Polymer Injection Molding Technology for the Next Millennium

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Abstract

Injection molding technology continually develops, with major milestones including the introduction of the first thermoplastic materials, the reciprocating screw design, the first hot runner systems, engineering materials, the introduction of microprocessors for machine control, Computer Aided Engineering flow simulation software, and recently the application of expert systems for optimized machine setup. This article presents a vision of injection molding for the next millennium to address current industry needs, then describes some needed developments to convert that vision to reality. The injection molding machine for the next millennium will pull together the whole injection molding story, i.e. ‘the big picture’ integrating existing fragmented ideas of machine, material, process, production, and information control with Computer Aided Design techniques to produce a fully optimized manufacturing strategy. In this paradigm, automation of machine setup procedures will become the normal practice, with each machine in a manufacturing plant having consistent setup/optimization procedures, eliminating the ‘black art’ of injection molding. Injection molding setters will re-focus their efforts on more complex molding issues that have eluded the design process, providing a specific direction for improving product quality. The ultimate aim is a machine that produces no scrap material and increased

product quality with reduced labor skill requirements, low energy consumption, and minimal maintenance.

Introduction

Injection molding of thermoplastics has emerged as the premier vehicle for delivering high quality, value added commercial products. Perhaps due to this success, there has been sustained pressure for increased standards of molded part quality while requiring reduced product development time and unit cost. It can be argued that the requirements placed on the molding process often exceed its capabilities. The lack of capability is sometimes evidenced by long product development cycles, excessive tooling costs, low process yields, and inferior product quality. As thermoplastic materials continue their thrust into advanced technical applications with multiple stringent requirements, the risks of proving out the injection molding process are becoming excessive. In fact, several industry managers have independently testified that "we are starting to see the migration of customers to other manufacturing processes for time-critical applications."

Fundamentally, the difficulties associated with injection molding arise from the lack of simple and consistent relationships between the machine inputs, part geometry, material properties, and molded part quality. In product and tool design, hybrid finite element/difference simulations can aid the design engineer. In tuning and regulation of injection molding, however, no method has had similar success in aiding the process engineer. Rather than focus on past achievements, this article proposes a vision for the injection molding process and identifies required development to convert that vision to reality.

In the manufacturing environment, where competitive commercial reality distances process engineers from development laboratories, advances in technology are often not realized. The next quantum leap in technology must be accepted and driven by material and machine manufacturers to allow the new technologies to be fully realized. The question that faces machine designers and molders is "what technologies will add a competitive advantage?" Many machine manufacturers claim to have taken the next quantum leap forward, yet only industry application will provide conclusive results.

Industry Needs

Machine manufacturers must deliver the 'forward thinking' technologies which address the requirements of the molding industry. The machine of the next millennium will have to accommodate these 'forward thinking' technological improvements in design, and also include solutions to problems that are not yet apparent. The immediate issues facing the molding industry are outlined below.

Computer Integrated Injection Molding [CIIM]

A conventional injection molding manufacturing facility is a widely distributed layout of machines, materials and processes under the control of manufacturing personnel. Well-organized but dispersed teams of manufacturing personnel encounter problems. In the manufacturing environment much time is spent by personnel communicating and interacting in an attempt to find the status of production, much of this human activity is inefficient. Therefore it may be as important for a centralized point of information to know the exact status of production as it is for the moldings to actually be manufactured. The CIIM system approach is to have computer control of the entire manufacturing facility, enabling automated machine setup and optimization of information as well as information flow for design, production, maintenance, material handling, and inventory control.   CIIM is described as the computer control and linking together of all functions in the injection molding manufacturing environment.

Improved Tool Development and Verification

Original equipment manufacturers are striving for shortened product development cycles. Since manufacturing is at the end of the product development cycle, tool manufacturers and molders are under enormous pressure to reduce the delivery of production tooling and molded parts. At the same time, Dacey [1] has implied that the costs of addressing tool modifications late in the product development cycle can greatly exceed the cost of initially developing more robust mold designs. As such, technologies and development methods need to be developed to not only reduce the tool turnaround time, but also increase the probability that the developed molds and qualification processes will fulfill the customer specifications.

Fast and Consistent Set-Up

Original equipment manufacturers continue to increase product variety while striving for reduced inventories in their supply chains. This trend requires molders to enact ‘just-in-time’ principles to provide more batches of reduced quantities. To maintain a cost advantage, the competitive molder must reduce the mold changeover time. Quick mold change systems are commercially available and suitable for machines less than 100-tons to 3000 tons. Such systems reduce machine ‘down time’ from hours to minutes, allow short runs to be practical, save on labor costs, and maintain production continuity. With automated tool storage and pre-configured temperature control systems, these systems form a repeatable and efficient tool change facility to enable ‘just in time’ molding. Even with quick mold changes, however, production start-up can be a prolonged process due to lack of set-up and control of proper molding conditions. As such, industry needs more consistent machine set-up and optimization procedures which guarantees molded part quality in reduced set-up times.

Reduced Product Cost

The global economy has grown substantially in the last few years that has resulted in high manufacturing utilization. Inflation in the consumer price indices, however, has remained below the historical average. Perhaps this contradictory behavior is due the attempts of original equipment manufacturers to contain and even reduce product costs. It is not unusual, for instance, for large customers to require a few percent reduction in component prices every year. If the supplier does not meet their demands, the customer goes elsewhere. As such, the molder is witnessing continued pressure to reduce molded part costs. The part production cost is a function of material utilization, machine requirements, energy consumption, cycle time, labor charges, and production yields. Since product cost is based on multiple factors, there are several approaches towards cost reductions that can and should be pursued. The potential for cost reductions will be discussed throughout this article.

Increased Recycling

The processing of recycled materials will be mandatory in the near future, Government legislation will enforce tough measures to ensure that polymeric materials are not simply dumped or incinerated. Large capital investment is required to develop viable technology/processes that cannot be acquired overnight. The recycling of polymeric material is presently less profitable that aluminum, paper; or glass due to the complications of polymer processing [2]. According to Frank Annighofer (German based head of Authur D Little’s European environment department) polymeric materials are recycled for political reasons. Environmentalists claim that volunteered inspection is not enough is to ensure that viable ecological processes are maintained. The hard fact is that the molding industry will have to accommodate the processing of recycled materials, through necessity, not desire.

Malloy [3] describes a process for manufacturing plastic lumber from recycled materials. This process is one example of how considerable value can be added to a formerly discarded polymeric product. The Earth's resources are finite, therefore humanity will have to demonstrate ingenuity for the gamut of materials used by today's consumer products.

Increased Product Quality

Original equipment manufacturers are increasing the quality standards of their suppliers, requiring rigorous quality assurance techniques from their molders. Failure to comply with quality requirements can result in severe penalties on the molder, and even the complete loss of business. As such, quality concepts such as control charts, process capability, six sigma, etc. are perceived as necessary and have become commonplace. Molders rely heavily on visual inspection and other sampling and quality assurance techniques. However, experienced practitioners are aware that the use of these quality processes does not guarantee molded product quality.

The plastics industry requires revolutionary quality control technology that provides 100% level quality assurance in an automated fashion, without any feedback from a human operator. No such system yet exists which can guarantee a diverse set of quality attributes across a diverse set of molding applications. However, molders and original equipment manufacturers are searching for the solution to guaranteed quality control.

Injection Molding 2010

A system schematic of the injection molding process is shown in Figure 1. The molding dynamics ultimately determine the part quality, converting temperature and pressure boundary and initial conditions to specific part attributes. The molding dynamics are governed by the laws of physics and, as such, are not mutable though design, process, and material even though engineers can attempt to influence the input parameters to achieve an acceptable set of outputs. The remainder of this section will address the vision for the remaining system components: 1) part/mold design, 2) instrumentation to witness the molding dynamics, 3) control systems to interpret the process, and 4) actuators to deliver the system inputs to achieve and ensure molded part quality.

Part/Mold Design

Figure 2 shows the close interactions that will exist between part design optimization, injection molding process/production simulation, rapid prototyping, and the injection molding process. The objective of the initial design stage will be to maximize the feasible molding window while simultaneously reducing cycle time and minimizing material usage. This initial stage will also determine machine and material selection based on suitability, availability, and cost. The second stage will involve rapid prototyping of the mold design, incorporating 'built in' pressure and temperature sensors for quality verification. The third stage involves pre-production verification of the mold design in pre-production while running injection molding simulations on-line with the actual process. This strategy will identify limitations/constraints in mold design and provide essential feedback for the design process prior to full production. In reality, two iterations of the design process should provide an optimum mold design, before commissioning of the production mold.

In the product development process, original equipment manufacturers cite product development time as a primary competitive measure. One vice-president of Hewlett Packard has testified that “a reduction of one month in the printer development time would result in additional profits in excess of the entire product development cost.” Consequently, there has been sustained pressure on tooling houses for reduced mold build times. This pressure will not be reduced until tooling time approaches some critical value (between one week and one month) for a typical industry application. Fortunately, two competing efforts are both working towards enabling technologies for the tool manufacturer: rapid prototyping (RP) and Computer Numerical Controlled (CNC) machining.

CNC and conventional machining processes are striving to remain competitive. Technological advances are being made on three conventional fronts: cutter properties, machine capability, and numerical control. The result of this progress is that both material removal rates and dimensional and quality control will continue to increase. However, rapid prototyping will likely become increasingly more prevalent and better-integrated into the design process throughout the next decade.

Current rapid prototyping efforts can be divided into two areas. The more common prototyping processes, such as stereolithography [4], aim to provide the design engineer with a real facility to make the transition from ‘art to part’ without the need to cut steel, from computer model to physical plastic part in twenty-four hours. Material and process advances in this area will permit functional parts with engineering properties to be produced by 2010. However, this process may never be suitable for large volume production. As such, alternative prototyping processes such as three-dimensional printing [5] and selective laser sintering [6] are being developed to rapidly generate mold tooling with minimal machining processes. Already, these processes have been used to manufacture some impressive mold components. In the next few years, material properties and process capabilities will be improved to the point of widespread commercial application. If these efforts are successful, original equipment manufacturers may be buying their mold tooling by the pound rather than relying upon a complex system of design quotes.

Recent work in tight tolerance molding has identified significant shortcomings in the conventional design and manufacture tooling principles. In particular, several commercial application studies recently found that the primary cause of defective moldings were due to two causes: 1) insufficient mold compliance/stiffness allowing out-of-plane distortion, and 2) loose tolerances, assembly guidelines, and metrology on the tool design itself, producing significant variance after mold servicing and assembly. These issues will become increasingly prominent as more applications demand higher precision tolerances. Two complementary methods will evolve to reduce tool development issues. First, guidelines and/or standards will evolve for tool design, assembly and metrology, and pre-production validation. Second, the use of structural analysis in predicting and correcting mold deflection will become commonplace. Between all these rapid prototyping and tooling developments, original equipment manufacturers can be assured that tooling will not be a critical issue in product development by the year 2010.

Part and mold designs will continue to focus on reduced material consumption through three different mechanisms. First, application design will continue the current trend towards thinner wall thickness, almost to the product design’s functional limits. Second, the utilization of hot runner feed systems in mold design will also continue – economics should convince molders that the technology is vital. Finally, the use of gas-assisted injection molding will also be fully realized. This will result in considerable material savings, but requires a rethink of standard mold design optimization principles. As a result of these activities, material consumption per application could be reduced an average of twenty percent.

To summarize all of these developments, mold development in the next millennium should become standardized with guaranteed four-week turnaround of pre-qualified tooling.

Instrumentation

The ‘eyes’ into the injection molding process have to ‘zoom-in’ on the quality influencing factors. This ‘focus’ will be achieved by developing either: 1) new instrumentation methods to see into the mold, or 2) intelligent interpretation of existing instrumentation technologies. Whatever the solution, success in the severe injection molding environment requires ‘bullet proof’ sensor technologies to be developed. It is proposed that measurement of polymer melt ‘state’ at the nozzle is most attractive from an industrial viewpoint, where sensor arrays would provide ‘bulk’ estimated cavity information independent of mold. This estimated cavity information will be complemented by new technologies, that provide process information without mold modifications or sensor positioning deliberations.

A measurement strategy based on ‘seeing into the mold’ will offer a realistic way of optimizing and controlling the injection molding process. Already a competitive advantage can be achieved with the use of cavity pressure sensors, i.e. potential for efficient production control [7]. The installation of sensor technologies for a molding application represents a small fraction of the overall development and tooling costs, typically less than one percent. As such, the installation of a pressure sensor close to the gates, within the first 30% of the flow length, is not an impractical requirement. In the future it would be a very positive situation if cavity sensors were installed as standard, this is feasible for tools with a reasonable number of cavities.   One exciting possibility will be the combination of sensors integrated directly into the hot tip bushings for easy measurement of cavity pressure.

An alternative to direct or indirect cavity pressure measurement, will be through the development of ultrasonic mold sensors.   Technology exists whereby cavity information can be derived from a single sensor located on the outside of the mold, this technology may provide the key to success, as new and existing tools can be measured without any tool rework costs.

One of the most important factors that is often overlooked by molders is the heat transfer process from polymer melt entering the mold cavity to the adjacent mold surface.   The efficiency of this process relates to the effective size of the molding window, therefore it is surprising to find that mold temperature control is regarded as an ancillary function.   Mold temperature measurement and control will become a more significant quality strategy.

Instrumentation technologies relating to the barrel/injection unit are predominantly: zone temperatures; nozzle and hydraulic pressure; and screw rotational speed.   The future machine will incorporate temperature and pressure sensor technology directly into the nozzle design for robustness.   The development of infrared technology will appear in the nozzle, as a realistic means of measuring melt temperature and deviations. During the injection phase, these measurements will enable on-line viscosity characterization for comparison to reference standards. The general vision for instrumentation is to permit direct inspection of molded part quality rather than simple measurements of the process which only permit quality inferencing.

Actuation

The goal of actuation in the next millennium is to deliver the polymer melt to the desired location at the desired pressure and temperature. Development of actuation technologies will be governed by three conflicting goals: greater output (in terms of pressure, velocity, etc.), greater precision of control, and energy efficiency. The first goal, greater output, is driven by the continued competitive pressure for shorter cycle times and reduced material consumption. Machine suppliers have responded with higher sustainable injection pressures, extremely fast ram velocities, and smaller shot capacities to reduce residence time. If greater output is realized, two additional complementary technologies are required to sustain molder competitiveness. First, greater precision of control is needed for consistent control of molded part quality, especially at higher velocities and pressures. This improved machine response will be delivered through enhanced hydraulic controls and truly adaptive control techniques. Finally, the use of electric machines and variable speed drives will provide mechanisms to economically deliver the higher injection pressures; an industry standard ‘power monitoring’ protocol will be a mandatory requirement by 2010, ensuring that only efficient machines remain in production. Table 1 summarizes current and future injection unit specifications for a typical 200-ton injection molding machine.

In the next millennium, ram velocity control will be delivered by 1) a fast response servo control valve as opposed to a proportional valve, or 2) an electric machine with a DC Servo motor. To achieve optimum product quality, the screw injection velocity/displacement profile must be profiled to maintain a steady melt front position during fill. Therefore a screw velocity controller is required that can accurately and precisely follow the set injection velocity/displacement profile. During the filling phase as the mold cavity is filled, the hydraulic injection pressure difference applied to the ram varies dramatically. Therefore during the primary injection phase there is a great difficulty in describing the process behavior by using a constant system model. Adaptive velocity control will form an integral part of machine of 2010, where the requirement is for a self-tuning high performance velocity controller that can accommodate changing process dynamics, regardless of screw wear and tool geometry, the polymeric material being processed, and the design of the injection molding machine. The integration of adaptive controllers to injection molding machines with different characteristic servo valves and hydraulic loops requires a flexible adaptive control strategy. A self-tuning adaptive controller has the advantage of on-line identification of the system model and re-tuning the controller based on the updated system model. Adaptive controllers can give higher performance and have the ability to be flexible between different injection molding machines, tool geometry and the polymeric material being used.

Process variants, such as gas-assist molding, co-injection, melt manipulation, injection-compression, and the rest will continue their encroachment upon conventional injection molding. Their advancement will be gradual, as no “killer application” has revolutionized the industry. Rather, these technologies will continue penetration of market segments on an application by application basis. One particular niche that continues rapid growth is the area of hot manifolds and in particular valve gating. Sequential valve gating for control of melt will continue to increase until it becomes commonplace. By 2010, the technology may be commercially viable to independently and completely control the thermoplastic melt entering each gate in a mold as shown in Figure 3. In this way, the process capability will rival that of closed loop cavity pressure control with unparalleled process flexibility [8]. Future systems will allow for control of melt entering individual cavities, with the screw forward movement resigned to generating the ‘melt flow’ but not direct control of cavity filling.

Control of melt temperature is fundamentally different than flow/pressure control with slower time response since temperature is largely dependent on conductive phenomenon with low thermal diffusivity materials. As such, temperature control has been recognized as a limiting factor in cycle time as well as control surface properties. Recently, several innovations have sought to improve temperature control in both the injection unit and mold cavity. Significant innovations in mold temperature control include low thermal inertia molding, advanced mold surface treatments, ceramic inserts, and heat pipe technology. While the mechanisms vary by approach, Figure 4 illustrates a generalized schematic of the operation. The principle is to match two sets of time dynamics through added degrees of freedom in the manufacturing process. Large amounts of energy will continue to be removed via conventional recirculating water/oil systems with fairly long time step response, on the order of minutes. On a local level, however, thermoelectric elements or other thermal actuators can control lesser magnitudes of energy in a much smaller time frame, on the order of tenths of a second. This combination provides heightened control of the melt during filling and solidification, resulting in improved aesthetics, birefringence, and structural properties.

Barrel heaters on the injection unit have drawn lesser interest, probably due to general belief that screw design has provided mechanisms for ensuring melt consistency. The primary advancement in the next decade will be enhanced time response and settling of barrel temperature, achievable by integrating machine and material-specific models in adaptive controllers. Profiling of melt temperature through the shot will be proposed and may become commercially viable by coupling the barrel heaters and plastication parameters through improved process models.

Quality Control

The three existing phases of polymer injection molding (injection, packing/holding, cooling) will likely remain in their present forms. Good machine optimization techniques are typically known by a small percentage of machine setters, and this information is rarely communicated. The next major step forward in machine control is the automation of injection molding machine setup procedures to eliminate the current ‘guess work’ in process control. The machine of 2010 will differentiate itself from today’s machines by understanding the significance of each phase and how the whole process interacts. The filling and packing/holding phases will benefit by the use of fully adaptive controllers, eliminating the requirement for manual tuning of machines after commissioning or maintenance. The pressure phase will adapt the packing/holding profile to accommodate on-line estimations of polymer solidification/ crystallization.

The vision is a manufacturing facility of machines that have the ability to self-optimize and eliminate molding defects, based initially on operator feedback, and later on fully automated feedback. This strategy will ‘free-up’ the best setters to focus and trouble-shoot the difficult cases, giving a consistent machine setup protocol for the whole manufacturing facility. On-line quality inspection techniques will provide an exciting area of development, promoting artificial intelligence. Imaging technology will be an area where breakthroughs are made, with opto-electronic and electromagnetic sensors becoming available that rival the capability of the human eye. It is envisaged that the ‘black art’ of injection molding will only be practiced in a rapidly declining number of manufacturing facilities which produce parts with reduced quality requirements.

The machine of 2010 must not be content producing molded parts without optimizing the process cycle time. In the high competition world of injection molding, managers are very aware of production costs but are at the mercy of the skill of their operators and setters. Moreover, cycle time optimization is often the last consideration if a tool is regarded as difficult to mold. A next step forward would be the facility for the machine to inform the setter of where cycle time is being wasted and the appropriate remedial actions. On-line gate freeze determination, to optimize the pressure control phase will be of significant assistance. Smart sensors will focus on each phase to determine the most efficient cycle time.

Control systems are not currently capable of automatically delivering 100% quality moldings. Interestingly, quality control is already not limited by the capability or repeatability of the machine actuators. Rather, it would remain unclear exactly what the ideal morphological history and control parameters should be even if an infinite number of degrees of freedom existed to exactly control the pressure, flow, and temperature at every point in the process. As such, further developments are necessary to determining the relationships between molded part quality and machine parameters. Modern injection molding machines operate with a high degree of repeatability but lack the capability to interpret real-time process measurements. This current lack of capability allows raw material variations, polymer melt rheology, and environment conditions to influence the molded part quality. Statistical process control is one approach to compensate for polymeric material variation in the manufacturing environment, but has been shown to provide only open loop control of molded part quality [9]. Closed loop quality control strategies are currently in their ‘early days’ – fully functional system that can cope with all the complexities of polymer melts will be some years in development.

Development Areas

This section proposes development areas that could enable the described vision to become reality. Before discussing these details, however, the authors would like to make a request to machine manufacturers and other technology developers. Technological innovation and commercialization would be facilitated with an open and standardized systems architecture for machine control. The fundamental structure of such a system is shown in Figure 5. A unified back plane/bus transmits protocols and data between multiple components active in the system. Such components might include:

- data acquisition;
- network communication;
- process controllers of the primary machine actuators;
- sub-process controllers for gas-assist, moving cores, sequencing valve gates, water and manifold temperature controllers, etc.;
- quality controllers; and,
- user interfaces to any of the above.

The architecture would permit a foreign component to be inserted into the system and automatically configured for the existing machine set-up. The new component could request data from the other components using a standard protocol, perform analysis on the data, present results to a local or remote operator, and upload new set-points to the machine or auxiliary controllers. With this standard architecture, the functionality, complexity, and cost of individual components would be significantly decreased as redundant sub-systems of previously independent controllers are eliminated. The barriers to product development would be lowered, resulting in a revolutionary period of new machines and auxiliary technologies being released to market.

Part/Mold Design

Three important areas should be improved to immediately impact product and mold development processes: 1) rapid prototyping, 2) computer aided engineering simulation, and 3) computer aided process planning. There are two fundamental shortcomings in rapid prototyping that need to be removed for widespread commercial success. First, the current rapid prototyping systems should be refined to increase the line resolution, speed, and level of part complexity able to be manufactured. These issues are mostly related to the system design and will be resolved in the near future as the technology matures. Second, structural integrity of the resulting prototypes need to be improved by an order of magnitude. Unfortunately, this is a materials science issue which is currently being investigated but will not be resolved in the immediate future. Finally, cost of both systems and supplies remain fairly exorbitant but should fall as widespread adoption of the technology continues.

Computer aided engineering simulation also needs to be refined to better address part and mold development needs. Current injection molding simulation software concentrates on accurately predicting velocity, packing/ holding and the cooling phases, relating the outputs to a fairly narrow set of part properties. The future CAE technologies should be more closely integrated with the mold design process, ensuring the establishment of a robust processing window.   It will be possible to initiate full design of experiment procedures using a ‘virtual’ injection molding machine.   The simulation models should incorporate the transient process dynamic behavior of batch processes, providing a truly realistic simulation environment.   The important issues to be overcome are: 1) the computational time involved; 2) accuracy of the predictive models; 3) incorporation of the plastication phase; and 4) integration of all phases and modeling of the injection molding batch operation.

Finally, all the advanced and conventional practices within the part and mold development process need further integration. In particular, there are several weak links which hamper the new product development process. For example, communication of the customer's critical product qualities are often not adequately defined by the original equipment manufacturer and communicated to the design engineer. At the same time, there is a lack of coupling between the mold design and process engineer, which results in tooling that fails to meet internal specifications. Throughout this poor process, time management of tasks is rarely conducted resulting in spurts of slack followed by intense rushes of activity. The outcome is frequently molded parts which are delivered late, over budget, with attributes that fail to meet customer expectations. As such, there is a critical need for improved business practices that formally interface the development tasks.

Instrumentation

Instrumentation has been an active area of academic and industrial research. Many instrumentation concepts have been proven feasible in laboratories but only a small subset ever become commercial. The primary difficulty with instrumentation is the lack of design robustness. Consider the case of an electrician mounting an infrared melt temperature transducer to a molding machine nozzle. Needing a longer attachment, the electrician prides himself as he cuts through the tough metal shielding, only to realize that he has cut the fiber-optic strands within. While this might seem improbable, such cases are in fact common occurrence. As such, instrumentation must be designed to be exceedingly tough and ‘bullet proof.’ At the same time, moreover, instrumentation must be designed with standard installation, electrical connection, signal conditioning. Due to previous poor experiences, molders are and will continue to be reluctant to incorporate instrumentation until such transducers are widely available on the market.

Having stressed the importance of transducer design, new transducer technologies should be introduced to better assess the quality of the process and resulting moldings. Recently, optical pressure and temperature transducers have been introduced to monitor the process with excellent time response and precision. Further gains in capability and packaging will surely continue. Of more interest, ultrasonic cavity transducers should be released to assess the state of melt crystallization and solidification for feedback control to the injection and packing stages of the molding machine. Similar instrumentation should be developed to precisely measure the volumetric check ring leakage with feedback to the plastication and injection stages. Wide area infrared temperature sensors could be installed to assess the temperature distribution across the part with feedback to the mold temperature controllers as well as the cooling stage. Optical and electromagnetic sensors could displace visual inspection for feedback to quality controllers. This is just a small sampling of the transducers which will become available. To summarize these development goals, instrumentation in the next millennium should permit the true inspection of polymer conditions and molded part quality attributes.

Actuation

The actuation devices used with the injection molding process have become fairly robust, i.e. high throughput, low sensitivity to noise, long mean time between failures, etc. It can even be argued that the available actuator performance is already suitable for most injection molding applications. As such, further fundamental breakthroughs in actuator performance are unlikely. However, industry examples abound where the resulting process conditions are less than ideal. Consider, for example, a 200 ton molding machine which injects at 400 mm/sec but fails to repeatably control the changeover to packing, or a 2000 ton molding machine which reaches the desired barrel temperature in thirty minutes but overshoots by 20C and requires another thirty minutes to settle.

Further developments are thus required towards the efficient usage and control of actuators. One of the more straightforward areas of development is the implementation of adaptive and self-tuning controllers. Many advanced controllers have been developed in the aerospace and process control industries that could be fairly easily adapted to provide improved control of the injection molding process. Such controllers should be self-diagnosing, capable of explaining operation faults, and communicating control performance to the process setter. This information is useful not only for process diagnosis but also direct comparison of system performance. Molders should be savvy enough to require their suppliers to provide such feedback.

Another area of development in process actuation is the use of actuators for non-conventional process control tasks. Such examples include feedback control of mold steel temperature (as opposed to control of water line temperature) or cavity melt pressure (as opposed to nozzle or hydraulic pressure). These strategies permit enhanced control of the polymer melt as compared to closed loop control of the molding machine. Given more degrees of freedom and advanced molding knowledge regarding quality, these additional actuators can provide a mechanism to directly control multiple part attributes on a local scale.

Quality Control

There are two fundamental development areas which need to be addressed for quality control. The lack of consistent machine setup procedures is perhaps the most obvious limiting factor for the injection molding industry. A standardized machine setup approach would assist machine setters to more efficiently accomplish their tasks. Automation of the task will allow the best setters to focus on eliminating the most difficult molding problems, while maintaining the overall standard of machine setup.

One reason that standards have not been developed, however, might be the incomplete state of molding knowledge. It is true that capable experts exist within certain application domains. However, no one person or corporation maintains an accurate knowledge base able to consistently address quality issues across the diverse spectrum of molding machines, material properties, mold geometries, and product specifications encountered across the plastics industry. The generation and communication of such knowledge in a consistent framework might be both the most important as well as the most difficult challenge for quality gains with injection molding. Research and development is required at all levels, from fundamental material and process models to extremely practical molding best practices. For this reason, diverse teams within the industry must partner to develop the vision, structure, and knowledge necessary to deliver ‘intelligent process control.’

Once such models become available, machine and retrofit suppliers should strive to incorporate quality systems in a ‘plug and play’ knowledge architecture. Such an approach would permit industry molders to customize standard practices to better address their molding needs, while at the same time providing a mechanism for translation of the molder knowledge back to the system developers. This approach will be viewed as highly unlikely and even inappropriate due to concerns of intellectual property, proprietary information, and competitive advantage. However, the potential benefits are immense. The only alternative is the status quo: isolated pockets of development resulting in inferior solutions available to the industry.

Conclusions

The plastics industry has been likened to a lumbering giant which is slow to adopt new technologies and business processes. With sustained international competition, however, this analogy is no longer appropriate as OEMs, tooling houses, material suppliers, and molders strive to reduce product development time while increasing productivity. New technologies for injection molding are being created and commercialized at a rate never before witnessed in the plastics industry. This article has put forth a vision for injection molding technology in the next millennium and proposed development areas to convert that vision to reality. Some principle recurring themes developed:

- consistent machine set-up and optimization procedures will be the next quantum leap through the adaptation of expert knowledge, computer simulation, and learning systems;
- computer integrated injection molding will allow control of entire manufacturing facilities, enabling optimization of information as well as information flow for design, production, maintenance, material handling, and inventory control;

- process robustness built into mold design should virtually guarantee acceptable moldings upon production start-up;
- optimization of material usage and part properties through melt conveyance techniques, a technology being steadily accepted;
- recycling of polymeric materials, either directly through injection molding or other related processing techniques. The molding plastics industry should anticipate legislation to force the mandatory recycling of materials; and
- open systems standards for molding machine design as well as process knowledge to facilitate development of new technologies to revolutionize the industry.

The historic rate of growth of the injection molding industry is 3.5% [10]. If the industry is to continue or increase this rate of growth, then the molding process' flexibility, capability, and productivity must be further increased. Otherwise, injection molding may loose ground to other conventional and novel manufacturing processes. The vision that has been presented in this article is more than feasible – certain elements already exist and are being practiced in secluded plants around the globe. The realization of this vision, together with the prosperity of the plastics industry, is in the hands of the reader.

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Figures

Table 1: Injection Unit Specifications of a Typical 200 Ton Molding Machine

Specification by Year	1970	1990	2010
Maximum Melt Pressure (MPa)	100	200	300
Maximum Injection Velocity (mm/sec)	80	150	400
Shot Size (cc)	100	100	80
Typical Power Consumption (kW)	40	25	20
Closed Loop Control	Analog	Digital PID	Digital Adaptive
Response Time (mSec)	40	20	10

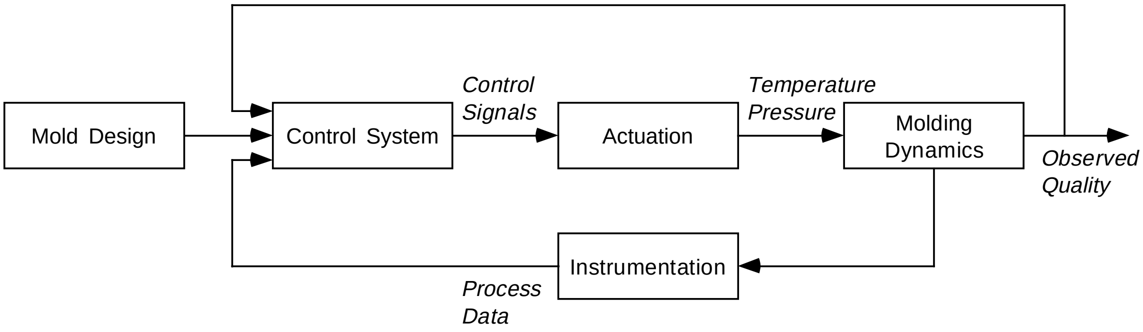

Figure 1: System Schematic of the Injection Molding Process

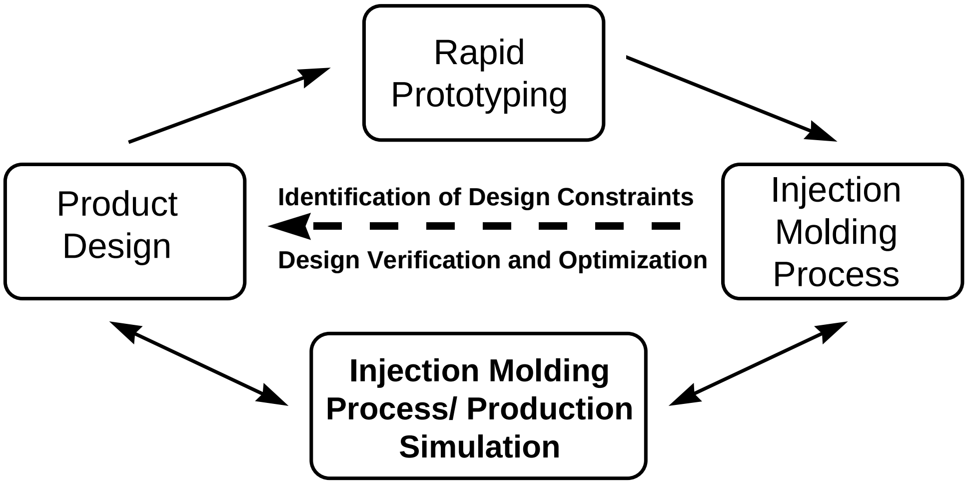

Figure 2: Computer Integrated Injection Molding

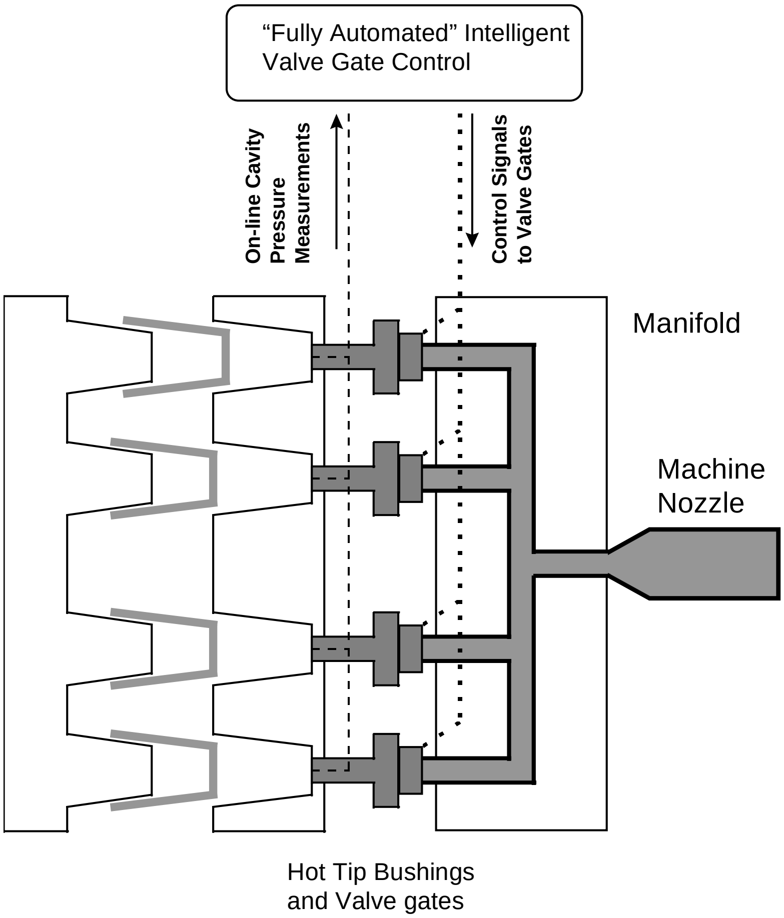

Figure 3: Multi-Cavity Melt Pressure Control

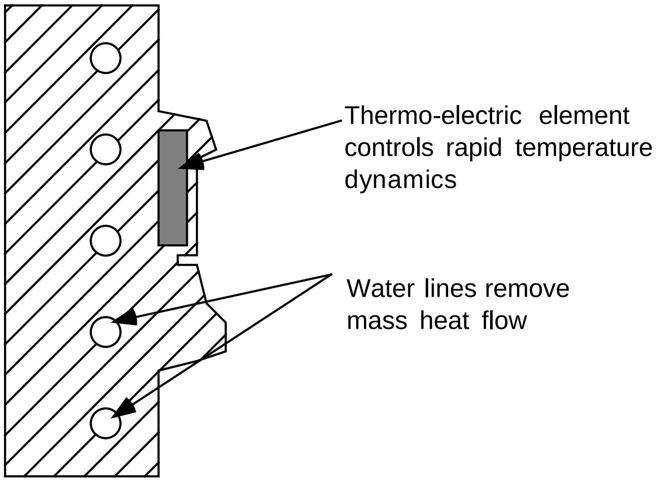

Figure 4: Low Thermal Inertia Molding

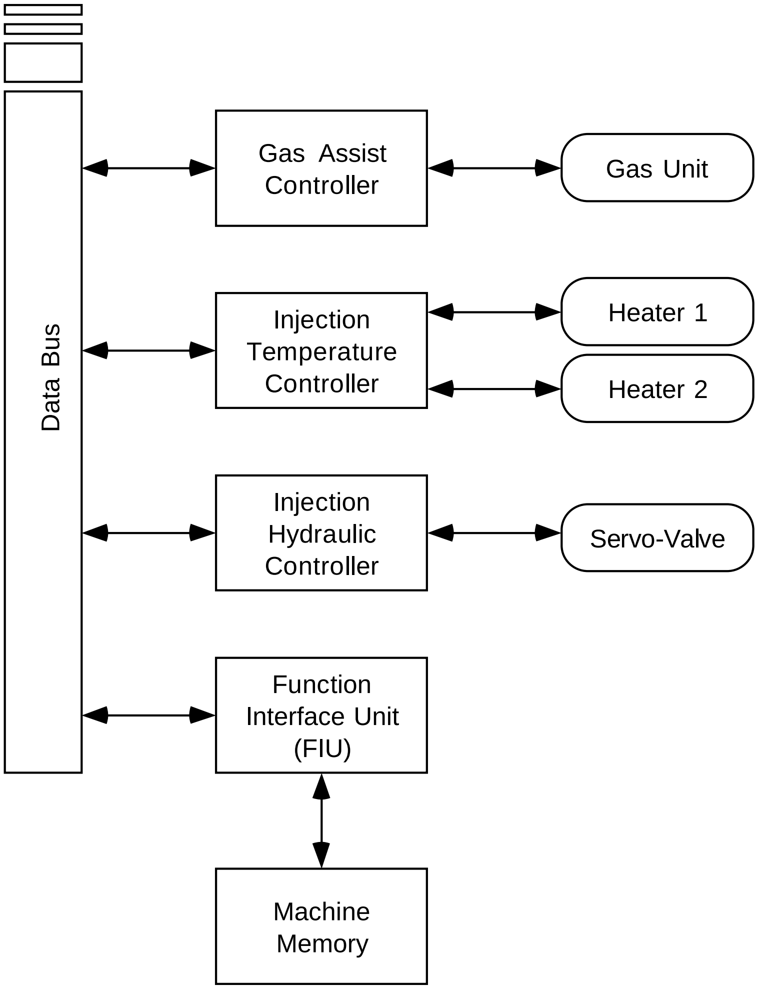

Figure 5: Open Molding Machine System Architecture