Energy and Waste Minimization in the Investment Casting Industry

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ABSTRACT

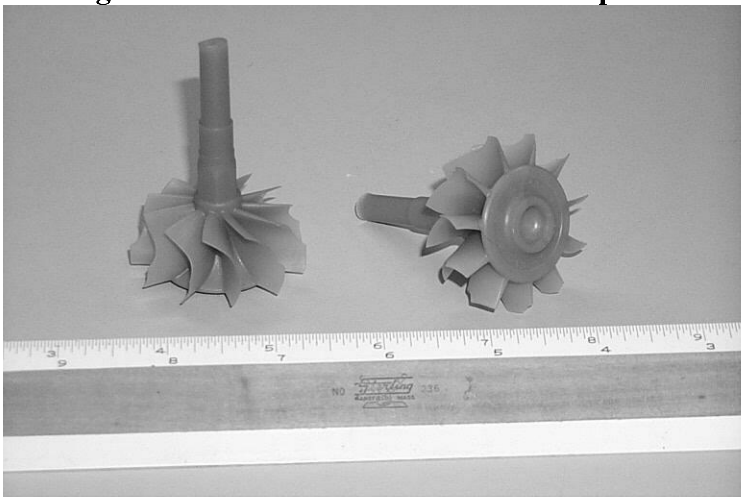
Investment casting is frequently the preferred, and sometimes the only manufacturing process capable of producing components requiring fine surface finish, complex geometries, or tight dimensional tolerances. Key elements that impact a foundry's costs include: labor within the "wax room" operations; energy consumption; scrap rate; and industrial waste. This paper describes a successful collaboration focused on reducing all these cost drivers. The objective of the project was to automate the welding of wax patterns onto runners to form "trees" prior to the forming of ceramic molds. This process is currently performed manually, typically by workers using flat knives heated over inefficient open flames until red-hot. This process is fraught with problems. As much as 30% of all foundry labor is consumed in the wax room. Excessive smoke and heat must be removed via the building's HVAC system, consuming additional energy. Inconsistent or defective wax welds frequently result in lost patterns or scrapped parts requiring re-processing of the metal (i.e., re-melting) and creating excessive waste wax and mold material that must be landfilled. The project described in this paper has resulted in a commercially available system that automates the wax tree assembly process, thereby reducing energy consumption, improving product quality, reducing scrap rates, and reducing labor costs. An added benefit is that it enables precision alignment of patterns, which potentially facilitates the automation of other downstream processes, yielding added energy savings and economic benefits. Consultation with over a dozen foundries has helped identify the critical required features of this system. This paper describes the motivation, justification, planning, execution and results of the project.

Introduction

The investment casting industry in the United States is faced with intense competition from foundries located in low labor-cost countries. Slowly but surely we are losing this strategic industry as US companies purchase castings offshore to reduce costs. Investment casting is used to produce many parts that could not be produced economically with any other available manufacturing process. Among the numerous components manufactured with this process are aircraft turbine blades with internal cooling passages, surgical instruments, and prosthetic hip and knee implants. The process can handle a very large range of materials and geometry's that would be impossible with other manufacturing processes. Figure 1 shows a wax pattern used to cast a typical investment cast part, a small turbine impeller.

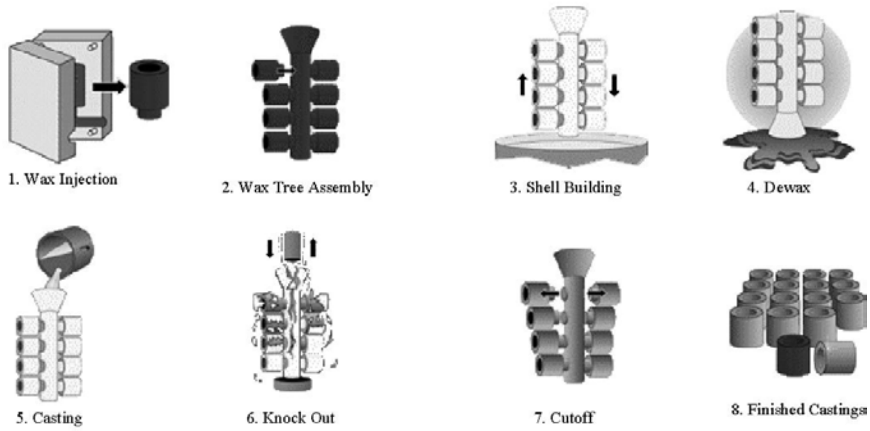
Figure 2 below shows the basic steps in the investment casting process. The nomenclature of each component of the wax tree assembly is labeled in Figure 3. MPI's customers, such as Sturm Ruger and the company's investment casting divisions, use MPI's injection molding machines to make wax patterns, one for each and every cast product made, and must attach them to wax runners to construct trees. These trees are then used to create a ceramic mold, from which cast parts are produced. In Step 2 of Figure 2 a manual process using a hot knife blade passed between the two wax surfaces is used to attach the wax patterns to the runners, as shown in Figure 4. Figure 5 shows hot knives being heated over an open flame. Alternatively, the pattern gate is dipped in hot "sticky wax" and then placed on the runner, which has been heated using a hand held torch as shown in Figure 6.

Figure 1. Wax Pattern of a Turbine Impeller



Source: Trucast, Ltd.

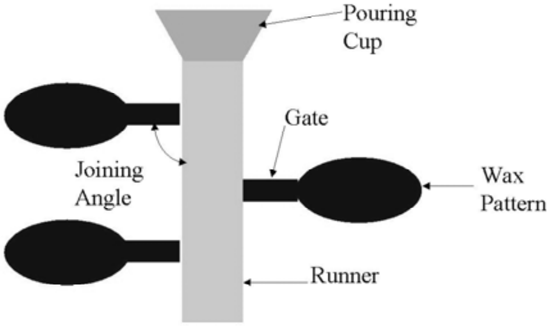
Figure 2. The Basics of the Investment Casting Process



Source: Ludwig 2000

The position and orientation of the wax patterns on the wax tree is critical to guarantee that wax flows out of the mold when heated in the autoclave, and to ensure a good flow of metal into the mold during the casting process. This manually formed joint should have smooth rounded corners so as not to create inclusions in the cast part. Inclusions are formed as a result of an undercut or sharp corner in the joint between the wax pattern and the runner. The flow of hot metal into the mold breaks off ceramic material from the sharp corner and carries these ceramic chips into the mold cavity, resulting in an inclusion and a scrapped part. Figure 7 below shows examples of good and bad fillets, as described by the numerous foundries surveyed by the research team. According to customer surveys, square corners where the gates meet the runner are undesirable but acceptable. In contrast, it should be noted that if there are any sharp inside corners in the wax tree, then there is a possibility that the sharp corner formed in the ceramic shell can break off during pouring and produce a void in the cast part. This void or inclusion of the ceramic material could lead to unacceptable parts or unnecessary rework.

Figure 3. Components of Wax Tree Assembly (Step 2 of Figure 2)

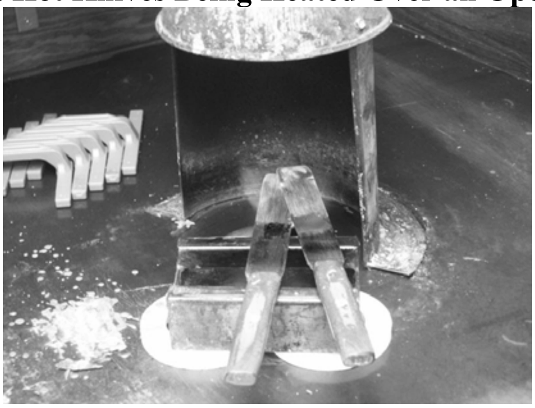


Source: Ludwig 2000

Figure 4. Worker Using Hot Knife to Apply a Wax Pattern to a Runner

Source: Pine Tree Casings 2003

Figure 5. Hot Knives Being Heated Over an Open Flame

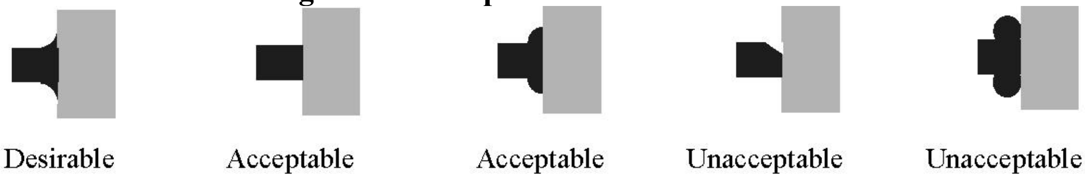


Source: Pine Tree Castings 2003

Figure 6. Worker Using "Sticky Wax" and Gas Torch to Apply Patterns to Runner

Source: Lamothermic Corporation 1999

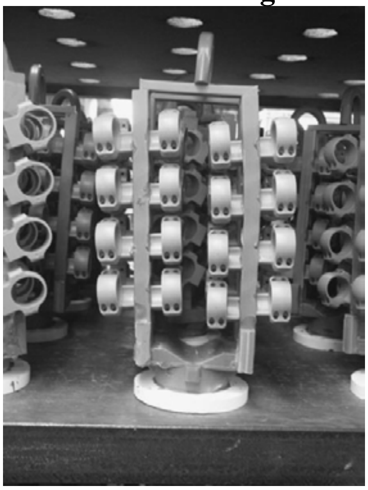
Figure 7: Examples of Good and Bad Fillets



Source: Ludwig 2000

An added problem with the manual assembly of wax trees is that there is poor alignment of the runners and patterns, as seen in Figure 8 below. While this does not cause a direct problem with casting, it does present significant challenges in the event one attempts to automate the cutoff of the cast parts from the metal tree. The precise alignment of patterns resulting from the automation of the wax tree assembly process will then facilitate the automated cutoff and grind of the cast parts.

Figure 8. Assembled Wax Tree Showing Crooked Patterns/Runner



Source: Pine Tree Casting 2003

Project Objectives

The objectives of this project were:

- To demonstrate the technical and business feasibility of automating the assembly of wax patterns to runners.
- To develop and demonstrate a commercial prototype machine that will be beta tested in an investment casting foundry.
- To demonstrate the potential labor savings, scrap and waste minimization, and reduced energy consumption associated with automated pattern assembly.

Project Motivation

The US investment casting industry is having a very difficult time competing with foundries located in low labor cost countries. Foundries are closing as their customers shift their sources to these off-shore suppliers. In order to re-gain its competitiveness the industry must develop and implement new technologies. The investment casting process is labor intensive and parts of it have been automated. The wax pattern production, ceramic shell buildup, and metal pouring process have all been automated, but the wax tree assembly process has not yet been successfully automated and has always been a difficult operation to mechanize. This is the most labor-intensive step and requires artistic abilities of the wax tree assembler.

There are in excess of 350 foundries in the United States that perform investment casting using the lost wax process, and more than 700 foundries worldwide using this casting method. Investment casting is typically preferred over sand casting where there is a requirement for high precision, complex geometry, and fine surface finish. Currently, nearly all investment wax tree assembly is performed manually, resulting in inconsistent pattern placement on runners, inconsistent welds, and lower than optimal volumetric efficiency. Also, workers are exposed to vaporized wax fumes from the welding process. As a result, the removal of cast metal parts from the casting runners, de-gating, and grinding is performed entirely by hand, a labor intensive and dangerous process. Workers are exposed to fumes, hot sputter, grinding dust, and risk of physical injury from hot, flying metal and from repetitive motion injury.

The investment casting industry is a very energy intensive industry. It is estimated that in 1997 the casting industry in the United States consumed between 200 and 250 trillion BTUs of energy (DOE 2003). Investment casting represents approximately 10% of all casting processes. Of the energy consumed in the industry an average of 55% is used in the melting process, 20% is consumed in mold making and processing, and another 7% is consumed in the post casting processes (DOE 2003). It is estimated that approximately 10% of investment cast parts are defective, requiring remelt and reprocessing. In certain applications where the quality standards are extremely high this number can be even higher. Thus, the potential for energy savings resulting from improved process yield may be as high as 1.6-2 trillion BTUs.

Currently there is only one system available for automated tree assembly, the Pattern Assembly Machine (PAM) manufactured by Fansteel-Escast in Sarasota, Florida. Fansteel-Escast claims that their system reduces the time to assemble wax trees by 50%, with greater consistency of pattern spacing and weld (Ellin 1985). However, the Fansteel-Escast machine has not been a commercial success due to the system's cost, complexity and lack of flexibility. Additionally, the Fansteel-Escast system requires that an operator individually load each wax pattern into the machine for assembly.

MPI, Inc. believes that the current situation represents a significant business opportunity. The automated pattern assembly machine resulting from this project will be an important addition to MPI's integrated wax room solutions.

Project Justification

Projects are expected to result in positive impact in three areas; energy, environment, and economics. While every project selected does not necessarily need to impact all areas equally, the automated pattern assembly project does hold the potential to favorably impact all three areas, as described below.

Energy Consumption

The resulting improvement in quality and yield will significantly reduce the down stream energy requirements. Improved yield from higher quality wax patterns means less metal heated. Accurate pattern assembly will allow for:
more patterns to be assembled per tree; a higher yield per metal pour, and part cut off with less metal removal during de-gating and final finishing. This project will enable MPI to later develop automated cutting and grinding systems where there is potential for significant energy savings. Also, a significant energy savings is anticipated from reduced loads on HVAC systems due to there being less smoke and fumes generated when compared to the manual assembly process, and the elimination of the numerous open flames found in most foundry wax rooms. The actual energy savings realized will be evaluated during the beta test of the pattern assembly machine developed during this project, anticipated to occur in the latter half of 2003.

Environmental-

The primary environmental impact of the proposed project is to reduce worker exposure to molten wax fumes that are a health hazard. A reduction of wax fumes released to the atmosphere will likely be possible due to better control of the welding process. The hot knives found in most foundries are heated to around 1200^{o}F while the process used with the automated system employs much lower temperatures. The improved quality and yield of the automated process will also result in a significant reduction in the amount of solid waste, primarily ceramic mold material, that must be land filled. There will also be a significant long-term impact on worker safety and environmental hazards once the cutting and grinding processes are also automated. In order to realize this benefit, however, the wax tree assembly process must first be automated.

Economic-

The long-range vision of MPI, Inc. is to offer complete wax room solutions for its customers. Currently, MPI products are in use in 131 foundries in the U.S., and an additional 100 foundries throughout the rest of the world. These pattern assembly machines will become the center of completely automated wax cells that will also include automated pattern and runner injection, inspection, and be networked with robotic handling units that are all integrated to the company's MIS system, thus closing the gap in creating the fully automatic investment casting foundry. MPI's customers will benefit from the resulting automation system. Improved process yield, lower energy and waste disposal costs, and enhanced worker safety will translate into improved competitiveness, capacity and market share.

Project Planning

Partners in the project include MPI, Inc., the New York State Energy Research and Development Authority (NYSERDA), and the Flexible Manufacturing Center (FMC), located at Rensselaer Polytechnic Institute (RPI) in Troy, New York. MPI, Inc., located in Poughkeepsie, New York, manufactures and sells wax room machinery to the investment casting industry. NYSERDA is a public benefit corporation created by the New York State Legislature in 1975 with the mission of providing funding to assist New York State manufacturers to develop and adopt technological improvements in response to their energy challenges. The FMC is an interdisciplinary research center within the Department of Mechanical, Aerospace, and Nuclear Engineering. The research team included MPI engineers, and the faculty, staff and students within the FMC.

The greatest technical risk associated with the project was that it might not be possible to consistently make strong welds with smooth fillets in an automated process. Second, there was uncertainty as to the cost effectiveness of an automated system. That is, would the anticipated cost associated with the capacity of the machine be justifiable? Third, there was a need to better define exactly what features and capabilities were required from the user's perspective. For these reasons, a decision was made to conduct the project in two phases. Phase I would address the technical and business feasibility issues, while Phase II would focus on the development of a commercial prototype automated pattern assembly machine that could be beta tested in a foundry environment. Successful completion of Phase I was required in order to proceed with Phase II. Phase I was planned to be completed in six months, and Phase II was planned for 30 months. Phase II commenced in January, 2001.

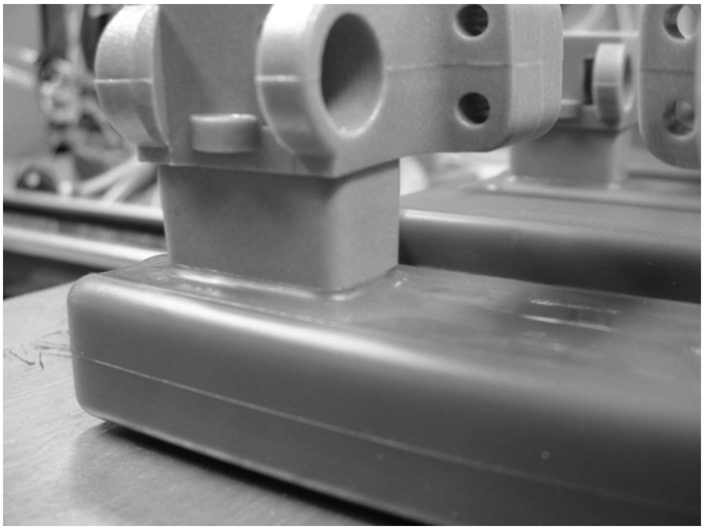
Project Execution

The focus of Phase I of this project was to demonstrate the feasibility of the automated pattern assembly concept. In order for automation to be feasible the wax welding process must produce strong, repeatable, smooth weld joints, with little or no dripping of wax. Also, the resulting process and machine design must be cost effective and robust for automation. Researchers within the FMC first addressed the automation of the welding process. Brainstorming sessions were held to identify several alternative approaches to automated welding. A variety of contact and non-contact methods were identified and evaluated for their ability to produce strong welds and smooth fillets. An Instron Universal Testing Machine was used to compare the fracture strength of the resulting welds, which were compared to those produced by manual welding techniques.

Experimentation with the preferred process identified an optimal set of process parameters that consistently produced a smooth fillet weld when performing a single weld. In order to be cost effective, however, a commercial machine would have to weld several patterns simultaneously. The research team then developed a concept design for an automated machine that we believed would produce multiple welds, of high quality, at a rate that would be cost effective. The resulting concept design included seven degrees of freedom, a variety of flexible fixturing methods to hold a range of pattern shapes and sizes, and a means to secure and manipulate a variety of runner configurations and geometries. In order to better define the required features of a commercial machine the MPI/FMC research team visited numerous foundries to collect data related to runners, patterns, waxes, and wax room labor. Foundry personnel were very helpful in defining what features would be required of a successful automated machine.

During Phase II we turned our attention to demonstrating the feasibility of the concept design developed during Phase I. To do this researchers designed and constructed a Proof of Principle Model (POPM), or concept prototype, located in the FMC laboratory.

Figure 9. Example of Smooth Fillet Weld Resulting from Automated Assembly Process with the POPM



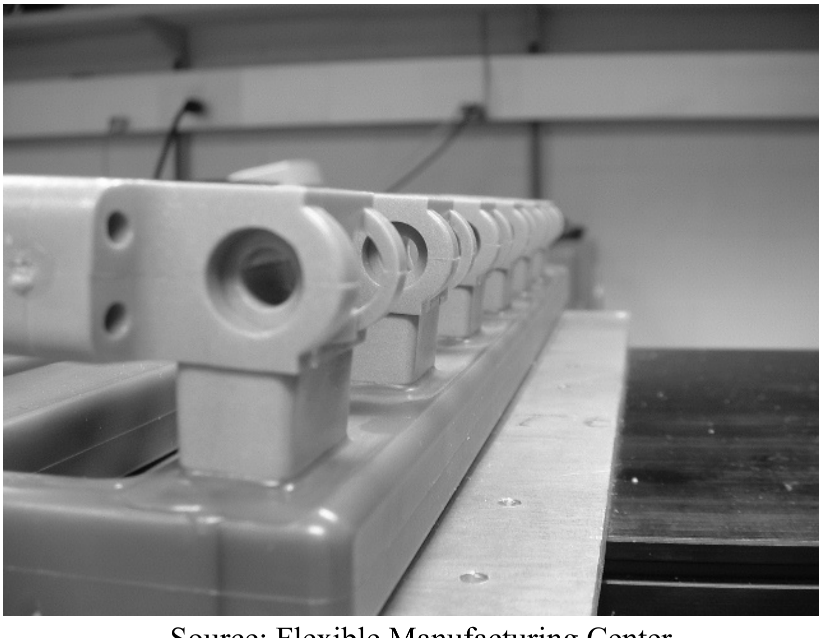
Source: Flexible Manufacturing Center

The POPM design incorporated only those critical features needed to demonstrate simultaneous welding of multiple patterns, provide a testbed for experimenting with various pattern and runner fixturing methods, establish process parameters for the commercial machine, and validate the projected cycle time for the preferred wax welding process. Control of the POPM was accomplished with a D-Space controller. The POPM was also useful in identifying a number of technical challenges that would have to be addressed with the design of the commercial prototype machine. We were successful in demonstrating both precision alignment of patterns and strong, smooth fillet welds, as shown in figures 9 and 10. These welds are far superior to those observed in the foundries that we visited.

Once we had learned all that we could from the POPM a demonstration was held for NYSERDA and a select number of representatives from foundries that had been helpful in defining the system requirements. While there was some skepticism of foundry personnel prior to the start of the project the feedback received from the attendees was very encouraging, and provided valuable marketing information.

The project team next proceeded to design the commercial prototype machine, designated the model 20-10, capitalizing on the lessons learned from experience with the POPM. Among the key design objectives were: ease of integration with other wax room systems; either manual or automated loading of patterns; allow for future addition of automated load/unload of wax runners; high precision positioning of patterns and runners; minimize operator intervention requirements; flexibility for ease of changeover from one runner/pattern combination to another; and minimized space requirements. MPI personnel took the lead in design of the 20-10, with FMC students, staff and faculty providing design and analytical support, and conducting experimentation when needed to validate the detailed design approaches. Frequent design reviews were conducted to insure effective communications and coordination of efforts. An extensive tradeoff analysis was conducted to decide between using commercially available robots or custom built motion systems for pattern handling and manipulation of the heated knife used for welding. Key elements of this analysis were: development lead time; the architecture of the machine's control system; ease of integration and programming; accuracy, repeatability and deflections of motion axes; connectivity for remote diagnostics and support; and costs.

Figure 10. Populated Runner Showing Precise Alignment of Patterns



Source: Flexible Manufacturing Center

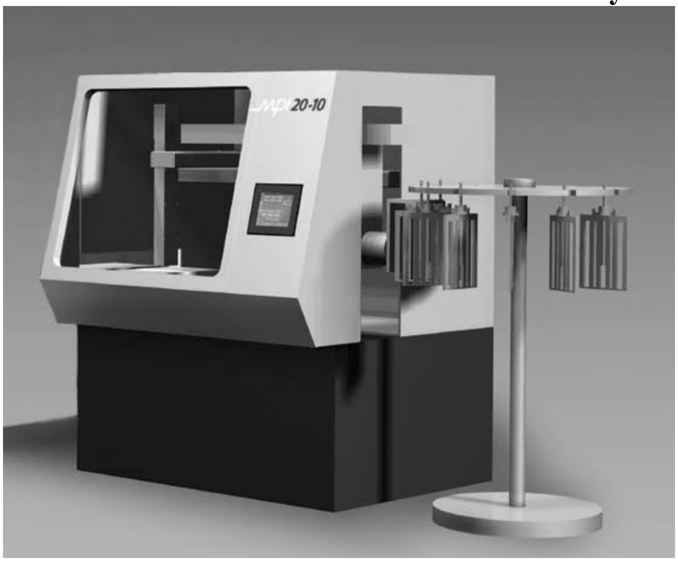
Project Results

The project team has succeeded in achieving the goals set forth at the start of the project. During Phase I we demonstrated a process with the ability to form superior strength welds with smooth fillets. We also demonstrated that the process cycle time would allow a commercial machine to meet the throughput needed if multiple patterns are welded simultaneously. With the POPM built during Phase II we demonstrated the ability to make multiple welds simultaneously, and to achieve precise alignment of patterns to a degree not found with manual tree assembly.

Figure 11 shows a rendering of the design of the commercial prototype machine, designated the model 20-10 being built at MPI. Key features of the machine include:

- Two commercial robots for manipulation of patterns and the electrically heated knife.
- Servo actuated runner station, designed for future integration with fully automated runner load/unload robot.
- Automated dial and pallet system for pattern loading.
- Automated knife clean and maintenance station.
- Quick-change tooling.
- Integration with MPI 45-12 automated wax injection system.
- User-friendly touch screen interface and PLC based controls.

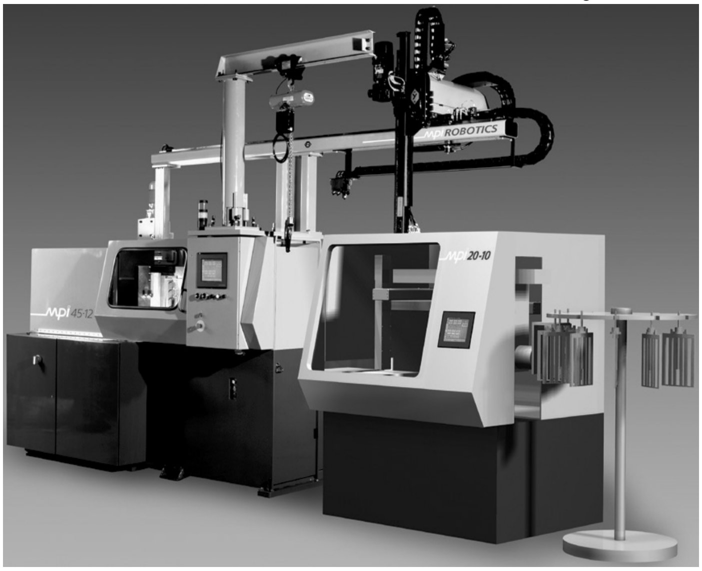
Figure 11. MPI Model 20-10 Wax Pattern Assembly Machine



Source: MPI, Inc. 2003

Figure 12 shows a rendering of the 20-10 wax pattern assembly machine co-located with the 45-12 automated wax injection machine. This is the configuration that will be beta tested in 2003 at Pine Tree Castings. The 45-12 is an automated machine that molds the patterns and transfers them to pallets on the pattern feed station of the 20-10. Initially runners will be manually loaded and unloaded in the 20-10, however, the machine has been designed for easy integration with a planned load/unload robot system.

Figure 12. MPI Model 20-10 Wax Pattern Assembly Machine Integrated with Model 45-12 Automated Wax Injection Machine



Source: MPI, Inc. 2003

Conclusion

This project is an excellent example of effective industry-university-government collaboration. Without the support of NYSERDA the project would not have been possible. The MPI/FMC team worked effectively together, with each organization contributing their unique strengths. Early in the project FMC researchers led the effort to develop and demonstrate the viability of the automated wax welding process and to generate the conceptual design that would eventually be implemented with the commercial prototype machine. The excellent laboratory and experimental facilities, and the analytical skills of the FMC faculty and staff contributed valuable information throughout the project. MPI's knowledge of foundry operations and the potential market insured that the efforts of the FMC researchers remained focused and relevant to industry's needs.

Later in Phase II MPI assumed a leadership position in the detailed design and construction of the prototype machine, with FMC personnel focused on designs for flexibility in end-of-arm tooling, and assisting with the architecture of the machine's software and controls for maximum flexibility, ease of use and remote connectivity.

The commercial prototype wax pattern assembly machine will be completed and begin beta testing at Pine Tree Castings during the summer of 2003. This important beta testing will provide the opportunity to determine the actual improvements in energy consumption, labor savings, and waste reduction. We believe this project will advance MPI's leadership position in providing integrated wax room systems to the investment casting industry, and bring them closer to the goal of a lights-out castings facility.

Acknowledgments

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