temperature-controlled conditioning tanks, and the piping, hoses, filters, and controls required for operation
3. The mold support or mold-handling system
4. The mold temperature-control system.

Activities in these four areas are interdependent. The chemical systems must form polymers with the physical properties required for the part being molded; the metering system must meter accurately and mix thoroughly; the mold support must position the mold to best facilitate the expansion process; and the mold itself must be designed to facilitate the flow of the mixed reactants during filling and expansion, and to control the temperature of the chemical reaction within a relatively narrow range. The fluid expansion operation inside a mold is particularly complex because it involves multiphase flow of reactive polymers that undergo rapid state changes.

Figure 2 shows a process flow diagram for a RIM process. Since the process is still in its prototype phase, all pre- and post-process operations are performed either manually or by offline dedicated systems. Engineering evaluation and quality inspection tests are performed at the end of a complex part molding process to provide the process engineers with early information on the status of the manufacturing process. Although the tests could indicate a variety of process problems at several levels of complexity, the level at which a process engineer may choose to diagnose a problem usually depends on his experience with the process and his training in modeling and analyzing the process. For example, a novice process engineer may try to resolve inconsistencies in part quality by making ad hoc changes in mold setup or RIM machine parameters because he does not recognize the true source of the problem. Diagnosing the actual cause of substandard part moldings requires careful analysis of parameter interactions at multiple stages of the molding operation.

The multistage diagram of the RIM process shown in Figure 3 is a simplified representation of the typical parameters that affect the process. At each stage, there are generally several options for modifying the process behavior. One such option is to change the reactivity of the chemical formulation, which, in the case of PIR formulations, is known to have a major impact on the processability of the material. For example, improved flowability could be achieved by changing the concentrations of the catalysts, or the blowing agents or some combination of the two. On the other hand, for duplicating the processing capabilities of a prototype operation on a delivery system, it is more appropriate to scale the reactivity up or down (within limits) by changing the impingement pressure at the RIM machine stage or the temperature of the mold at the mold setup stage. The best or the optimal of the available alternatives is generally not obvious and may require a thorough and careful analysis of multivariate effects on the response surface of the characteristic properties.

In addition to understanding the process behavior modifications produced by intra-state parameter variations, the process engineer also needs to study their effect on the process over the succeeding stages. For example, the complexity of a part to be RIM-molded is usually determined by the overall size of the part and the maximum cumulative resistance to flow through the mold. If the part is too big and/or the flow resistance is too high, then the part may have to be made from two or more simpler molds. This decision, in turn, will govern the appropriate settings of the mold setup parameters at a succeeding stage. The process variables that may affect the molding quality are:

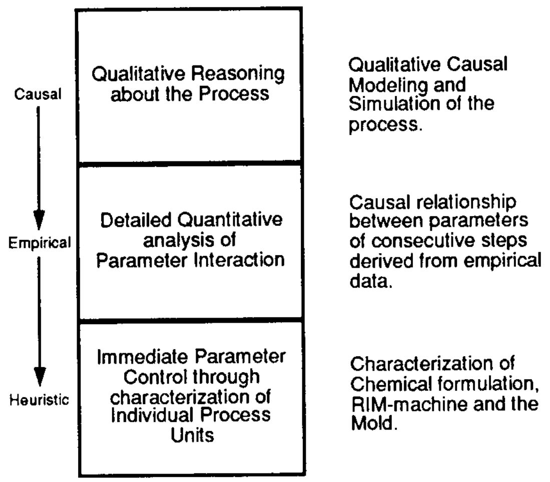

Figure 1. Multilayered representation of process knowledge

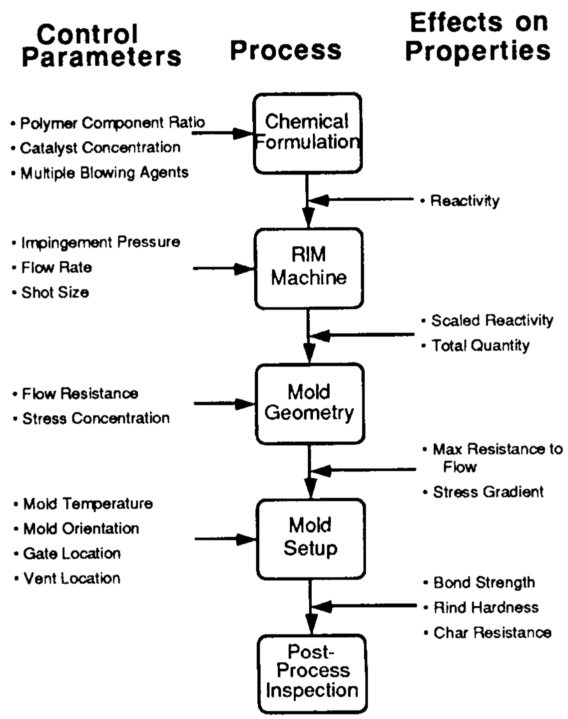

Figure 3. Functional decomposition of the RIM process showing typical control parameters and their effect on the process

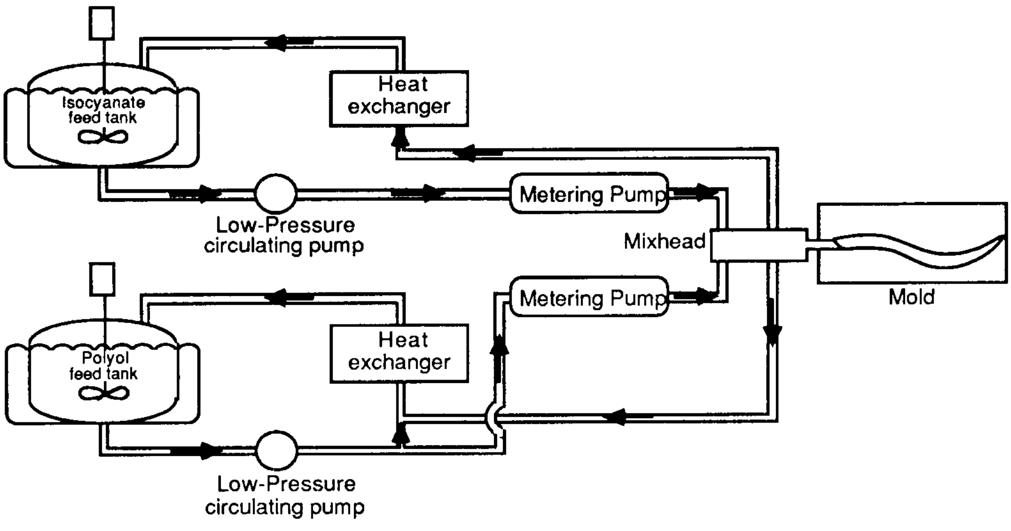

Figure 2. The RIM Process

- Polymer component ratio
- Catalyst concentration
- Mold temperature
- Mold orientation
- Impingement pressure
- Gate location
- Vent locations
- Shot size.

Some typical problems resulting from lack of control of one or more of these variables are:

1. Incomplete fill - Failure of the expanding foam to reach all parts of the mold cavity
2. Voids - Presence of large blowholes or pinholes in the molded part
3. Warp - Bent part, deviating from flat condition or dimensions out of tolerance
4. Flash - A film of excess material outside the mold cavity
5. Density Reject - Part density not within specification
6. Hardness Reject - Rind hardness not within specification
7. Strength Reject - Tensile strength not within specification.

Some of these problems belong to a class referred to as gross defects; i.e., these are quality defects in the molded part whose remedy requires gross adjustments in one or more control parameters. Such problems are best handled by resorting to the use of heuristics. For example, the presence of large voids in a molded part is usually attributed to lack of appropriate vent holes in the mold to bleed off air entrapped during the expansion process. Hence, the system can capture this knowledge through a rule as follows:

IF there is evidence of LARGE VOIDS in the part
AND there is CERTAINTY > 0.9 of VOIDS due to ENTRAPPED AIR
THEN provide VENT HOLES in the mold where the voids are found

Other problems are more subtle and require careful analysis to establish the ideal window of process parameter values. All problems regarding properties that are out of specification belong to this class.

KNOWLEDGE BASE

The knowledge of the system consists of information on chemical formulations and part geometries that have been used in the past and have relevance to the ongoing process development. Each chemical formulation exhibits a characteristic behavior which can be expressed in terms of its state changes over time (for reactive chemical systems, such behavior is also referred to as its reactivity). Qualitative descriptions of observable states, such as "cream," "gel," "string," and "tack-free," then generate a quantity space [Forbus] for a continuous process over a temporal dimension. The case history for each chemical formulation is thus represented by such a quantity space because it contains critical phase transformations of the fluid which provide important information regarding the processability of the chemical formulation.

The case history for part geometry is grouped into classes of parts requiring similar startup process parameters. Currently, there are three distinct part classes: spherical, rectangular, or prismoidal. Within each class, there are further fine-grained distinctions or subclasses. Assignment of a part to a particular subclass is determined by the number and type of its primitive flow obstruction features. Such a classification scheme minimizes the process development time significantly by encompassing mold schedules already developed for parts in the subclasses of the case history.

Process data acquired from the RIM machine and the process-monitoring instruments are represented in the form of records. Query language facilities of a relational database manager are used to generate data summaries, which are then used by the analysis module as needed to derive individual parameter effects on the processability of the material. All data within the analysis module are represented in the form of arrays because of their efficient representation of numeric processing algorithms as well as graphics algorithms to communicate the parameter effects graphically to the user.

The knowledge base also contains data analysis and data interpretation schemas. These determine when to call certain analysis functions to determine statistical distributions and variances, and provide methods for evaluating the effects of individual parameters on the behavior of the process, respectively.

KNOWLEDGE REPRESENTATION AND CONTROL

The process diagnostic knowledge of the system consists of heuristics represented in the form of production rules [Davis] and data objects. The rules explicitly state the relationship between part defects and the actions that could remedy such defects, while the object framework is a representation of data on gross visual defects and the test results on the properties of the molded part. Generally, objects belong to one or more classes and have properties with value slots, as shown in Figure 4.

The parameter effects are represented in the form of intensities, distributions, and explicit mathematical formulations [Blum] and may be accessed from the knowledge base and/or database by the inference engine. All data analysis and interpretation schemas have a Shank's "script" [Shank] flavor. The schemas are represented as frames [Stefik], enabling them to be instantiated with relevant parameter values.

The system inferencing scheme is mainly data-driven/forward chaining. The initial set of findings establishes the focus of attention, which then controls the evaluation of only those hypotheses which are relevant to the current line of reasoning. Hypotheses that share common data objects are grouped into clusters called "knowledge islands." The presence of such clustering significantly improves the speed and efficiency of inference. Hypotheses within a knowledge island are organized hierarchically and are explicitly categorized to control the order of their evaluation. Such a categorization is necessary to ensure a consistent dialogue with the user-- a dialogue that is logically relevant to the problem under consideration.

Sample Session with RIM-PDA

The control within the system is illustrated in Figure 5. The user usually needs advice from the system if a new part with a different geometric configuration is being considered for molding or a new chemical formulation with a different reactivity characteristic is being evaluated for use as a molding material. The user initiates a dialogue by generating an appropriate event to inform the system that a new set of mold schedules is required. The system searches through the case histories to find the mold schedules of a case which closely resembles the current one. The startup set of schedules is then used to execute the first iteration of the molding operation. In-process sensory data collected during the molding operation, together with the post-process test results, are then analyzed to inform the user of the health of the process. If the user informs the system about any problems in the quality of the molded part, the system enters the refinement phase [Bharwani], diagnosing the source of the problem and recommending a new set of mold schedules each time a problem is reported.

CONCLUSIONS

This paper has addressed process development as a generic engineering task and identified its demands on advanced information technology. A coupled system is proposed to take advantage of conventional algorithmic approaches as well as state-of-the-art artificial intelligence methodologies to cope with the identified tasks. Several issues identified earlier are currently under investigation. Mechanisms for switching between layers of reasoning based on the type of question asked of the system have yet to be developed. Additionally, the concept of a quantity space for causal simulation needs further refinement.

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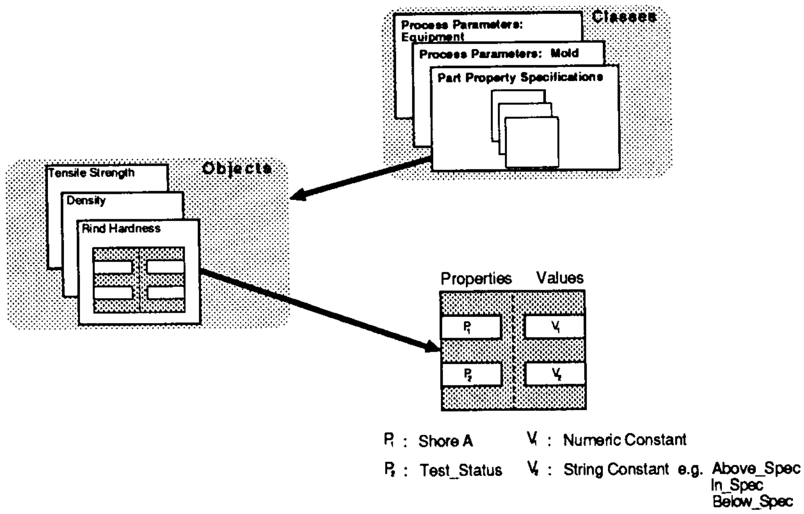

Figure 4. Class/Object Data Structure

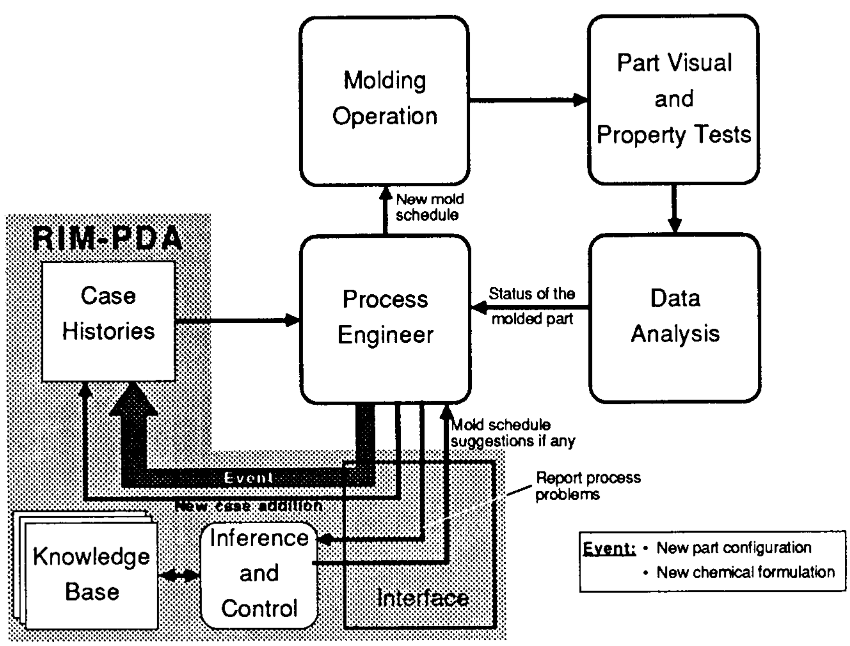

Figure 5. RIM-PDA Control Scheme

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