Final Technical Report

Energy Efficiency Instrumentation

DOE Award Number: **DE-FC36-04GO14230**

Project Period (March 2005 – September 2013)

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Report Date: December 2013

Acknowledgment, Disclaimer and Proprietary Data Notice

Acknowledgement: This report is based upon work supported by the U. S. Department of Energy under Award No DE-FC36-04GO14230.

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Proprietary Data Notice: None in report.

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List of Acronyms

CAD Computer aided design
CNC Computer numerical control
HAZ Heat affected zone
PWHT Post weld heat treatment
NDE Non-Destructive Evaluation

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Executive Summary

As with any manufacturing operation, the metalcasting processes have several sources of variation. Additionally, the metalcasting industry routinely produces a wide variety of complex shaped components, which often exacerbates the problem of determining the source of variation. The goals of this project were to develop better tools and strategies to collect and manage process and product information. Based on industry feedback, five areas were selected based on the amount of variation caused by this source or the potential for improvement in terms of energy, emissions and competitiveness. These five areas were:

1. Heat Treatment Control Strategies
2. Semi-Automated Grinding
3. Surface Mapping Software
4. Study of Impact of Repairs via Weld Gouges
5. Rapid Pattern Making Machine

Heat treatment of steel castings is a critical step to achieve the material properties and product performance. Buyers of castings as well as the producers have traditionally been very conservative on the heat treat control practices that they specify or utilize. While other researchers have worked on heat transfer models, it is impractical to model the mix of random orientations and packing of many casting designs for an analytical solution. Therefore, this project utilized new sensors and control strategies that can better assess the temperature of castings during heat treatment, and can more accurately control the temperature instead of relying on several iterations of heating and delays. Specifically, embedded thermocouples that accurately measure the temperature of a block that is a surrogate for the actual castings in the load are used. Surrogate blocks represented those castings that have the heaviest section sizes and longest time to reach critical temperatures as well as those that have thin section sizes which would be susceptible to overheating. To access this data in a practical manner, the thermocouple wires extended to just outside of the movable portion of the heat treatment ovens, and then transmitted wirelessly from there to the office. These techniques were transferred to industry through publications and presentations and then again by industry personnel relating their success of implementation.

Post-solidification processes are a major portion of the time and labor expended to produce a steel casting, especially for larger castings. During these processing steps, arc air, welding and grinding are commonly used to remediate those areas of the casting which do not meet the customer requirements. Some of this processing is in expected locations, such as where risers and gates had been removed, while others are in unexpected locations such as inclusions and hot tears. This project developed a prototype system for the grinding processes that partially removed the human operator from the operation. Despite advances in vision systems, human operators are still needed to determine where and how much grinding is needed on a casting surface. This project developed and demonstrated a prototype system in which the machine applies the force, but the human is used to control the movement of the grinder via an external position controller. The laboratory scale prototype system was successfully demonstrated, but further commercialization is stalled due to the large investment necessary to move this project to an industrial scale machine.

If the casting producer had accessible information about the original surface condition of the castings prior to the post-solidification processing, better process control decisions could be made. While the casting surface is inspected at least once and maybe several times, this information is rarely collected because of the difficulty in collecting and managing it. When the data is collected, it is often via paper sheets which are hard to access to determine short or long term trends. This project worked to develop a software system to collect, manage and access surface quality information. An existing prototype of the software had been developed and demonstrated, but was not ready for use on the factory floor. With this project, the software was made more robust and usable by working on interface, database, security, and connectivity aspects of the software. With this software, a casting producer can readily track the surface condition of the castings to allow them to spot quality trends and make informed process control decisions. These decisions will ultimately reduce the rework and scrap of the castings. The software is currently in the hands of several industrial users.

As mentioned above, the surface condition of the casting is inspected and areas that are not acceptable are removed via arc air, replaced with weld metal, and ground smooth. These decisions are made based on the customer requirements. Despite the intent of the customer to improve the performance of the component, the additional processing may actually have a negative impact on the component performance. To investigate this, a controlled experiment was conducted at three steel casting producers and with different alloys. Test castings were produced, and gouges of different sizes were inflicted on the casting and the metal replaced via welding. The material was characterized via hardness testing in and out of the weld zone and with and without post weld heat treatment. This study showed the negative impact of these processes. This work, coupled with other work on ‘effect of defects’, can help the designer to make better decisions regarding acceptable surface conditions. Ultimately, the information communicated via this effort will allow the production of castings with less need for arc air, welding, grinding and post weld heat treatment operations, and achieve a casting with better material performance.

To produce a steel casting, most generally, a pattern is made which is used to create the sand mold. Patterns are expensive; for example, the cost for a pattern that is approximately a one meter cube is a few tens of thousands of dollars. The lead time for such a pattern is often two to four months. Because of these costs and lead times, making changes to a casting or pattern design is problematic. While recent advances in additive manufacturing methods allow for the direct production of sand molds, this approach remains expensive and is inherently limited by the single use of the mold. A rapid pattern making system was developed which will produce large patterns (current system is a 1.2 meter cube capacity but there is no technical hurdle in going larger) with no need for process planning of the pattern production. The system will allow a casting producer to receive or create a pattern in a few days from relatively inexpensive materials. This will allow the producer to prototype different casting and pattern designs to confirm or adjust needs to accommodate such issues as dimensional changes, gating and solidification shrinkage. The system will enable the producer to respond to customer needs more rapidly, without the risk of a large time and cost investment in pattern tooling. The rapid pattern making system had been previously prototyped and demonstrated but was not practically viable. This project enabled a more robust system with a new controller that is being used to demonstrate to industry the use of this system. Commercialization plans through state economic development offices have been initiated now that a reliable system exists.

This project collectively looked at areas of the steel casting production process which could help reduce the rework, scrap and energy consumption required. Through these efforts, casting producers are better equipped to control their processes and specify processes that better meet their customers’ needs.

1. Introduction

This project addressed five areas of metalcasting production that can reduce the process and product variation and significantly improve competitiveness. The steel casting industry was the targeted industry for this project, however the majority of the effort would apply to other casting industry segments. The software to manage surface inspection data would be applicable to the many processes that employ a surface inspection process. The technologies investigated are somewhat unrelated; however each was identified as a manner in which the metalcasting industry could improve the variation of their processes.

Reduction in heat treatment time has a direct impact on the natural gas usage. Conservative heat treatment rules have been specified by the customer and used by the industry to help ensure that material property targets were met. Most of the heat treatment operations are dependent on the transformation of the steel alloy to austenite. The conversion to austenite is very quick (e.g. a few minutes); however the doubt remained on whether the castings had achieved the desired transformation temperature. Blocks with embedded thermocouples are occasionally used to validate a process, but this is very impractical on a daily basis because the thermocouple wires are cumbersome, expensive, and hard to manage. This project, in part, relied on thermocouples that were connected to a wireless transmitter, immediately outside of the furnace structure. These thermocouples were placed in blocks that could be left in the furnace structure; hence, the thermocouple wires were not disturbed between loads. This allowed for the capture of the temperature of the blocks, which, if placed in the slowest areas of the furnace to heat up, would ensure that all of the castings of similar or less thickness were also at temperature.

Grinding is necessary step in casting production to render the surface acceptable per the customers' standards. This applies to those areas that have to be ground every time (e.g. risers and gates) and other areas that need surface improvement (e.g. location of welding to remediate inclusions, burnt on sand). Being essentially a manual process, the grinding operations are subject to significant variation. This variation makes the production of castings more difficult to manage as well as more difficult to spot quality trends because they are lost in the everyday variation. In an attempt to improve this process, this project developed a prototype grinding system that would automatically remove those surface areas that were identified by the operator as needing to be rectified. There has been much success in robotic grinding systems for grinding castings. However, in each of these cases, the production numbers was great enough to justify a fixturing system to accurately locate the parts. The operator is also necessary and cannot be replaced by modern vision systems because of the short run nature of the products, wide variety of geometries, and the random locations and magnitude of the grinding that is required.

All of the surface problems that do need the customers' standards need to be resolved, consuming valuable resources. Ideally, the information to quantify this surface quality would not only be tracked on an individual casting basis, but also the specific locations on the casting. Only with a valid view of this information can a process engineer make an informed decision on the control of critical process variable. However, this data has been expensive to collect, and therefore, rarely collected. Through this project, a Surface Mapping system was advanced from a prototype stage to one that has been transitioned to industry. This software allows the user to enter the geometry of specific surface problems onto the model of the casting. This information is uniquely stored in a database and then can be accessed via meaningful output screens.

Inclusions or other casting surface issues are often remediated on steel castings via arc air, welding and then grinding. This project investigated the metallurgical damage that is inflicted by these processes. Studies were done on different alloys, and showed that a casting consumer should rethink what surface condition is acceptable given the metallurgical differences in the weld area compared to the original casting material.

The Rapid Pattern Making System was advanced to a stage that can be employed by industry to rapidly make patterns. In this sense, the term rapid refers the lack of the need for any process planning decision that needs to be made once a solid model of the pattern is created. The 'rapidness' of this system is akin to the rapid prototyping systems that can immediately produce a part from a solid model. However, unlike traditional rapid prototyping processes, the Rapid Pattern Making System can produce patterns from actual traditional pattern making materials and on a much larger scale. The system used here can build a pattern of 1.2 meter cubic volume.

2. Background

Prior to this project, the principal investigator executed projects that collected and analyzed extensive information on the actual production systems used at a variety of steel casting producers. The previous work characterized the product flow and investigated reasons for delays. A major finding was that the production systems became much more complicated because of rework that was required during the post solidification finishing operations. The variation of the effort required of individual castings at several foundries was further collected and analyzed, however it was difficult to find any singular root causes due to the multiple sources of variation. Any increase in product or process variation had a direct impact on the amount of labor and energy resources which were required to complete production of the parts. Publications from these earlier studies are listed below. It was from this basis that this project was organized to create instrumentation strategies to help casting producers to better monitor and control the variation of their products and processes. This project focused on five separate areas that would assist the metalcasting industry in improving the efficiency of their operations through reduction in process variation, rework and scrap. While each of these areas has a common final outcome, the areas had different approaches. Hence, this section is organized to provide the background for each of these areas.

Daricilar, G., F. Peters, and M. Blair, "Visual Assessment of Casting Surface Quality," Material Science Technical Conference, Pittsburgh, PA., September 2005.

Harwood, B., C. Samuelson, B. Bishop, R. Stevenson, F. Peters, "Variability: Causes, Concerns, and Corrections," Steel Founders' Society of America T&O Conference, Chicago, Illinois, November 2004.

Menning, A., R. Stevenson, J. Anderson and F. Peters, "Assessing Process and Product Variability," Proceedings of the Steel Founders' Society of America Technical and Operating Conference, Chicago, IL. November, 2003.

Menefee, A., J. Anderson, F. Peters, A. Menning, and T. VanVoorhis, "Initial Studies Towards Reduction in Variability in Steel Foundries," Steel Founders' Society of America – Technical and Operating Conference, Chicago, Illinois, November, 2002.

Peters, F., J. Anderson, A. Menefee, and P. Patterson, "Solutions to Improve Ergonomics and Productivity," Steel Founders' Society of America-Technical and Operating Conference, Chicago, Illinois, November 2001.

VanVoorhis, T., B. Bernard, and F. Peters, "Impact of Variability on Productivity, WIP and Lead Time," Steel Founders' Society of America-Technical and Operating Conference, Chicago, Illinois, November 2001.

VanVoorhis, T., F. Peters, and D. Johnson, "Developing Software for Generating Pouring Schedules for Steel Foundries," Computers & Industrial Engineering, Vol. 39, pp. 219-234, April 2001.

Peters, F., M. Beyersdorfer, and T. VanVoorhis, "Instigating Changes to Production Systems," Steel Founders' Society of America-Technical and Operating Conference, Chicago, Illinois, November 2000.

Peters, F., T. VanVoorhis, and T. Rolling, "Re-Engineering Casting Production Systems – Successes and Opportunities," Steel Founders' Society of America Technical and Operating Conference, Chicago, Illinois, November 1999.

Peters, F. and T. VanVoorhis, "Current Steel Casting Production Practices," Steel Founders' Society of America Technical and Operating Conference, Chicago, Illinois, November 1998.

Peters, F and T. VanVoorhis, "Re-Engineering Casting Production Systems," Proceedings of the 1997 Steel Founders' Society of America Technical and Operating Conference, Chicago, Illinois, November 1997.

2.1 Heat Treatment Control Strategies

This effort is focused on providing heat treatment control solutions for batches of randomly oriented and packed loads of castings, as represented in Figure 1. Other researchers have successfully modeled the heat transfer that occurs during the process but this has been typically limited to simpler part geometries and/or packing of the parts in regular patterns. [Depree 2010, Hassan 2008, Mochida 1997, Rong 2006, Tagliafico 2004]. The approach identified here will provide a reliable estimate of the actual temperature of the castings, regardless of their geometry and loading, on an ongoing basis for every heat treatment batch.

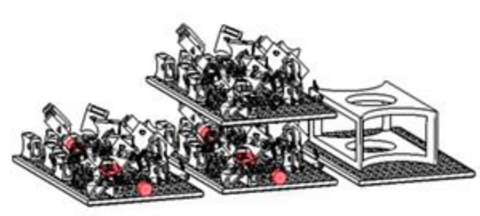

Figure 1: A figure showing the random orientation of many different castings which is the typical loading of a heat treatment batch.

The steel casting industry has utilized conservative practices in heat-treating in the austenite region. The rule of thumb was to heat the furnace to a temperature above 1400 F, and then maintain the furnace at this temperature for "1-hour-per-inch" based on the largest cross section thickness in the load. The author has not identified the exact origin of this rule, but it may have arisen as a way to cope with poor equipment design in the past that lead to non-uniform heating [Monroe 1984]. Although its beginnings are not known exactly, past research has identified this practice as troublesome and has attempted to eliminate its usage. In 1958, Briggs [Briggs 1958] conducted research with this purpose in mind. He stated that: "...after the information of this report is available to the purchasers of steel castings, the 1-hour-per-inch rule will be discarded from specification..." The application of this conservative practice continued in spite of Briggs' work as noted by additional work in 1981 to eliminate the practice. Patterson [Patterson 1981] investigated the mechanical properties of castings in shortened heat treatments. Based on his results, he concluded: "…that the information contained in this report will be an aid to the operators of foundries in their efforts to convince purchasers of steel castings that the 1-hour-per-inch rule is not metallurgically necessary." Although Patterson's report amply demonstrated that heat treatment times could be shortened without degradation of mechanical properties, the industry continued using its conservative practices as before. Voigt [Voigt 2004] noted the continued usage of the '1-hour-per-inch' rule in his 2004 work to develop heat treatment qualification procedures. He documented that: "While most steel foundries use 1-hour-per-inch guidelines to establish proper heat treatment time, the practice of this rule varies between foundries." His work did not attempt to eliminate the '1-hour-per-inch' rule but rather focused on standardizing the practices currently in place to ensure quality. For instance, Voigt [Voigt 2004] reported that many foundries use in-house standards or requirements as specified by the customers, which can vary based on the available standards. For example, ISO 683 recommends a soak time of one half hour for austenitizing once the casting has reached the appropriate temperature; whereas, ASM 2759 1c recommends soak times based on section thickness as shown in Figure 2. The Steel Heat Treatment Handbook [Totten 1997] mentions the current usage of the '1-hour-per-inch', but can only suggest other empirical methods that are furnace and load specific as solutions to replace the rule of thumb.

Thickness (1) Inches	Thickness (1) Millimeters	Minimum Soak Time (2), (3), (4), (5) Air or Atmosphere	Minimum Soak Time (2), (3), (4), (5) Salt
Up to 0.250	Up to 6.35	25 minutes	18 minutes
Over 0.250 to 0.500	Over 6.35 to 12.70	45 minutes	35 minutes
Over 0.500 to 1.000	Over 12.70 to 25.40	1 hour	40 minutes
Over 1.000 to 1.500	Over 25.40 to 38.10	1 hour 15 minutes	45 minutes
Over 1.500 to 2.000	Over 38.10 to 50.80	1 hour 30 minutes	50 minutes
Over 2.000 to 2.500	Over 50.80 to 63.50	1 hour 45 minutes	55 minutes
Over 2.500 to 3.000	Over 63.50 to 76.20	2 hours	1 hour
Over 3.000 to 3.500	Over 76.20 to 88.90	2 hours 15 minutes	1 hour 5 minutes
Over 3.500 to 4.000	Over 88.90 to 101.60	2 hours 30 minutes	1 hour 10 minutes
Over 4.000 to 4.500	Over 101.60 to 114.30	2 hours 45 minutes	1 hour 15 minutes
Over 4.500 to 5.000	Over 114.30 to 127.00	3 hours	1 hour 20 minutes
Over 5.000 to 8.000	Over 127.00 to 203.20	3 hours 30 minutes	1 hour 40 minutes
Over 8.000	Over 203.20	(6)	(7)

NOTES:

1. Thickness is the minimum dimension of the heaviest section of the part.
2. Soak time commences as specified in 3.4.2 as modified by 3.4.2.1.
3. In all cases, the parts shall be held for sufficient time to ensure that the center of the most massive area has reached temperature and the necessary transformation and diffusion have taken place.
4. Maximum soak time shall be twice the minimum specified, except for subcritical annealing.
5. Longer times may be necessary for parts with complex shapes or parts that do not heat uniformly.
6. 4 hours plus 30 minutes for every 3 inches (76 mm) or increment of 3 inches (76 mm) greater than 8 inches (203 mm).
7. 2 hours plus 20 minutes for every 3 inches (76 mm) or increment of 3 inches (76 mm) greater than 8 inches (203 mm).

Figure 2 Soak time for annealing, normalizing, and austenitizing based on section size in ASM 2759 1c5

The purpose of these standards is to ensure that each load receives sufficient heat treatment. The methodology used to qualify a treatment is generally based on some correlation to section size. Although the focus is on time, temperature, and section size, a quality heat treatment requires more than that. A review of what is occurring in austenitizing heat treatments is appropriate to understand why these conservative rules are in place.

The purpose of heat treatment is to modify the microstructure to obtain a wide variety of desired material properties without changing the chemical composition or shape [Monroe 1984]. There are many types of heat treatments that heat into the austenite region as a precursor to subsequent processing such as austenitizing**,** homogenizing, normalizing, annealing, and the heating prior to quenching**.** For carbon and low alloy steels, the castings are heated above 1340 F to obtain a uniform austenite grain size without coarsening, to attain a uniform structure, and to relieve internal stresses [Brooks 1979, Brooks 1992].

The change in material properties is possible because iron has different solid phase configurations. At high temperatures, it shifts from a body-centered cubic crystal (alpha ferrite) to a face-centered cubic crystal (gamma austenite). The process of shifting allows the solid to redistribute carbon and change its crystal size. Carbon interacts with iron by either dissolving into its crystal lattice or forming a hard, brittle compound called cementite or iron-carbide (Fe_3C). The concentration difference between each phase has the ability to redistribute carbon. The solubility of carbon in cementite is 25%, austenite is 2%, and ferrite is 0.025% [Brooks 1992]. By controlling the location and size of ferrite and cementite, the mechanical properties can be changed. Pearlite is bands of alternating ferrite and cementite.

Modifying the cooling rates from the austenite region alters the ferrite and cementite distribution. The key principle in the final microstructure is the rate of temperature change and its control on nucleation and grain growth [Brooks 1992]. Faster decreases in temperature generate more nucleation sites available for ferrite growth promoting finer microstructures and distributing the cementite more uniformly throughout the microstructure. Slower decreases in temperature promote ferrite grain growth and coarser microstructures. Thick layers of cementite are concentrated in locations surrounding the large ferrite crystals. Additionally, rapid temperature changes can trap the carbon in the ferrite phase to form martensite (body-center tetragonal crystal) [Brooks 1996].

This effort will focus on the soaking portion of the process in identifying its completion in preparation for subsequent cooling. The process strategy centers around four considerations: heat soak delays, soaking temperature uniformity, austenite formation, and carbide diffusion [Brooks 1992, Monroe 1984]. The process strategy suggested by this research can be broken down into two distinct phases: process soak and process hold as shown in Figure 3. The thermocouple measurement shown represents a single casting's temperature. Process soak, not to be confused with soak mentioned previously, is the time required to bring the entire casting to a steady state in temperature. Heat transfer mechanisms determine its length. Process hold is the time needed to fully austenitize and diffuse carbides in the casting once at an equilibrium temperature. Phase transformations and diffusion mechanisms control its duration.

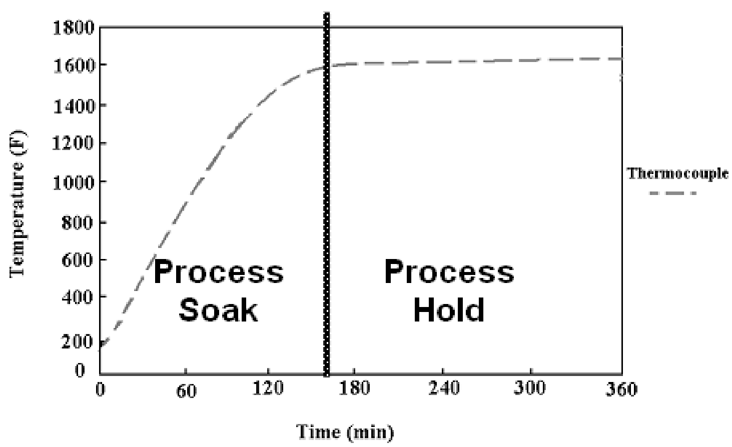

Figure 3 Time-temperature profile showing the soak and hold phases of the process strategy.

2.2 Semi-Automated Grinding

Grinding is used to create casting surfaces that comply with the customer requirements. The locations, size and shape of material removed from each casting are different even though they are made from the same pattern. In this type of material removal process, a conventional automatic system is often not feasible and the material removal is accomplished via tedious manual processing. Manual operations have the advantage of an intelligent operator and are very flexible; however, humans can also be prone to inconsistencies and lower efficiency. In addition, there are significant ergonomic issues associated with a human operator removing large amounts of metal via hand grinding.

Automated grinding operations have been implemented for some steel casting operations and more extensively in iron and aluminum casting operations. Advances have allowed these automated systems to rely on force feedback and other sensors to determine how much material needs to be removed from a particularl casting. However, in each of these solutions, the part has to be accurately fixtured and the areas that are to be ground need to be known a priori. The major limitations of these approaches for many steel casting operations is the need for fixturing which would be very difficult to justify based on the short runs of a wide range of parts. Furthermore, while there are the expected areas that are to be ground, many of the exact locations are not known until visualized by an operator. Specifically, this effort is focused on finding a solution for cleaning room problems that have the following characteristics which make it unique:

Unknown orientation: Customized fixturing for each casting cannot be justified because of the low volume and product diversity. Therefore, the orientation of each part varies.

Unknown locations: Because of the variability in the casting process, each casting is different and therefore the locations that need to be ground are unknown. This grinding is in addition to expected grinding such as removal of parting lines and riser contacts.

Unknown desired surface: The CAD drawing of the casting may exist, but since casting orientation is unknown the surface beneath an anomaly is unknown.

Unknown anomalies: The shape and size of anomalies are irregular and unpredictable due to variability in the metalcasting process.

Grinding robots and automated machines are widely used to grind the expected locations on medium and high volume castings. However, current automation solutions are not feasible for lower volume products. In order to grind different casting types, changes must be made to programs, fixtures, and possibly the machine itself. The steel casting industry produces a wide variety of lower volume products. It is not feasible to construct fixtures that would facilitate the use of robots to accommodate this product diversity. Therefore, an automatic material removal approach that is significantly different than the commercially available grinding robots is required.

A general material removal strategy must be able to deal with the unknowns listed above, and the machine should meet the following requirements:

Flexible: The system shall not require any software or hardware changes for different types or sizes of objects or a different surface.

Autonomous: Other than a few initial inputs, the machine should be able to operate independently without human input and control. An appropriate path and force should be calculated and real-time adjustments be made according to the initial input and feedback.

Consistent quality: Resultant castings need to consistently have a surface without discontinuities.

The system developed to meet these system constraints is described in the discussion below.

2.3 Surface Mapping Software

Inspection of steel castings is routinely performed to insure the quality of castings and identify any areas that need to be reworked in order to satisfy customer requirements. Numerous inspection techniques including ultrasonic, radiographic, and visual inspection are used to identify specific surface and near-surface regions that exhibit flaws [Blair 1995]. Common flaws (which are referred to here as anomalies) such as hot tears, porosity, and inclusions, significantly increase production costs and manufacturing lead time [Carlson 2002, Sigl 2003, Lin 2009]. Typical data collection procedures for inspection use paper forms to record the locations of different types of anomalies by drawing the approximate location of an anomaly on a simple 2D outline of the casting. These forms usually end up in a file cabinet, often to be forgotten. While this type of data has great potential in contributing to continuous improvement efforts in the steel casting process, the processing of the data is problematic, making it virtually impossible to mine the data for meaningful analyses.

Accurate assessment of steel casting quality is an essential component of an effective continuous improvement program in metalcasting operations. Undesirable results of the casting process (such as porosity, sand, or cracks) require additional processing that increases order fulfillment time and unit cost. A more proactive approach in which data on surface anomalies are collected and analyzed to identify root causes is described here. The data collected include the geometric region where the anomaly occurs and specific casting and inspection identifiers such as pattern cavity, shift, heat code and inspection date. Surface

Mapping Software for mapping, tracking, and analyzing surface anomalies using a simple markup tool that an inspector can use to draw on a 3D representation of the casting has been developed. The system is based on the DirectX engine that is used to display and interact with STL models of the casting. The data are stored in a relational database (MySQL) which can be configured by the user. A frequency map is used to calculate the intensity of anomalies on the surface of a casting based on specific search criteria. Specifically, the work in this project is to develop and improve upon a system original proposed by von Busch [von Busch 2008].

2.4 Study of Impact of Repairs via Weld Gouges

Recent research on cleaning room variability revealed a common practice at several foundries where small surface defects (porosity and inclusions) are gouged out using arc air, creating a much larger volume that must be filled with weld metal. Further investigation revealed three general reasons for this practice. The first was to investigate how far the defect continues below the surface of the casting. The second explanation was that the operators are unable to gouge smaller holes with their equipment. A third explanation was that a small weld repair would result in an area of unacceptably high hardness. Current research at the University of Alabama-Birmingham is addressing the first issue by researching the effectiveness of non-destructive evaluation (NDE) to determine what lies beneath a surface anomaly. If the second reason is valid, then better equipment needs to be used to eliminate this practice. This effort will investigate the third potential explanation.

This experiment investigated the metallurgical effect that is caused by different size welds on common steel casting alloys with various initial heat treatments, and with and without the use of post weld stress relief. Little published information on this subject could be found. Potential savings from reducing processing times and material usage could exist. Furthermore, it might be better to leave a surface anomaly than potentially cause metallurgical damage by repairing it via welding.

The proposed study investigated which variables had a significant effect on the microstructure and resulting hardness of the weld pool, heat affected zone, and base metal of the repaired casting. Experiments were conducted where various size weld cavities were created and filled with weld metal. The cross-section of the weld was then analyzed including microhardness tests in the weld pool, heat affected zone, and base metal. The welding samples were made at two steel foundries and the testing was done at Iowa State University.

2.5 Rapid Pattern Making Machine

A common method of making metalcastings is to start with a pattern, roughly the shape of the final component, which is used to make a sand mold, which in turn creates the cast component. The time and cost to produce a pattern is often high, which significantly limits the responsiveness of the metalcasting process to respond to new market needs or process changes.

There are a host of rapid prototyping methods available, but these methods are generally not applicable for producing a pattern approaching the meter scale because of the time, costs and durability of the available materials. This effort focused on a hybrid system which conventional material removal processes (CNC routing) coupled with a software system that decomposed the solid model of the pattern into layers for which the process planning could be done automatically, with no human intervention.

3. Results and Discussion

This section is organized to provide the results of the five different areas studied.

3.1 Heat Treatment Control Strategies

The heat treatment process can be broken into three stages: ramp, soak, and hold.

- Ramp: the time needed for the controller thermocouple to reach the set point temperature specified by the operator.
- Soak: the time after the set point temperature is reached, but energy continues to be introduced into the load to increase its temperature.
- Hold: begins when the coldest location in the load reaches an equilibrium temperature. Its duration is dependent on the operational practices, which dictate the length of the heat treatment process.

These stages are shown in Figure 4. Note that the ramp stage is determined by the controller thermocouple that traditionally is placed in the roof (or other location) of the furnace and measures the furnace environment temperature and not the temperature of the load itself. In Figure 4, there are several lines representative of thermocouples in the load. The soak ends when each of these reaches an equilibrium temperature. Except for some special cases, this information on the load temperature is not known, so the actual end of soak cannot be determined. Typically in practice, a prescribed combined soak/hold time commences once the ramp step is complete. A common practice is to prescribe one hour of soak/hold time per inch of the maximum casting section thickness [Totten 1997].

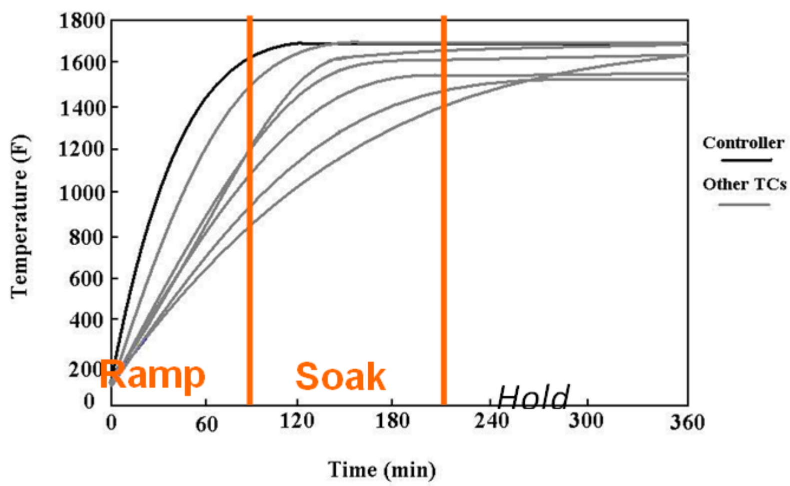

Figure 4 Time versus temperature of a representative heat treatment process to illustrate the ramp, soak and hold periods.

A major thrust of this effort is to develop a better system to collect information useful in determining the actual start and stop of each stage using alternative information rather than relying solely on the furnace air temperature.

One of the main reasons for the heat treatment cycle for carbon and low alloy steels is to allow the steel to transform to austenite. The extent of austenitization is time and temperature dependent (Table 1.) Patterson and Bates [Patterson 1981] identified the time required for various grades of steels to complete austenitization. Their studies demonstrate that the transition from ferrite to austenite is relatively fast once the critical temperature has been reached. This implies that the heat treatment process could stop soon after it was determined that the load has reached temperature.

Table 1 Time required (minutes) versus temperature (°F) for complete austenitization of three alloys. [Patterson 1981]

Temperature (°F)	Plain Carbon	1.3 Mn-0.25 Mo	2.4 Cr-0.95 Mo
1650	<17	2	17-30
1700	<17	<2	<17
1800	2	<2	2
1900	<2	<2	<2

Another purpose of the heat treatment process is to diffuse carbides resulting from segregation during solidification. While homogenization across the entire casting length is practically infeasible, isolated homogenization of carbides across dendrites is possible. Varkey and Voigt [Varkey 2001] showed that the required holding times are less than those used in the current conservative practices.

Figure 5 illustrates a generic austenitizing heat treatment control strategy employed by many steel foundries. The cold load is heated until the furnace set point temperature is reached, at which time a holding period commences. In actuality, this holding period is a combination of the soak and hold times previously defined. A common method of determining the length of this soak/hold time is based on the maximum casting section size in the load, such as 1 hour per inch. Some foundries have shortened the soak/hold time based on past knowledge or based on experiments that they have conducted to determine the amount of time to reach austenization in their furnace for a particular section size.

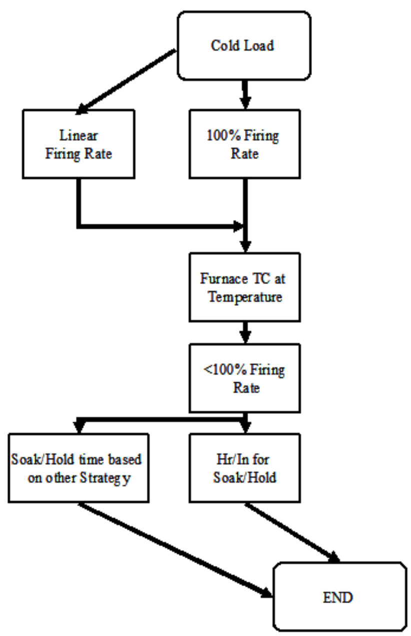

Figure 5 Typical heat treatment control strategy

Figure 6 represents one of the proposed process changes in which this project is working to justify. Instead of relying on an air thermocouple to control the ramp cycle, a thermocouple embedded in a thin casting section comparable to the smallest section in the load is used. This embedded thermocouple will be referred to as being in a 'hot' location, relative to the remainder of the load. Given that the same set point temperature is used, this strategy would cause the furnace to reach a higher temperature since there would be a delay in heating the center of the casting in which the thermocouple is embedded. This higher furnace temperature will drive heat into the load quicker. This change will increase the ramp stage; however, it will reduce the total cycle time and energy required. This improvement was tested and reported earlier [Harwood 2005]. A concern is that the castings could be damaged if the furnace is driven to a higher temperature. However, an actual temperature profile experienced by a thin casting is being utilized in this strategy to alleviate this concern.

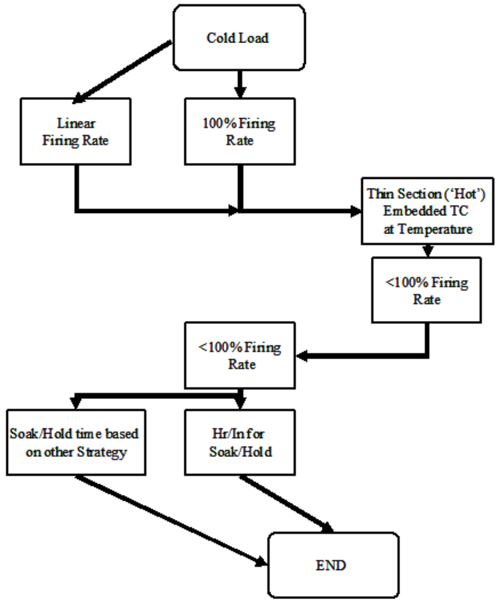

Figure 6 Control strategy using an embedded thermocouple in a thin 'hot' section to control ramp stage

Another proposed change is to use thermocouples embedded in thick sections, comparable to the largest sections within the load. These embedded thermocouples, referred to as being a 'cold' location will then supply the data to determine when the load reaches the desired temperature. This is represented in Figure 7. This would eliminate the use of prescribed soak/hold times, which start when the air thermocouple reaches temperature. This direct reading of 'cold' locations should save time and energy because it eliminates the conservative practices. This method would be beneficial in that it assures that a 'cold' location actually reaches the required process temperatures. One obvious concern is that the embedded thermocouple may not be in the coldest location of the load. Additional experiments were conducted this year by having more than one embedded thermocouples in potential cold locations. Embedded thermocouples in multiple potential 'cold' locations provide a much higher probability of assessing the true 'cold' location. This data will be presented below.

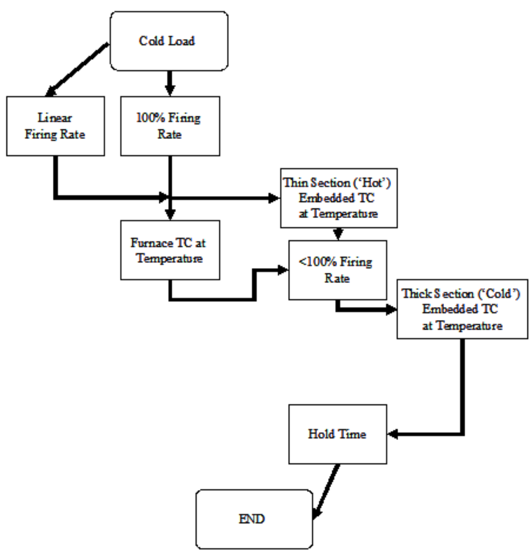

Figure 7 Heat treatment control strategy using an embedded thermocouple in a thick 'cold' section to determine end of ramp/soak.

One control option, which was initially presented in [Harwood 2006], is shown in Figure 8 This method does not rely on the temperature of the load, but rather the gas flow rate, or firing rate, needed to maintain the set point temperature. Theoretically, during an uncontrolled ramp the firing rate is 100 percent, but once the control thermocouple reaches the set point the firing rate drops to an equilibrium value. At this point, the constant firing rate is only being used to maintain the furnace temperature, with no change in load temperature. While this information indicates that the load is at equilibrium temperature, it does not indicate the value of the minimum temperature. However, this is no worse than the common method depicted in Figure 4 where the minimum load temperature is also not known. Additional data were collected, and will be presented below, to support this control strategy.

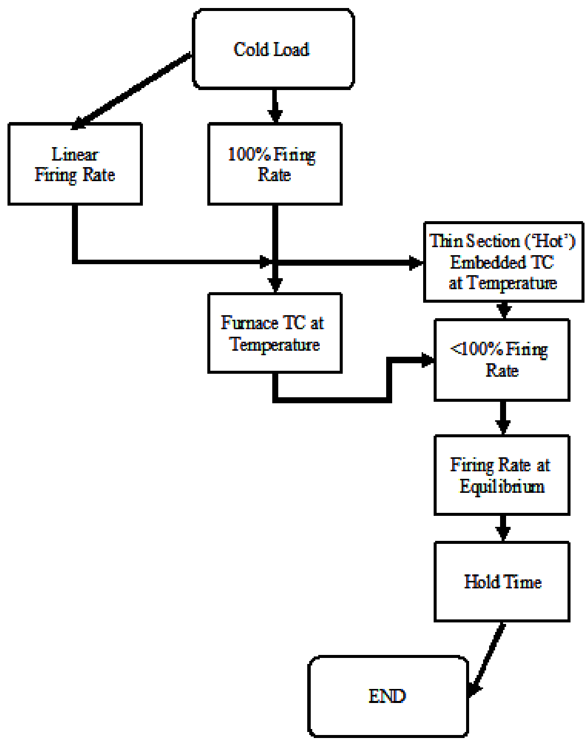

Figure 8 Heat treatment control strategy using the firing rate signal to determine end of ramp/soak.

To understand the response of the load once ramp is complete, time-temperature profiles were collected at four industrial partners for twenty-two heat treatment loads. The loads contained castings of various section thicknesses with embedded thermocouples to record the actual casting temperatures. The analysis presented here examines the variability in soak times after ramp completion for various section sizes. As mentioned earlier, conservative practices are designed to accommodate temperature variations in the load. However, after examining the maximum amount of soak time needed for various section sizes from the instrumented loads, justification for these rules is undermined [Harwood 2006].

Data was collected from steel castings with embedded thermocouples with section sizes up to eight inches. Furnace sizes ranged from a 15x11x11-ft car bottom furnace to a 10x10x2-ft front-loading furnace. A total of 174 thermocouple readings are shown in Figure 9. In order to make a comparison among loads with different controller set point temperatures, this figure plots the temperature attained as a percentage of the load's set point temperature. The plot shows the time required to achieve a particular percentage of the set point temperature. The time is measured from the end of the ramp stage. At time zero, the controller (but not necessarily the castings) has reached the set point temperature, which indicates the start of the soak/hold stage. The 92% of set point temperature value is of particular interest because it corresponds to a minimum temperature of 1500°F for all loads, meeting the minimum requirement for austenization and carbide diffusion. Within two hours, 96% of the thermocouple readings reached 92% of their set point temperatures. Those loads taking more than two hours were densely packed or had noted problems with the furnace maintenance. Furthermore, 85% of the measured values reached 92% of set point temperature in under an hour.

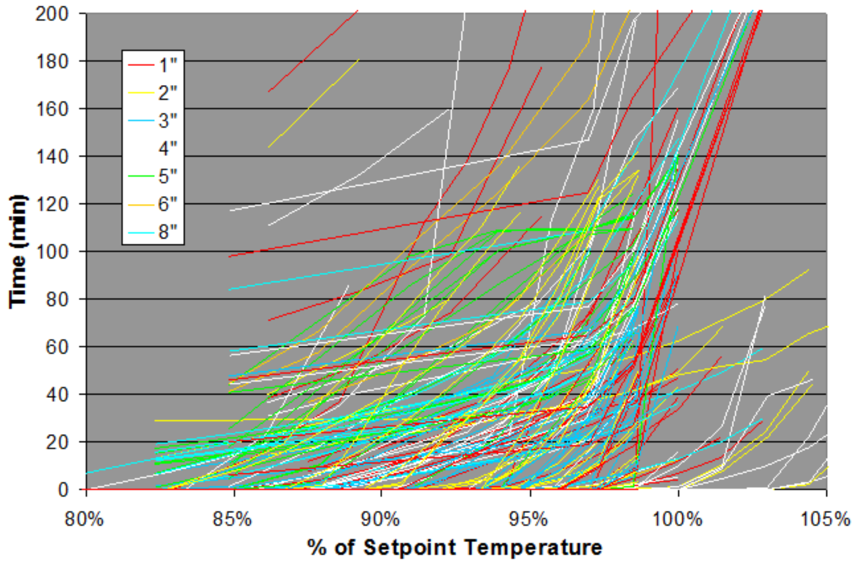

Figure 9 Instrumented load data comparing the time delay after completion of ramp to the % of the set point temperatures.

The time to reach temperatures above 92% of the set point temperature increased dramatically, signifying that the temperature is approaching equilibrium. No strong patterns were identified between section size and time to reach a percentage of the set point temperature as the 'hour-per-inch' rule uses. This data helps support the claim that the 'hr-per-inch' rule is too conservative.

Table 2 presents the data from Figure 9 in an alternative format. The data was compared to the specified 'hour-per-inch' time for each section size. For example, the soak time for all 2" data was normalized over 2 hours. For the "% of set point" temperatures chosen (left column), the number of readings which achieved this temperature is shown in the second column. Of the readings accounted for in the second column, the fraction of the hr/inch rule needed to achieve that "% of set point" temperature is shown on the right side of the table. For instance, 173 of 174 measurements reached 92% of the set point temperature. Of these 173 measurements, 94% of them reached 92% of the set point temperature within 50% of the time specified by the hr/inch rule.

Table 2 Percentage of trials which achieve a % of the set point temperature in a given fraction of the time prescribed by the hr/inch rule.

% of Set Point Temp	# of Readings	Fraction of Hr/inch Rule Used					
		25%	50%	75%	100%	150%	200%
85%	174	93%	97%	97%	98%	99%	99%
90%	173	88%	95%	97%	98%	99%	100%
* 92%	173	82%	94%	97%	98%	98%	99%
95%	167	70%	91%	96%	97%	98%	98%
100%	79	41%	62%	78%	81%	89%	95%
105%	28	46%	57%	68%	75%	79%	79%

This shows the difficulty in the load achieving the set point temperature. Specifically, only 79 out of 174 readings (45%) ever reached 100% of the set point temperature. Of those that did reach the set point temperature, only 81% were able to reach that temperature in less than the full time specified by the '1-hour-per-inch' rule. This suggests that it is infeasible to expect a load to actually reach the set point temperature. It would be more realistic for industry to expect the load to reach temperatures of 95% of the set point temperature. In this data set, 167 out of 174 readings attained this value. Of these 167 values, 91% attained the set point temperature in half of the time specified by the hr/in rule. Since there is less temperature difference as the castings approach the set point temperature, a higher set point temperature would heat the castings quicker.

Additional field studies were conducted at two steel casting producers to gather evidence to support the proposed changes to heat treatment control strategies. At each location, embedded thermocouples were used to record the temperature of representative castings within the load. Test blocks were chosen of similar size to the production castings being heat treated. Each test block had ¼ inch holes drilled to the center. Type K Thermocouple wire was inserted into these holes and packed with furnace blanket. At Foundry A, thermocouples were connected to a chart recorder and measurements were sampled every ten minutes. Foundry B thermocouples were connected to thermocouple data loggers, which sampled every minute during the heat cycles.

Firing rate data was collected using data loggers, which had a 4-20mA signal range, as shown in Figure 10. The loggers were connected, in series, between the furnace controller and the gas valve and sampled every 10 seconds. These loggers were relatively inexpensive, priced under $100.

Figure 10 Data logger, with USB port for easy download of firing rate data.

At Foundry A, the castings being heat treated were between 500 and 2000 pounds, with section sizes ranging from two to eight inches. Foundry A's furnace is a rail car bottom of 20x12x12-ft with a platform where castings are stacked. The furnace has gas-fired burners controlled in three, equally sized zones. Each zone has a control thermocouple and controller. Figure 11 shows a generalized illustration of the production casting load and the placement of the instrumented test blocks. The test blocks, with a length and width of 36 and 12 inches, respectively, were instrumented with embedded thermocouples in the five and eight inch sections.

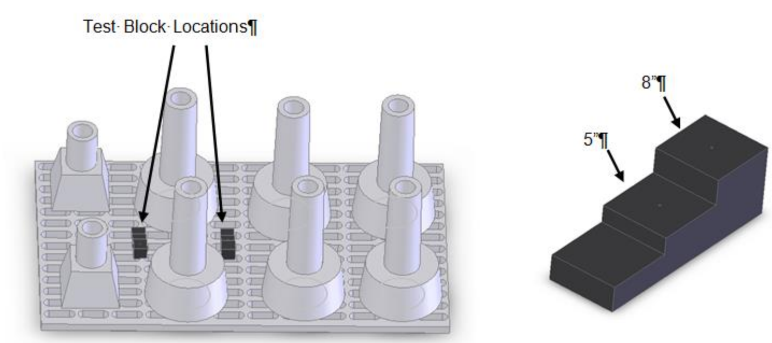

Figure 11 Generalized illustration of the heat treatment loads measured at Foundry A and the geometry of the instrumented test blocks.

At Foundry A, data collection was conducted on the heating cycle for two quench loads. Figure 12 and Figure 13 plot the temperature of the embedded thermocouples along with the firing rate for two of the three zones. (There was a data collection error for the third zone.) These figures show a drop in the firing rate (heat input) as the control thermocouple reaches the set point. Even though the entire load has not reached the set point, the heat input into the system and the rate at heat is driven into the load decreases. This is based on the prescribed heat treatment control strategy which relies on the control thermocouple which measures the furnace environment.

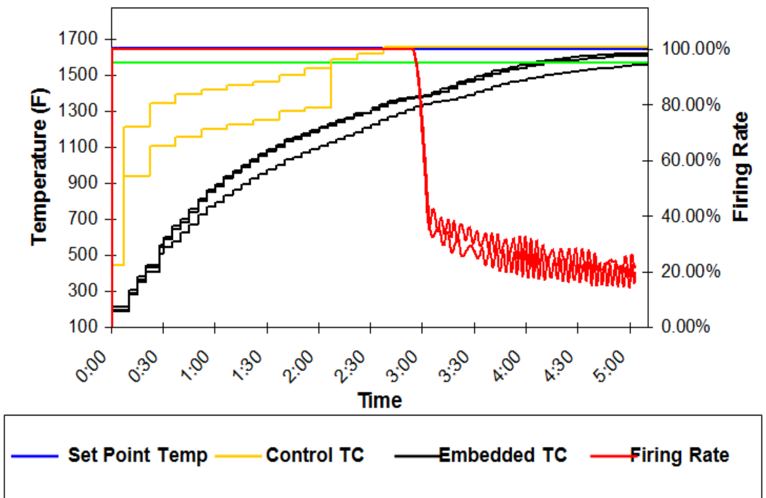

Figure 12 The temperature of the control thermocouple and in the embedded casting sections and the firing rate during the heating cycle of quench & temper trial A2.

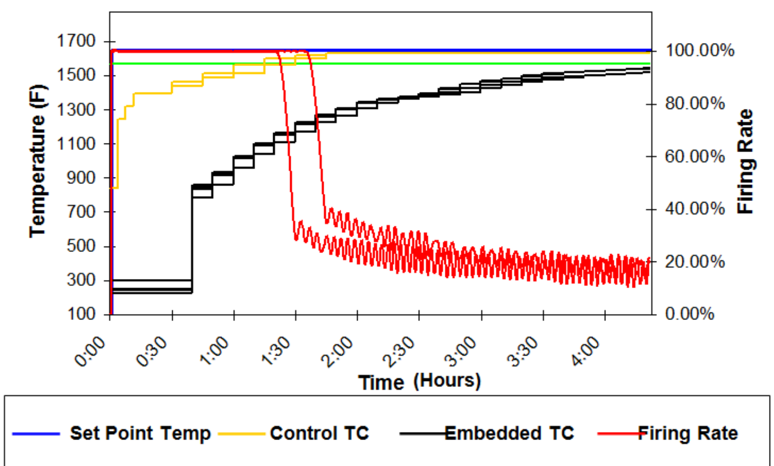

Figure 13 The temperature of the control thermocouple and in the embedded casting sections and the firing rate during the heating cycle of quench and temper trial A1.

Foundry B's production castings range from 10 to 1000 pounds, with section sizes of one to eight inches. The furnace has a rail car size of 15x11x11-ft, upon which skids of castings are loaded. The furnaces have one control thermocouple and controller, and a forced air system to move heated air through the load. The skids, of size 6x4-ft, are typically piled with small castings. Five to six thermocouples were deployed in each of the loads investigated. Two kinds of test blocks were used that had three and five inch sections. These test blocks were loaded on the bottom of the production castings to be treated.

Two normalizing loads on different furnaces were instrumented at Foundry B. Furnace loading configurations that were instrumented are illustrated in Figure 14. For trial B1, there are five skids of small castings with a total weight of 8000 pounds. Trial B2 has three skids of small castings and one 2800 pound casting for a total weight of 9000 pounds. The location of test blocks in trial B1 were farther apart than trial B2.

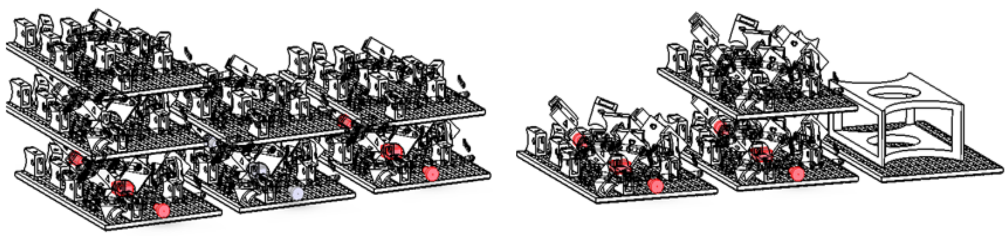

Figure 14 Illustration of the heat treatment loads at Foundry B. Trial B1 on the left and B2 on the right. Positions of the instrumented blocks are shown in red.

Figure 15 shows the temperature and firing rate for B1. Interestingly, when the control thermocouple reaches its set point causing the firing rate to drop, three of the six embedded thermocouples are already above the set point temperature. The thermocouples with the lower readings are all on the bottom skid with two skids above it. The skid with higher temperature reading only has one single skid stacked on top, and is located on the edge of the rail car. More castings surround the lower temperature skid and soak up more heat, causing the lower temperatures. When the firing rate drops, energy from the higher temperature area slowly transfers to the lower temperature area within the load during the soak phase. Figure 15 shows that the temperatures measured by the embedded thermocouples are equalizing.

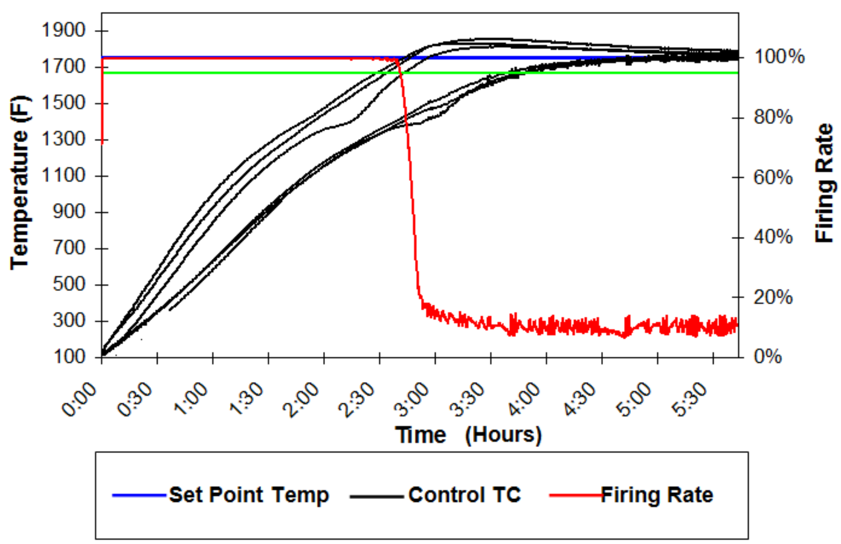

Figure 15 The temperature in embedded casting sections and the firing rate during the heating cycle of normalizing heat treatment, trial B1.

Figure 16 shows that in trial B2 temperature uniformity is greater and all test blocks rise above set point by the end of the cycle. Despite a greater load weight in trial B2, overall cycle time for B2 is shorter than B1. There are two possible explanations for this. First, the load in trial B1 is more densely packed. The results of trial B2 may demonstrate that uniform positioning of castings in a load may yield shorter cycle times, due to more flow of heat to the load and heat having less distance to penetrate at any point in the load. These differences based on loading would support the need for instrumented loads. Secondly, as noted previously, the test blocks in trial B2 were positioned closer together, which could explain why temperatures were more uniform in trial B2.

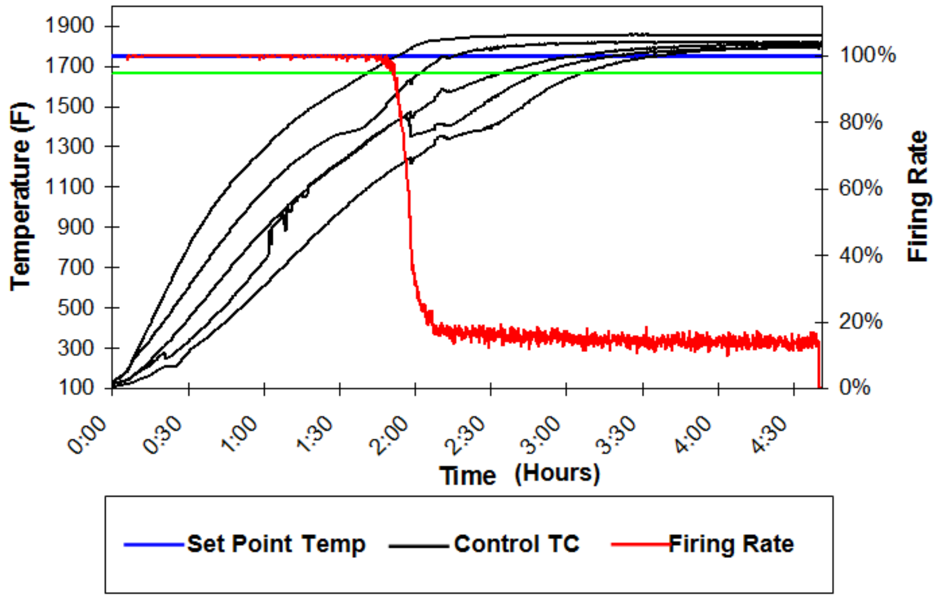

Figure 16 The temperature in embedded casting sections and the firing rate during the heating cycle of trial B2.

Also at Foundry B, one tempering load was recorded. An illustration of the loading is shown in Figure 17 and the results are shown in Figure 18. This load was instrumented with six embedded thermocouples; two in five inch sections and four in three inch sections. The results show one thermocouple, embedded in a five inch test block section, consistently reading a lower temperature than the other five test blocks. This test block was in the bottom, center position of the load. In addition, because of the loads lower set point (1285 °F) heat transfer is dependent of convection through air circulation. Unlike the quench and temper loads at Foundry A, the density of packing in this load inhibits airflow to the center of the load, where the low temperature thermocouple is located. The occurrence of a lower temperature throughout the load could be attributed to the larger section size of five inches, when compared to the other three inch section test blocks. However, after reviewing load conditions and the results, the lower temperature is probably due to the density of the load packing. This is especially evident when considering another test block located elsewhere in the load maintains a temperature very similar to the three inch test blocks.

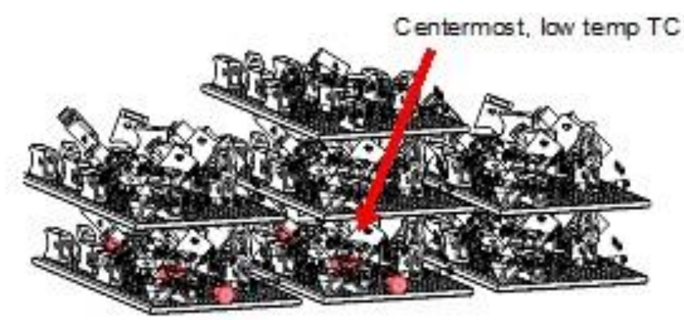

Figure 17 Illustration of loading and placement test blocks for trail B3.

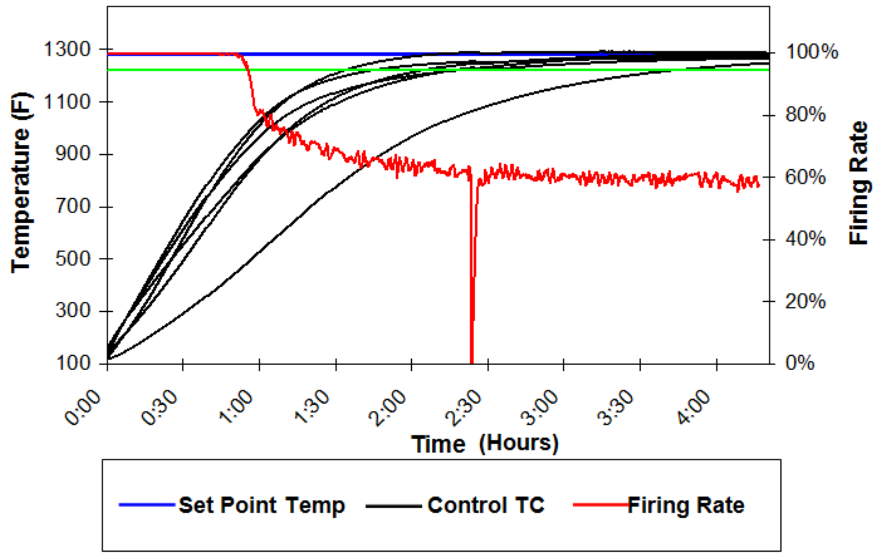

Figure 18 The temperature in embedded casting sections and the firing rate during tempering, trial B3.

Thermocouple wires connected to data loggers were used for data collection during these trials. While it was successful, the use of thermocouple wire for ongoing instrumentation of production loads would be impractical. The wire is expensive, subject to breakage, and difficult to manage when loads are moved in and out of the furnace. As an alternative, a wireless thermocouple device was also used, with successful results. In this application, the thermocouple wire only needs to run from inside the load to the exterior of the furnace environment to the transmitter. The signal is then relayed to a receiver. One permanent option for using this device is to mount the transmitter on the bottom exterior of the car bottom (of a car bottom furnace) as shown in Figure 19. The signal can then be easily transmitted, without dragging wires.

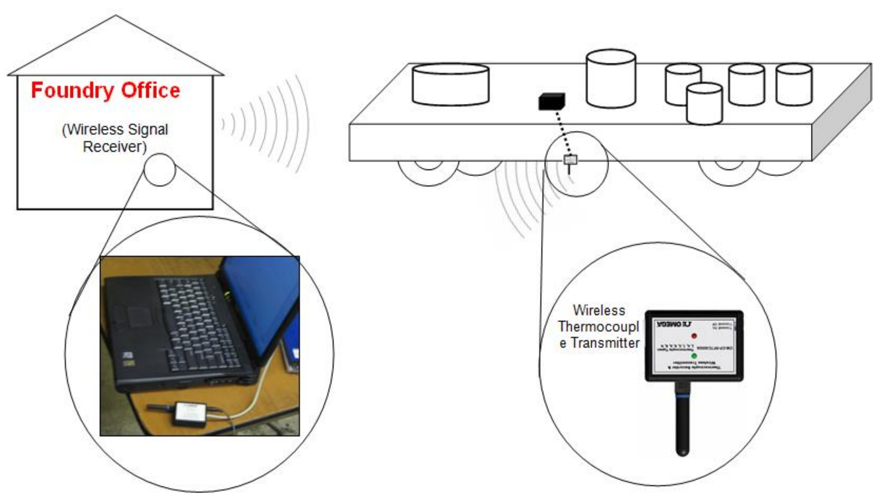

Figure 19 Illustration of using a thermocouple located on a car bottom furnace, attached to a wireless transmitter under the car that transmits temperature data to a computer located in the foundry office.

Wireless thermocouple data loggers open the door for designing systems with permanent test blocks in every heat treatment load and the data used for real time control. The transmitter's small size (0.8 x 1.7 x 2.7") allows it to fit most anywhere. It can withstand temperatures to 158°F and has a stated range of 120 feet, line of sight. The software and hardware can be obtained for under $450.

Controlling heat treatment operations with real time data still appears to be promising. Current strategies rely on empirical rules, which are conservative, but still do not ensure that the castings actually attain the desired temperatures.

Determining that the load is at equilibrium by monitoring the firing rate would be beneficial since this data is easy to collect. Work is continuing on the analysis of the firing rate signal to determine when the load is at equilibrium and to show that is a viable signal for process control.

Future case studies will integrate the use of an embedded thermocouple in a thin section (hot location) to control the ramp duration with the use of embedded thermocouples in thick sections (cold locations) to determine the end of soak/hold. There was a limited use of a 'hot' section thermocouple reported previously [Harwood 2005]. However, there has not been a full scale implementation of using both 'hot' and 'cold' thermocouples to control a heat treatment load. Multiple 'cold' location thermocouples will help ensure that the coldest location is actually recorded.

Future trials will continue to use the wireless thermocouple system to further demonstrate its effectiveness in a steel casting production environment, eliminating the need for expensive and hard to maintain thermocouple wires.

3.2 Semi-Automated Grinding

This section presents an overview of a semi-automated grinding system. The grinder will process any casting surface visible from above. The grinder will be the same as or similar to hand grinders currently used in the steel casting industry but guided by a machine rather than an operator. The grinder is mounted on a three-axis apparatus that will provide movement in the X, Y and Z directions. To allow additional access to castings, the grinder rotates about the Z (vertical) axis in the setup stage, but not as a controlled axis during the grinding operation.

To accommodate automated grinding, a compliance mechanism is incorporated that attaches to the tool to prevent potential tool damage caused by large cutting forces, while maintaining cutting efficiency. A simple design of a suspension system that satisfies this requirement is illustrated in Figure 20. When the grinding wheel plunges into anomalies requiring excessive material removal, the spring compresses and the grinder rises to reduce cutting force. Also, when needed, the spring is used to increase cutting force on the part. The deformation of the spring can keep the grinder working on the anomaly most of the time. An alternative option is a rigid system with a force sensor, but the system may not be quick enough to respond to a high force condition.

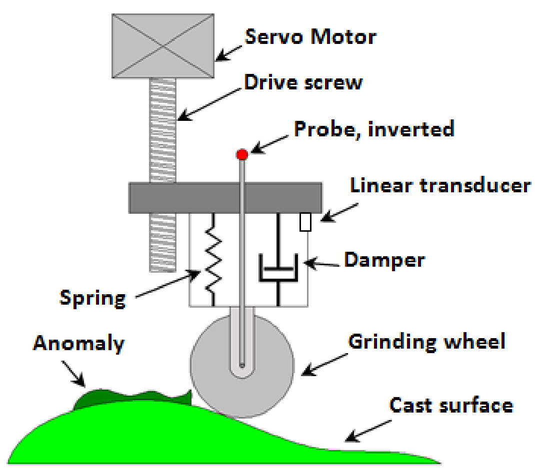

Figure 20 Suspension system to allow grinder to traverse obstructions

The angle between the grinding wheel axis and the part will affect the surface finishing result. This angle is shown in Figure 21. It is not trivial to calculate the optimal angle, even if the CAD model of the casting is given and the orientation of the casting is known. In an automated system with limited inputs, allowing this angle to change during grinding would be difficult. Therefore, once the part is fixtured in the system, a rotation angle, θ, of the grinding wheel axis is not changed.

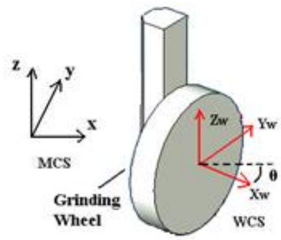

Figure 21 The grinding wheel show the rotation angle θ that is fixed during a grinding cycle.

In the prototype system, the user enters critical information and the system autonomously works to remove anomalies in designated areas. The following is a description of the information required of the user. Grinding locations can vary for each casting, so they are marked manually. Points need to be sampled from the part surface to generate an approximation of the desired surface, designated as a set of boundary points $\{b_i\}$. Another set of boundary points $\{s_i\}$ is used to indicate the area where good surface points can be sampled to create an approximated surface beneath anomalies, shown in Figure 22. The reference points are points sampled on the smooth (good) surface of the casting within the sampling area defined by *(S-B)* outside the anomaly area.

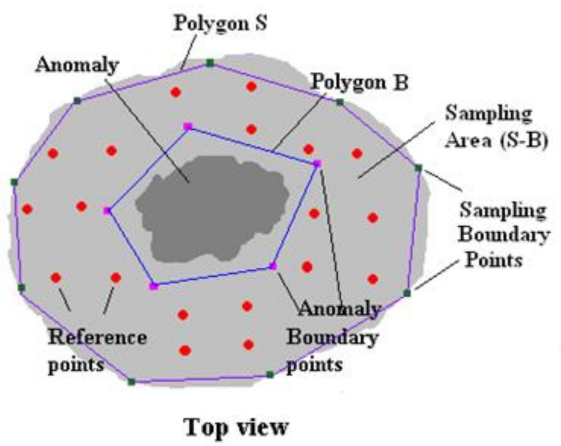

Figure 22 Anomaly boundary points, sampling boundary points and reference points

The approximated surface can be derived from the reference points to the entirety of the containment boundary B defined by the boundary points. For planar surfaces, the approximated plane within the anomaly boundary can be calculated from an equation defined by three nonlinear points located anywhere on the surface. For non-planar surfaces, surface approximation methods usually can only calculate the surface points within the convex hull of the sampled points. For this research, geometries are limited to the following surface patches: planar surface patch, concave surface patch, convex surface patch and saddle surface patch, Figure 23.

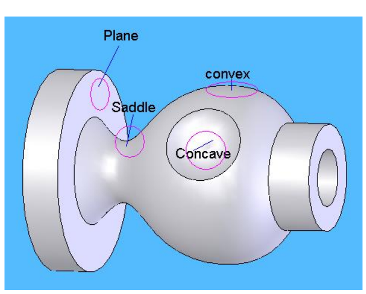

Figure 23 Simple surface patches that can be accommodated in this system.

It is not practical to determine shape and size of anomalies because anomaly shape is usually unrelated to desired part surface beneath anomalies. The system must be able to automatically handle any anomaly, no matter its size or shape.

The automatic material removal procedure is illustrated in Figure 24. Initially, the operator provides several inputs to the system: 1) the rotation angle θ of the grinder, 2) the desired surface type (planar, straight swept, or free-form), 3) a set of anomaly boundary points, and 4) a set of sampling boundary points. At this point, the remainder of the operation is automated by the computer control system. First, reference points are sampled automatically on the good surface within the sampling area defined by anomaly and sampling boundaries. Next, an approximated surface (approximation of the desired surface) in the anomaly area is constructed from reference points.

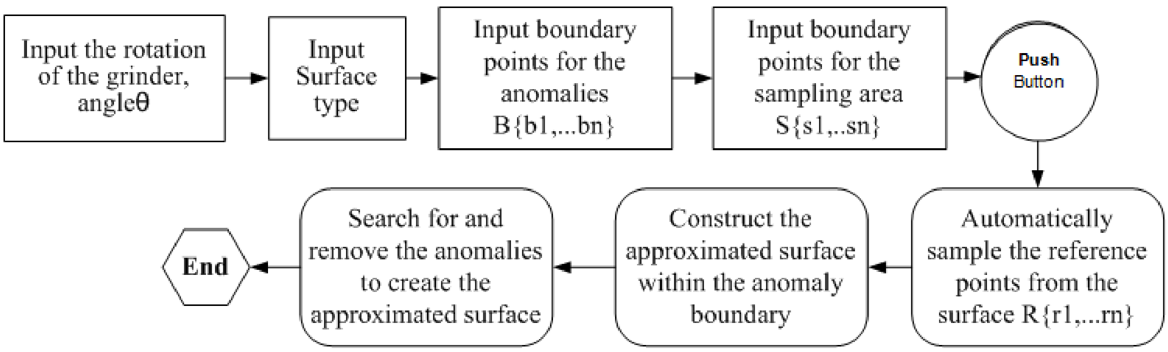

Figure 24 The automatic material removal procedure

Generally speaking, more complicated surfaces require more data points. The goal is to have a simple and feasible method that can easily be implemented in an automatic system. Since it is not feasible to have an automated system that can handle any surface, this work is limited to some common surface types: planar surface patches, straight swept surface patches, and simple free-form surface patches. Straight swept surface patches are created by sweeping a section curve along a straight line. Surface patches other than planar and straight swept surface patches are considered free-form surface patches. There are three simple free-form surface patches considered here: concave surface patch, convex surface patch, and saddle surface patch, Figure 25.

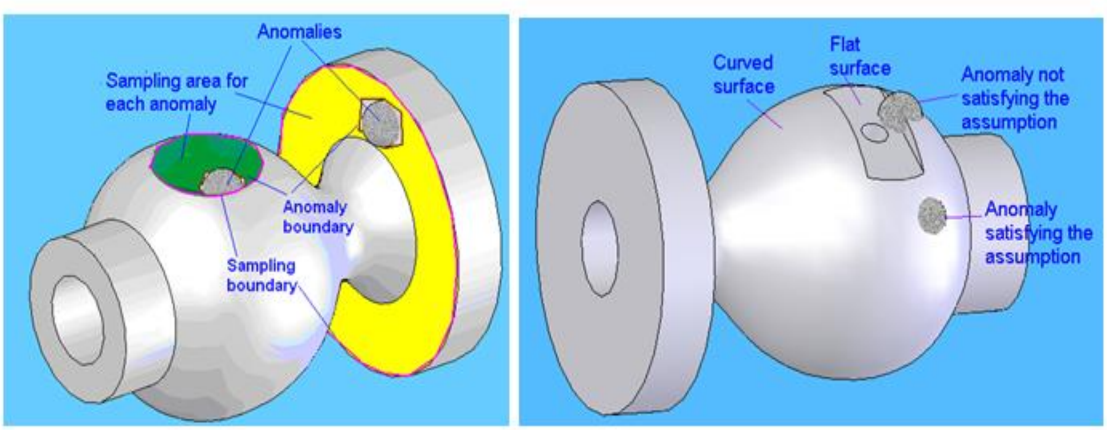

Figure 25 Example of anomaly sampling areas and location a) sampling areas and boundaries for two example anomalies; (b) acceptable and unacceptable anomaly locations

The point sampling strategy includes two main parts:

1) How many points to sample on a certain surface
2) Where to sample these points.

Simulations were conducted to search for possible sampling patterns. A desired surface was formed by mathematical equations and simulated measurement variation of ±0.005 inches was added to the desired points when they were sampled. The following sections describe three methods suited for planes, swept surfaces, and some free form surfaces.

Planes: It is known that to define a plane three points are needed and should be spread away from each other to reduce the impact of measurement error. However, in this system it is not necessarily possible to sample points spread far apart, so tests were done to determine the results of randomly sampled points. A designated number of points were sampled on the surface within a rectangular area of 5 by 4 inches. A random measurement error within ±0.005 inches was added to each sampled data point. This showed that although three non-collinear points can define a surface, if not sampled properly they may cause excessive error. Three data points that were spread 2 to 2.67 inches apart gave results close to random sampling with four data points. But since it cannot be guaranteed that the sampling area is large enough, a simpler recommendation is to randomly sample at least four points on the plane.

Straight swept surface: A straight swept surface is constructed by sweeping a curve along a line. Straight swept surfaces can be approximated given the line and a section of the curve perpendicular to the line. To determine the impact of the measurement error, experiments were done to test how many points provide a good fit for a line by the least square distance method. Results show that points need to be spread apart if only two are sampled. If sampled randomly, three points will give a much better result. For simplification, the system will choose the longest line segment of the designated line direction in the sampling area and sample three points at the middle and ends.

Simple Free-form surfaces: An algorithm, Wang [Wang 2007] was developed to determine how many points need to be selected to represent the free-form surfaces. Points are selected on sets of curves that are perpendicular to each other, and traverse the surface. Once the operator inputs the points that define both the surface sampling boundary and the boundary of the anomaly to be removed, the system automatically determines how many sampling points and a sampling pattern in order to approximate the desired surface after grinding.

1) Planar surfaces:
   - The operator inputs boundary points and designates it as a planar surface.
   - The automatic system checks the anomaly boundary points.
   - If the number of anomaly boundary points >= 4 no more points will be sampled orelse the operator will be required to sample more points on the surface.
   - A least square method is used to fit a plane through the anomaly boundary points and additional points, if any.

2) Straight swept surfaces:
   - An operator inputs the following information:
     - Direction of the line when projected to the x-y plane
     - Anomaly boundary points
     - Sampling boundary points
   - The automatic system will sample based on the above information.

3) Simple free-form surface
   - An operator will input surface type, anomaly boundary points and sampling boundary points.
   - The system will create the smallest rectangle containing the anomaly boundary. Sides of this rectangle are parallel to the x or y axes in the working coordinate system.
   - Based on size of the rectangle, the system will determine how many equally spaced curves need to be created along each side.
   - For each curve, four points are sampled, two on each side of the anomaly, one of which is close to the anomaly boundary and the other close to the sampling boundary.

In the cleaning room, overgrinding must be avoided. As long as the ground surface is smooth and within the tolerance zone, a positive volume difference between the ground surface and the desired surface is acceptable (more can always be removed in a post-processing step). Thus, the approximated surface should be no lower (in the z-axis of the machine coordinates) than the desired surface. This can be achieved by shifting the approximated surface in the z direction for a specified distance.

For planar surfaces, there should be no shift distance because three non-linear points will define a plane. But with measurement error, the approximated plane could be under the desired plane. Worst case is that all samples points contain maximum negative error, so a safe shift distance would be the absolute value of the accuracy of the sampling device.

Path planning is very important in automatic material removal processes. In most of the common material removal processes such as CNC machining, path planning is based on known part and stock geometries, including location and orientation. In the case of CNC machining, very specific numerical control (NC) code can be generated to specifically guide the cutter through a set of efficient toolpaths. However, that is not the case with most steel casting cleaning room grinding operations, since the size, shape and location of the anomaly is presumed to be unknown.

The prototype system utilizes a universal path planning method for material removal on parts with unknown anomalies. This path planning method searches through designated areas for anomalies and a force feedback module determines the next step in real time, ensuring that every movement removes some material. This method enables the removal of all anomalies on any part without changing programming codes. The methodology can be most aptly described as a “search and destroy” technique, whereby the grinder is contained within a set of boundaries and instructed to remove anything in its path until the surface under the anomaly has the desired shape of the surrounding areas.

The following assumptions are made without impacting universality of the proposed path planning method:

1) Desired surface after grinding is approximated from reverse engineering areas near anomaly.
2) A boundary polygon is given that contains anomalies that need to be removed, indicating working areas on the surfaces. It doesn’t specify exact locations of each anomaly, but gives an area that the path planning method will be searching for the anomalies.
3) Cutting force is allowed to change in a range. Maximum force is an empirical value under which the tool can safely and efficiently work. Minimum force is also an empirical value.
4) Anomalies are usually thicker than maximum depth of cut.

Figure 26 presents the structure of the grinding system. The operator uses a joystick to interface with the machine via computer. The control algorithm combines commands from the operator and feedback from the sensors to decide movement of the machine to perform appropriate grinding.

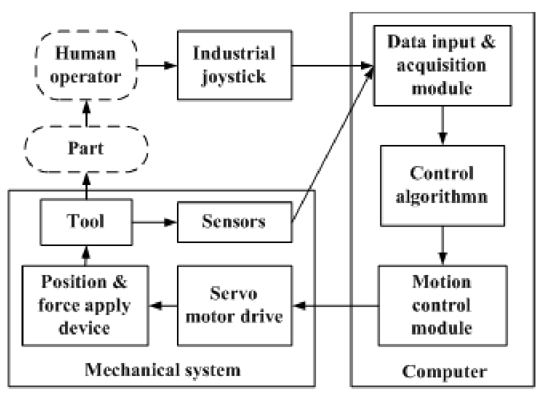

Figure 26 Structure of the automatic system

The mechanical system is comprised of a three axes gantry system, which corresponds to three degrees of freedom in the x, y, and z axes. Another degree of freedom is added to allow the grinder to rotate about the z axis, which is used to set up the orientation of the grinder. Movements of the system are driven by servomotors. The position and force device is attached to the gantry system.

The joystick should contain all control buttons for the system, since it is the primary operator interface with the system. They include:

1) Movement control: The joystick can move the gantry system along the x, y and z axes, or rotate grinder about the z axis;
2) Control mode switch: It is used to switch the system between automatic mode and manual mode;

3) Recording: After moving the probe to desired locations of each boundary point, a button can be used to tell the computer to record it;
4) Start: After setting up the work and pushing the “start” button, the machine will automatically sample reference points and work on designated areas automatically;
5) Emergency stop button.

Via the data input and acquisition module, the computer will receive commands from the joystick and read the sensors. The computer program will analyze the inputs and the real-time feedback signals from the sensors, and based on the working mode and the control algorithm, generate proper signals to control the axes through the motion control module. The program will also prompt the user and guide them through the input process.

To provide a proof of concept for the automated grinding system, a small-scale prototype was developed. This system was used to test both the automated point sampling and the path planning methods presented in this research. In this system, a Dremel brand small grinding tool was used as the material removal device.

In the prototype, a Gantry III system with servomotors from Techno Inc. was used, with a 13.7’’ by 11.4’’ by 6.8’’ work volume. A small fixture of 3’’ by 3’’ was used to keep the parts in position. National Instruments (NI) motion control card PCI-7350 was used to drive the servomotor to target positions on reference surfaces. It has a built-in velocity control that keeps feed rate to a designated constant value and input channels work like a basic data acquisition module. NI motor power drive MID-7654/2 was used to convert commands from the motion control card to voltage signals that actually move the servomotors. Figure 27 shows a picture of the gantry system, NI servo motor drive and the fixture.

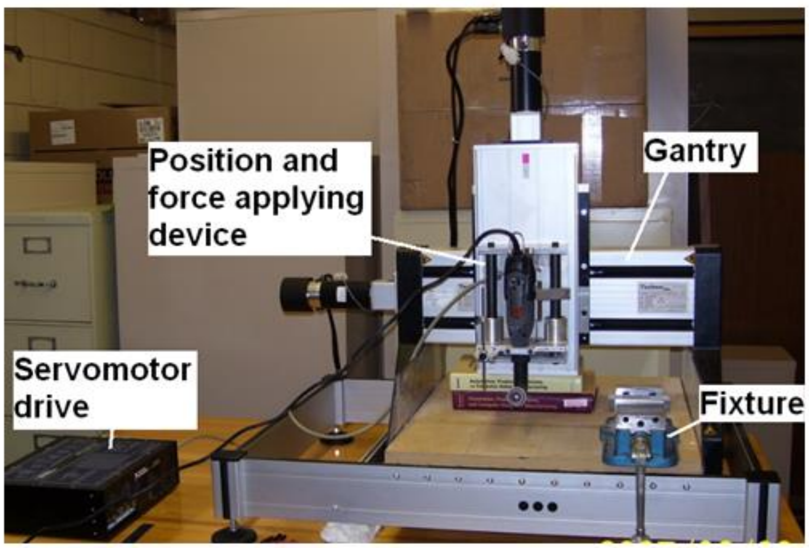

Figure 27 The Gantry III system, the servomotor drive and the fixture

Limitations of the Dremel tool required changes to the prototype design of the position and force-applying device, Figure 28. The Dremel tool used as the grinder is not powerful enough to bear the 60 lbs force in the full-scale design; it can only afford a force at around 0.5 lbs before stopping the wheel. Since the weight of the moving part of the device has exceeded the 0.5 lbs limit, the spring is put underneath the moving part. However, the calculation method for force stays the same, so it will still be able to verify the strategies in this paper. The damper was also not needed in this prototype system. A Schaevitz LC500 Linear Variable Digital Transducer (LVDT) was used to measure the Z height of the tool.

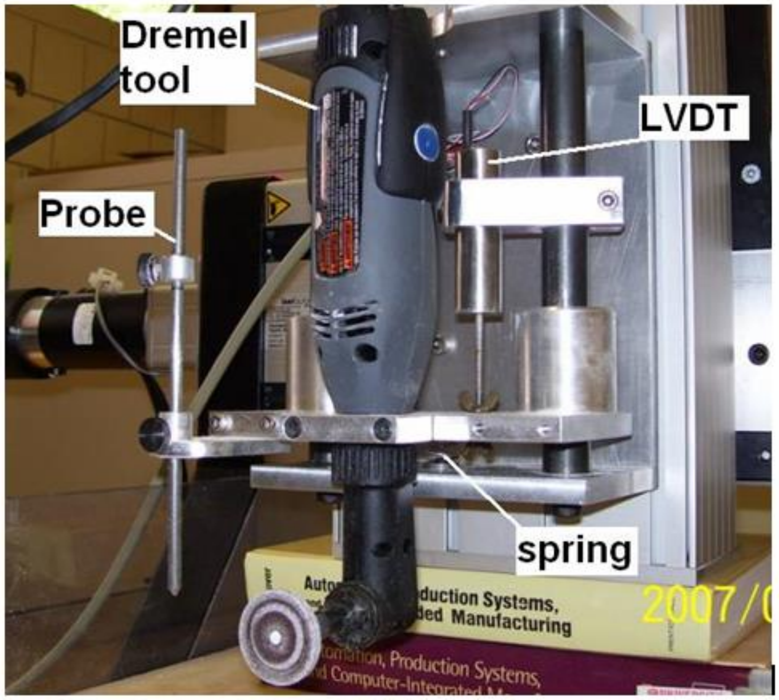

Figure 28 The position and force-applying device in the prototype

The computer interface is used for all inputs. The start button initiates the program to begin the automatic sampling of surface points based on anomaly and sampling boundary points. This is followed by the automatic removal of anomalies using the path planning strategy.

The patterns for the parts that were ground were produced on a rapid prototyping machine. A rubber mold was used to transfer the design into an epoxy sample. This material was chosen because it matched the capabilities of the Dremel tool, but still provided a realistic material removal scenario. Three surface samples with anomalies were tested, and are shown in Figure 29. They were:

1) A flat surface with a sloped “H” anomaly;
2) A concave cylindrical surface with a “selected radio button” anomalies;
3) A convex spherical surface with two separated irregular shaped anomalies.

The total time including sampling used for the three parts was 32 minutes, 15 minutes and 27 minutes respectively.

The parts were laser scanned after the automatic grinding operation, as were a set of control parts that had the same underlying geometry less the anomalies. Reverse engineering software (Rapidform) was used to reconstruct surfaces before and after grinding in order to compare the corresponding surfaces. Figure 29 shows the actual epoxy parts before and after the automatic grinding operation. The last row of Figure 29 provides comparison scans between ground parts, and parts that were produced without anomalies, which represent the desired surface. The bottom of Figure 29 has a color scale indicating the size of the discrepancies. As can be seen from the maps, the differences average about 0.3 mm (0.012inches). Note that the largest discrepancies (red areas) were due to the molding process, and are not in an area that was ground. This proves that the surface sampling method and path planning method are effective.

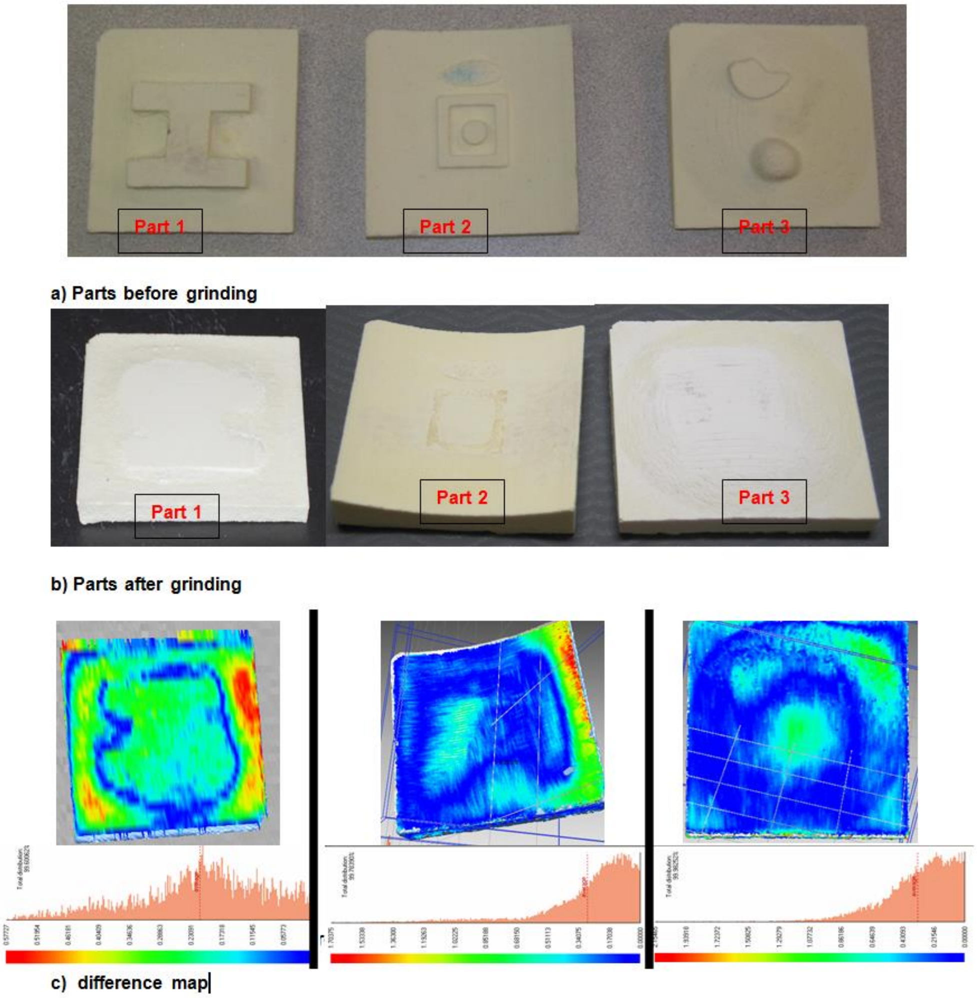

Figure 29 The three sample parts produced on the prototype system a) before grinding b) after grinding c) a difference map between the ground part and the nominal part.

Current material removal methods for unknown objects are inefficient, inconsistent, and an ergonomic hazard. Mechanization of cleaning room grinding is needed to improve efficiency when producing low volume products. Current automatic machines are not able to accommodate grinding of anomalies in unknown locations.

An automatic grinding system was designed and demonstrated via a prototype system. This system includes a simple point sampling strategy as well as a surface approximation method to guide the system to sample an adequate number of points. The approximation surface was used as a reference surface in the machining process. Path planning logic was developed to search and destroy anomalies, and together with a selected hybrid position and force/velocity control method, the path planning strategy was able to guide the tool within a designated working area with constant contact of anomalies. The path planning strategy is also universal to all objects and anomalies; no programming codes need to be changed for different parts. The implementation of a proposed automatic grinding machine was illustrated and the process and path planning strategies were verified to be effective and efficient. Although the implementation was scaled down and the material was not steel, the significant achievement illustrated was that a completely autonomous grinding system is feasible. The laboratory setup proves that neither a manual operator nor a set of custom NC code is necessary. The algorithms and point sampling strategies are unaffected by the 3-axis machine, therefore scaling to a more powerful system with a grinding stone should be generally straightforward.

3.3 Surface Mapping Software

Tracking the location of anomalies on the casting surface helps foundries understand and gain better control of their process. Anomalies are defined as surface areas which must be mitigated before the customer will accept the part. Common anomaly types include inclusions, burn on sand, cracks, and shrinkage. While the potential process control benefits from the data are great, the challenge of collecting it in an appropriate format is difficult. This prevents many foundries from doing so, hence the need for the Surface Mapping Software.

The two main components of Surface Mapping Software are a Windows application (based on the DirectX graphics engine) and a MySQL database that stores inspection and configuration data. To configure the system, a database is created to implement the entity relationship structure depicted in Figure 30.

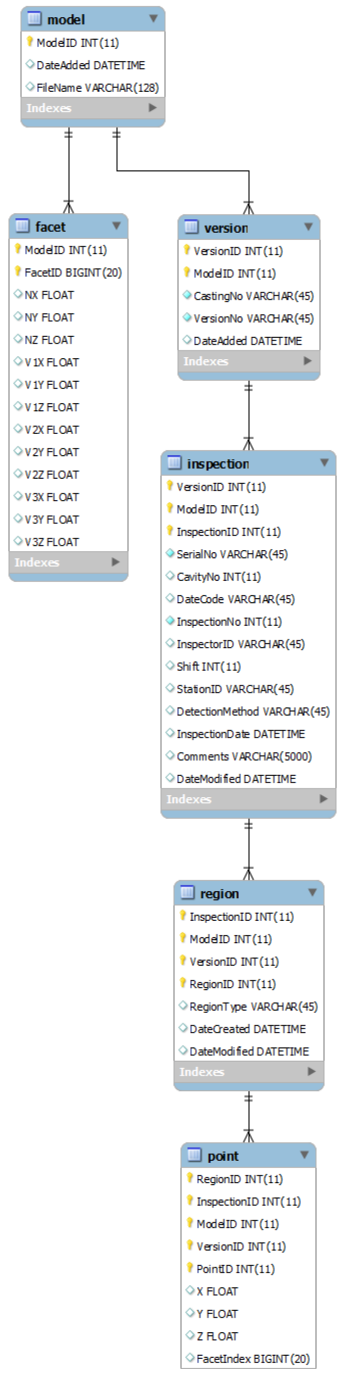

Figure 30 Entity Relationship Diagram

The Model entity represents the 3D CAD model of a casting which can be associated with multiple versions of a casting. The data for the CAD model is stored as a set of Facet entities in a mesh format and is used to display the casting model in the application. The Version entity defines a unique version of a casting; this is analogous to a pattern revision. For each version, there can be multiple actual parts and multiple inspections for each part. Each part can be tracked with a serial number and/or heat code number. Each Region entity represents one anomaly with a user defined description of the type of anomaly (e.g., dirt, porosity, or cracks). The geometry of an anomaly is described by multiple points defined in the Point entity. We describe this geometry in more detail in a later section.

The database can be installed on any computer that will be accessible by the application over the Internet. For companies with Internet firewalls, this can provide data security by limiting the access to computers within the firewall. Multiple databases can be supported through the database configuration. The IP address of the database server must be specified along with the name of the database and a user account that has read and write access to the database. The connection can be tested to insure that the computer running the application can connect to the database.

Before inspection data can be recorded, the 3D CAD models for the castings must be loaded into the system. All models must be in binary STL format which is supported by most CAD software.

After Mapper is configured, inspection data are recorded with the Windows application by first entering descriptive data for the casting and inspection. In addition, the anomaly regions that are drawn by the user on a 3D CAD model as shown in Figure 31 are also recorded. The user can modify the view of the CAD model using the view controls on the right side of the window which include zooming and panning functions. Before drawing a region, the user must select the type of anomaly by clicking on the appropriate icon at the top of the CAD model. The objective of these data entry functions is to make it very simple to collect data on the shop floor.

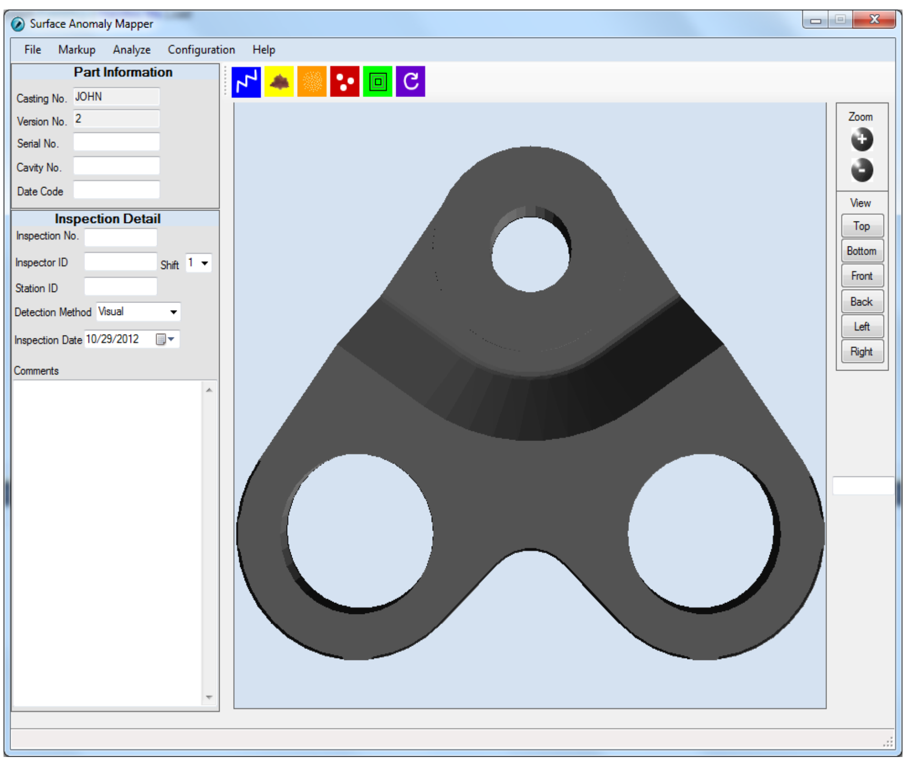

Figure 31 Main data entry screen showing inspection descriptors on left, choice of 'defects' on the top, and choice of views on the right.

The descriptive data can be used in subsequent analyses to group or differentiate inspections. The terms in the descriptive data shown on the left side of Figure 31 are defined in Table 3. In addition to this data, the user can enter additional comments about the inspection.

Table 3 Descriptive data to define the casting and inspection details

Data Field	Description
Casting No.	Corresponds to a specific casting (sometimes referred to as pattern number)
Version No.	Combined with Casting No., it represents a unique version of a
Serial No.	A code that can uniquely identify a part
Cavity No.	Specifies which cavity was used in the mold
Date Code	A code that can correspond to the pour date
Inspection No.	Identifies the order of the inspection in a possible sequence
Inspector Id	Identifies who performed the inspection
Shift	The shift when the inspection was performed
Station ID	The location in the facility where the inspection was performed
Detection Method	Type of inspection method (e.g. visual, mag particle).
Inspection Date	Date of this inspection

Anomalies are defined as 2D simple polygons (i.e., a set of line segments arranged in a closed path such that no segments intersect) that are projected onto the casting surface. The user sketches the outline of an anomaly on a specific view of a 3D CAD model of the casting, resulting in a finite set of points that we use to create simple 2D polygons. These polygons are then stored in the database attached to the other part descriptors. While sketching is convenient for the user, it is inherently imprecise from a mathematical point of view, leading to outlines that are not simple polygons. One case occurs when line segments in the outline intersect with each other as shown by the examples in Figure 32. For the first example we trim the additional line segments to form a simple polygon. In the second example we create three distinct polygons by separating them at the intersection points.

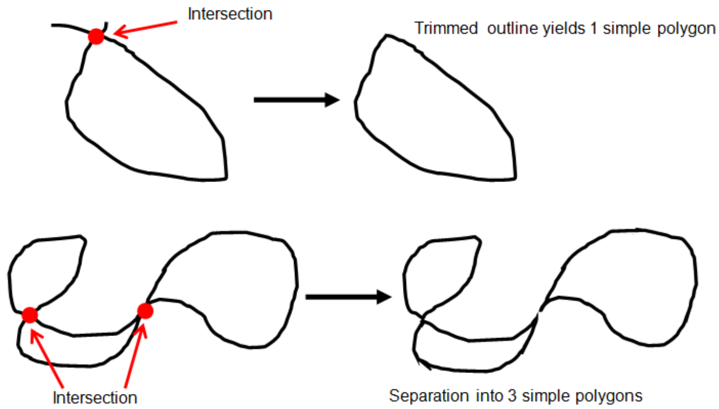

Figure 32 Trimming of an intersecting outline

The other exception occurs when the sketched path does not close as shown in Figure 33. In this case we force closure by connecting the end points and then checking for intersections as in the previous case. For any anomaly region, the user has the option to easily delete the entry, if it is not acceptable.

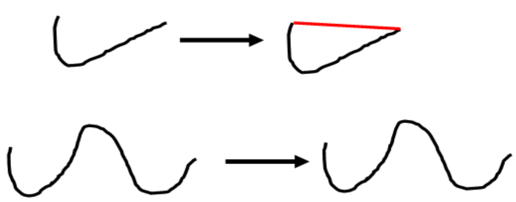

Figure 33 Closure of Open Paths

After a simple polygon is defined, it is transformed into a set of facets by triangulation as shown in Figure 34. Triangulation is performed to create a mesh that can be overlaid on the 3D CAD model in the application. For triangulation of a simple polygon, Meisters' Two-Ears theorem is used [Meisters 1975]. To minimize the storage requirements in the database, we only store the set of points that define each simple polygon as shown in Figure 34.

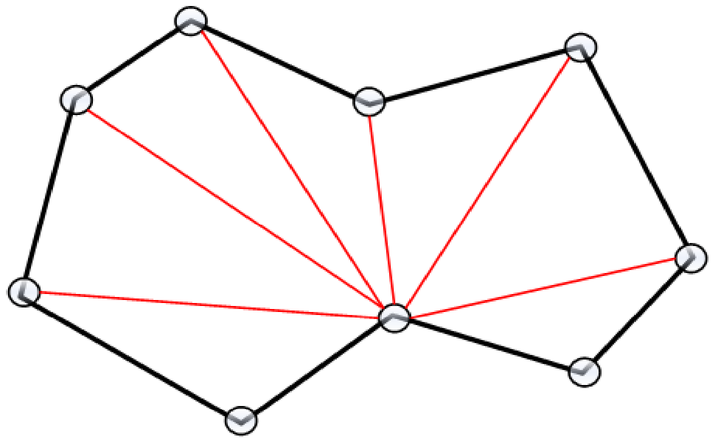

Figure 34 Triangulation of a simple polygon

Analysis of the data begins with defining a subset of data that will be analyzed. As shown in Figure 35, the first step is to select a casting number. After this selection, the dataset is refined by selecting additional data fields as we move from left to right. When the selection is complete, the corresponding records are retrieved from the database for an analysis.

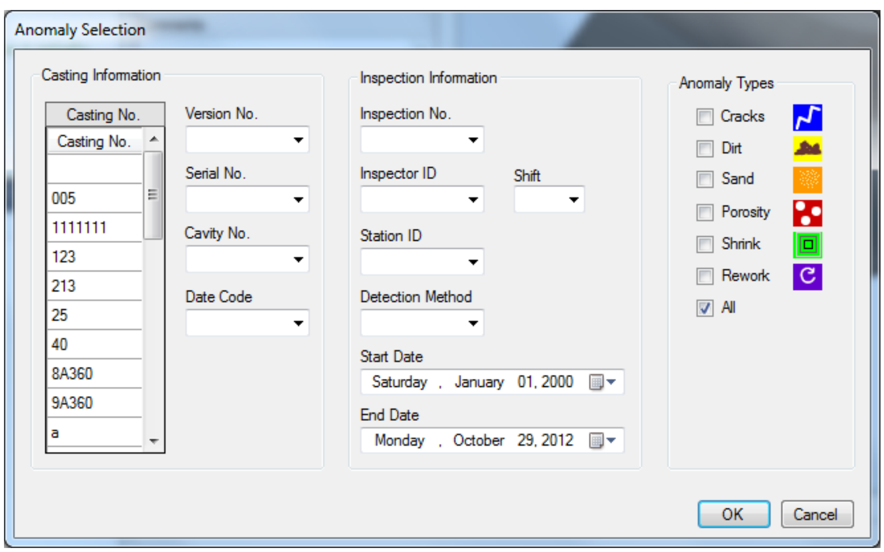

Figure 35 Data Selection for Analysis

The goal of a frequency map is to identify regions of a casting that consistently have one or more anomalies. The map is generated by intersecting the simple polygons entered by the user and counting the number of overlapping intersections. Given that each polygon is represented by a as a set of triangles, all the intersections of the triangles are found by clipping one triangle with another, forming a new simple polygon which is then triangulated and the process recursively finds the next intersection. This results in a frequency map as shown in Figure 36 where the colors correspond to ranges of anomaly occurrences in that location on the part.

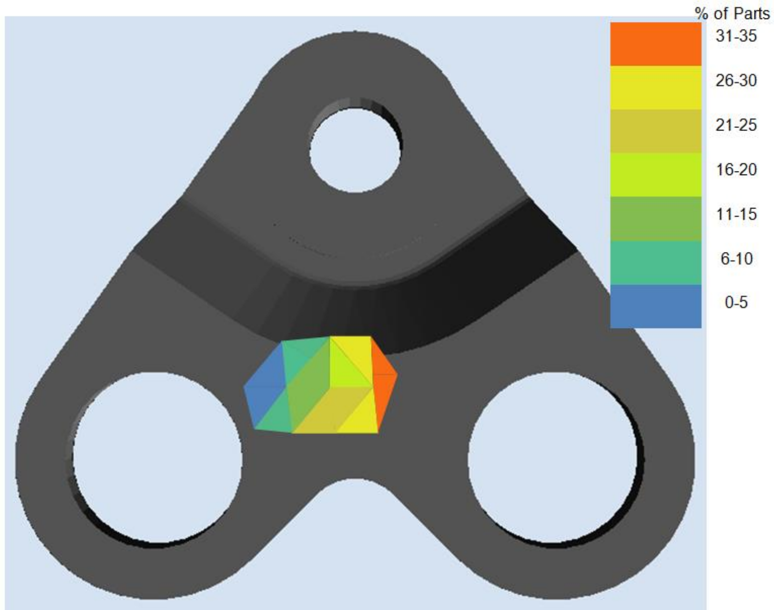

Figure 36 Example software output of a frequency map showing the location and occurrence of anomalies plotted on a view of the part

Continuous improvement of casting quality is predicated on understanding the effects of design and process parameters on individual castings. Collecting data on casting anomalies coupled with meaningful analyses that provide insights into problem areas in a casting are critical steps in the continuous improvement process. We have described a new system for capturing anomalies electronically by sketching regions on a 3D CAD model in which anomalies are observed for a specific casting. The system stores the anomaly information in a database and provides analysis of anomaly regions.

3.4 Study of Impact of Repairs via Weld Gouges

Casting samples were provided by steel casting producers. At each company one individual performed all the gouging and/or welding to eliminate operator-to-operator variability. The gouges were made to the dimensions specified, then filled with enough weld material to fill the hole. For all of the tests, the weld samples were done in pairs. One of the samples went through a post weld heat treat and the other did not. Some of the procedures employed to prepare the samples for analysis are listed in Table 4.

Table 4 Process and procedures used to prepare samples at three foundries.

Foundry	A	B	B	C	C
Alloy	8620	8630 modified	C12A	8630	1030
No. of Samples & Heat Treat	1 set N&T 1 set Q&T	1 set N&T 1 set Q&T	2 sets N&T	1 set N&T 1 set Q&T	1 set N&T 1 set cast
Type of electrode	E110T1-K3 1/16” Dia. Wire Shield gas: 100% CO_2	E110T5-K4 FCAW 3/32” Dia Shield gas: 100% CO_2	E505T-mod. FCAW 3/32” Dia Shield gas: 75/25	Not reported	Not reported
Preheating	No	Yes	Yes	NR	NR

The alloys supplied by the foundries consisted of 8620, 8630 modified, 8630, 1030, and C12A. Because of similar properties, the 8620, 8630 modified, and 8630 were combined for analysis. Each sample was cut in half across the weld revealing a cross section that is free of surface carbonization that may have formed during heat treatment. Figure 37 shows the terminology used to describe the size of a weld. The weld cut area is found by multiplying the width and depth of the weld. The samples were then ordered based on the approximate weld cut area from smallest to largest, Table 5, Table 6, Table 7 and Table 8.

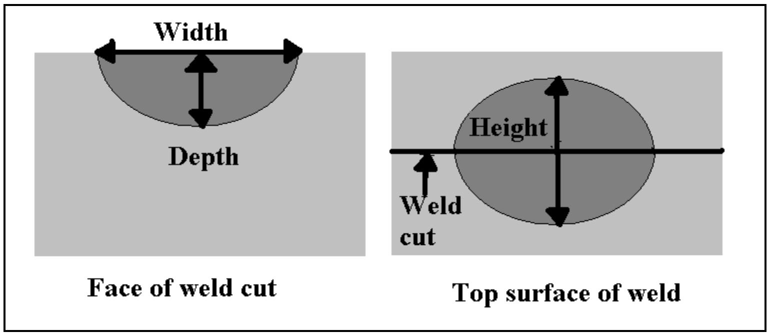

Figure 37 Terminology used to describe the size of the weld samples.

Table 5 Summary of welding samples of alloy C12A, which were normalized and tempered, sorted by the cut area size (weld width X depth).

Alloy: C12A					
Initial Heat Treatment: Normalize & Temper					
No PWHT			PWHT		
Foundry	Sample No.	Cut Area (in^2)	Foundry	Sample No.	Cut Area (in^2)
B	1C	0.33	B	1C	0.44
B	2C	0.38	B	2C	0.50
B	3C	0.75	B	3C	0.93
B	4C	0.91	B	4C	0.98
B	5C	1.55	B	5C	1.62
B	6C	1.63	B	6C	1.69
B	7C	1.78	B	7C	1.90
B	8C	2.03	B	8C	2.21
B	9C	2.75	B	9C	3.66
B	10C	3.38	B	10C	4.27

Table 6 Summary of welding samples of alloy 1030, which were as cast or normalized and tempered, sorted by the cut area size (weld width X depth).

Alloy: 1030								
Initial Heat Treatment: Normalize & Temper						NO Initial Heat Treatment		
No PWHT			PWHT			No PWHT		
Foundry	Sample No.	Cut Area (in^2)	Foundry	Sample No.	Cut Area (in^2)	Foundry	Sample No.	Cut Area (in^2)
C	1T	0.31	C	1T	0.23	C	1T	0.23
C	2T	0.35	C	2T	0.66	C	2T	0.42
C	3T	0.99	C	3T	1.22	C	3T	0.49
C	4T	1.94	C	4T	1.36	C	4T	1.06
C	5T	2.97	C	5T	2.81	C	5T	1.31

Table 7 Summary of welding samples of alloy 8620, 8630, and 8630m, which were normalized and tempered, sorted by the cut area size (weld width X depth).

Alloy: 8620, 8630, & 8630m					
Initial Heat Treatment: Normalize & Temper					
No PWHT			PWHT		
Foundry	Sample No.	Cut Area (in^2)	Foundry	Sample No.	Cut Area (in^2)
A	1N	0.11	A	1N	0.11
A	2N	0.22	A	2N	0.22
C	3N	0.42	C	3N	0.23
B	4N	0.56	B	4N	0.44
C	5N	0.74	C	5N	0.49
C	6N	0.96	C	6N	0.50
A	7N	0.78	A	7N	0.78
B	8N	0.77	B	8N	0.81
A	9N	1.03	A	9N	1.03
C	10N	1.06	C	10N	1.37
A	11N	1.33	A	11N	1.33
C	12N	3.44	C	12N	1.46
B	13N	1.48	B	13N	1.56
B	14N	2.08	B	14N	2.08
B	15N	3.86	B	15N	3.76

Table 8 Summary of welding samples of alloy 8620, 8630, and 8630m, which were quenched and tempered, sorted by the cut area size (weld width X depth).

Alloy: 8620, 8630, & 8630m					
Initial Heat Treatment: Quench & Temper					
No PWHT			PWHT		
Foundry	Sample No.	Cut Area (in^2)	Foundry	Sample No.	Cut Area (in^2)
A	1Q	0.11	A	1Q	0.11
A	2Q	0.22	A	2Q	0.22
C	3Q	0.57	C	3Q	0.46
B	4Q	0.44	B	4Q	0.55
B	5Q	0.84	B	5Q	0.69
A	6Q	0.78	A	6Q	0.78
A	7Q	1.03	A	7Q	1.03
C	8Q	1.71	C	8Q	1.13
C	9Q	1.93	C	9Q	1.23
A	10Q	1.33	A	10Q	1.33
B	11Q	1.63	B	11Q	1.63
C	12Q	2.13	C	12Q	1.63
B	13Q	1.97	B	13Q	1.93
C	14Q	2.18		14Q	
B	15Q	3.32	B	15Q	4.16

The samples were first surface-ground and then polished using decreasing grit sizes, from 180 grit per inch to a 3 µm particle size. The samples were etched to identify welding zone locations for hardness measurements. For the 8620 and 8630 samples, a bath of 2-3% Nital was used to etch. Only one or two seconds was necessary to obtain a quality etch. Because of the corrosion resistance of the C12A alloy, an 8 minute etch with pure sulfuric acid was needed to distinguish between weld zones. After etching, each sample was rinsed with water, then with ethanol to prevent streaking, and dried with compressed air.

Vickers hardness measurements were taken with a load of 500 grams. Indentations were taken in four zones: Weld pool, HAZ1, HAZ2, and base metal. The weld pool is the gouge in the sample that was filled in with weld material. HAZ1 is defined as the thin heat-affected zone just outside of the weld pool. HAZ2 is defined as a zone thought to have experience grain growth during the welding process. Finally, the base metal is the outer area of the sample, which has retained the original cast microstructure. The indentations for the weld pool and HAZ1 areas were taken at random places within the zones' clearly defined boundaries. Since there was no clear visible boundary separating HAZ2 and base metal, HAZ2 measurements were taken as close as possible to, yet still outside of, the HAZ1 boundary. The base metal measurements were taken as close to the edge of the sample as possible. From sample to sample, the same number of indentations was generally taken. Additional indentations were taken to increase confidence in obtaining an accurate representation of the hardness. HAZ2 measurements were eventually not used since they were essentially the same as those reported by the base metal.

The samples were analyzed for hardness in each of the zones across the surface of the weld cut. Figure 38 shows a representative sample. Figure 39 and Figure 40 show micrographs taken from 8620 samples for their base, HAZ1, HAZ2, and weld metal.

Figure 38 Picture of sample 5Q with no PWHT from alloy 8620.

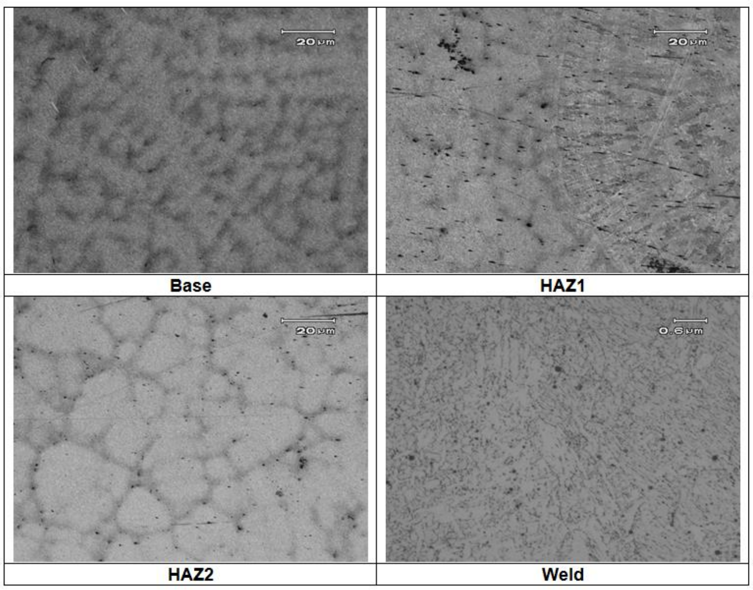

Figure 39 Micrograph of sample 6Q with PWHT from alloy 8620.

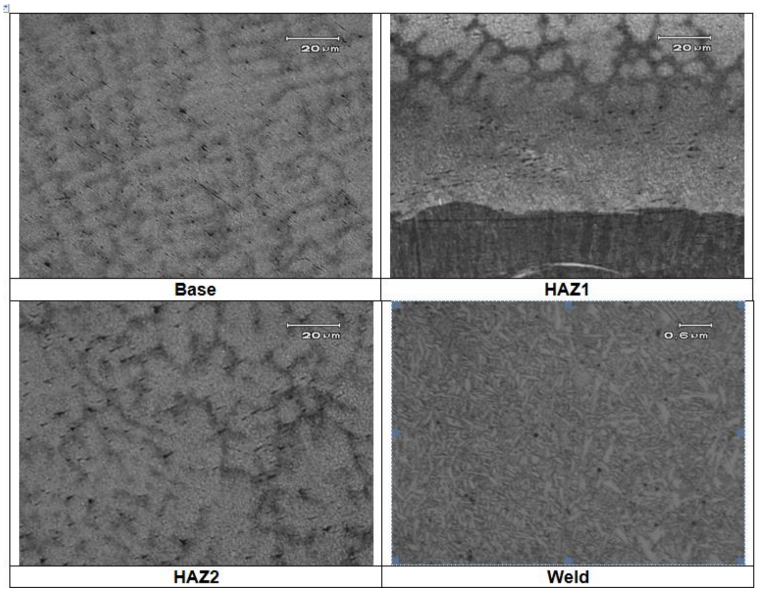

Figure 40 Micrograph of sample 6Q with no PWHT from alloy 8620.

Figure 41 and Figure 42 are the results from the 8620, 8630, and 8630m with quench and temper. The hardness values reported are averages from each individual sample. Sample area increases as the sample number increases for all of the figures. Figure 43 and Figure 44 are the results from the 8620, 8630, and 8630m with normalized and temper. Figure 45 and Figure 46 show the hardness results from alloy C12a. Figure 47 shows the average hardness values for 1030 samples.

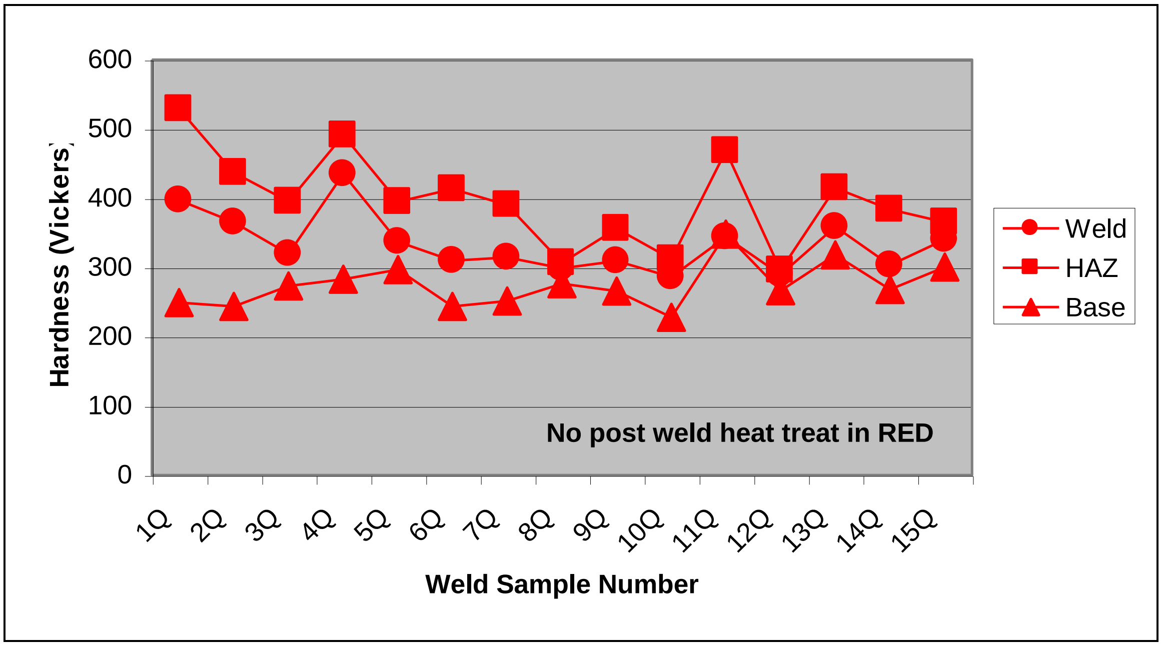

Figure 41 Plot of a sample's hardness in the weld, HAZ, and base metal for alloy 8620, 8630, and 8630m with quench and temper and without PWHT. The weld size increases with increasing weld sample number.

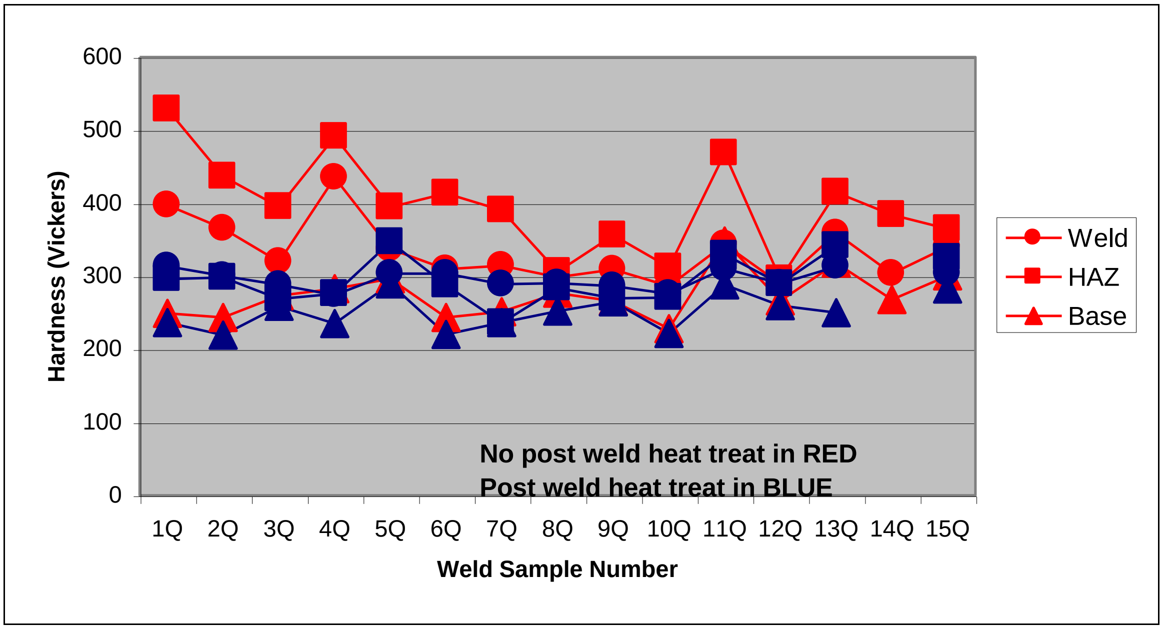

Figure 42 Plot of a sample's hardness in the weld, HAZ, and base metal for alloy 8620, 8630, and 8630m with quench and temper and with and without PWHT. The weld size increases with increasing weld sample number.

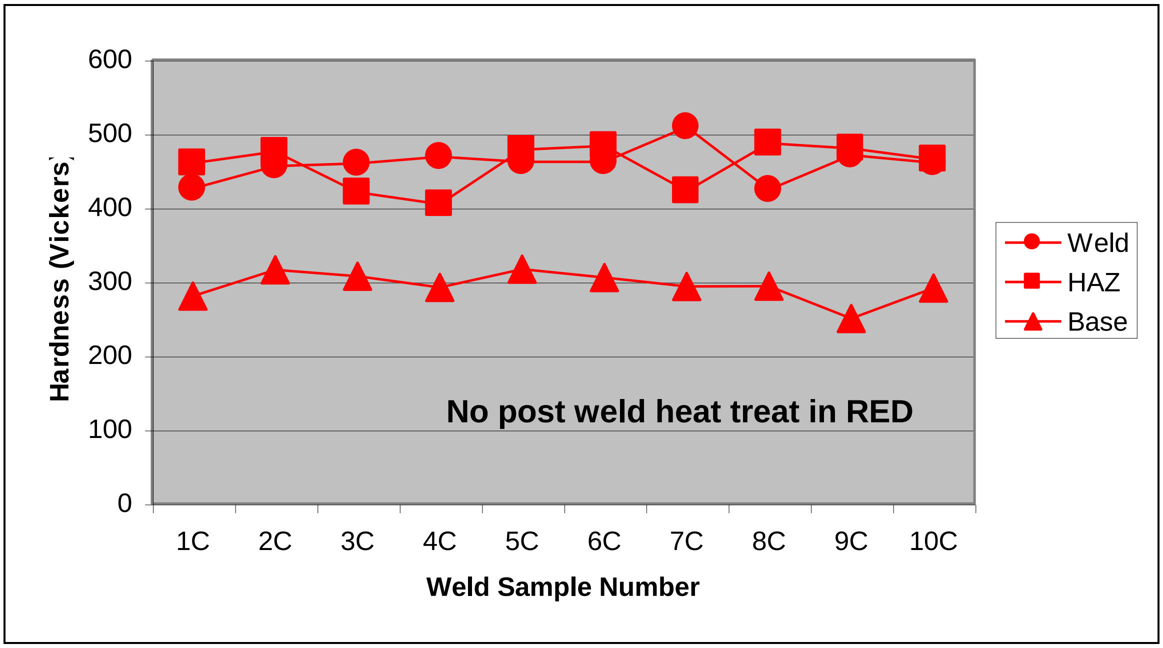

Figure 43 Plot of a sample's hardness in the weld, HAZ, and base metal for alloy 8620, 8630, and 8630m with normalize and temper and without PWHT. The weld size increases with increasing weld sample number.

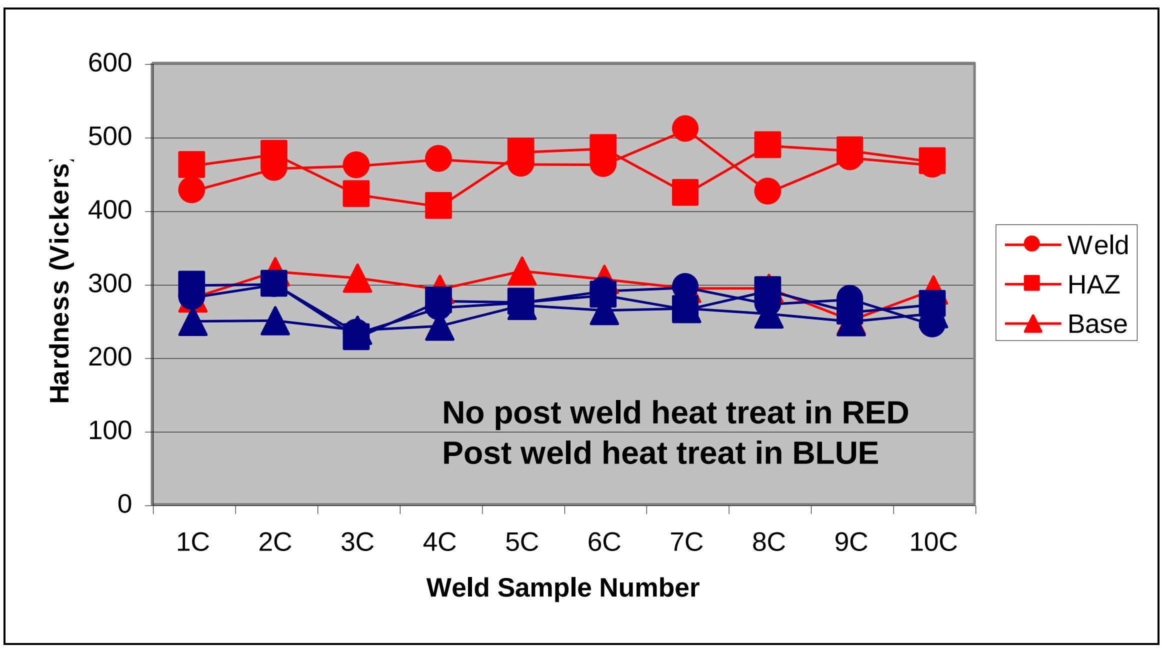

Figure 44 Plot of a sample's hardness in the weld, HAZ, and base metal for alloy 8620, 8630 and 8630m with normalize and temper and with and without PWHT. The weld size increases with increasing weld sample number.

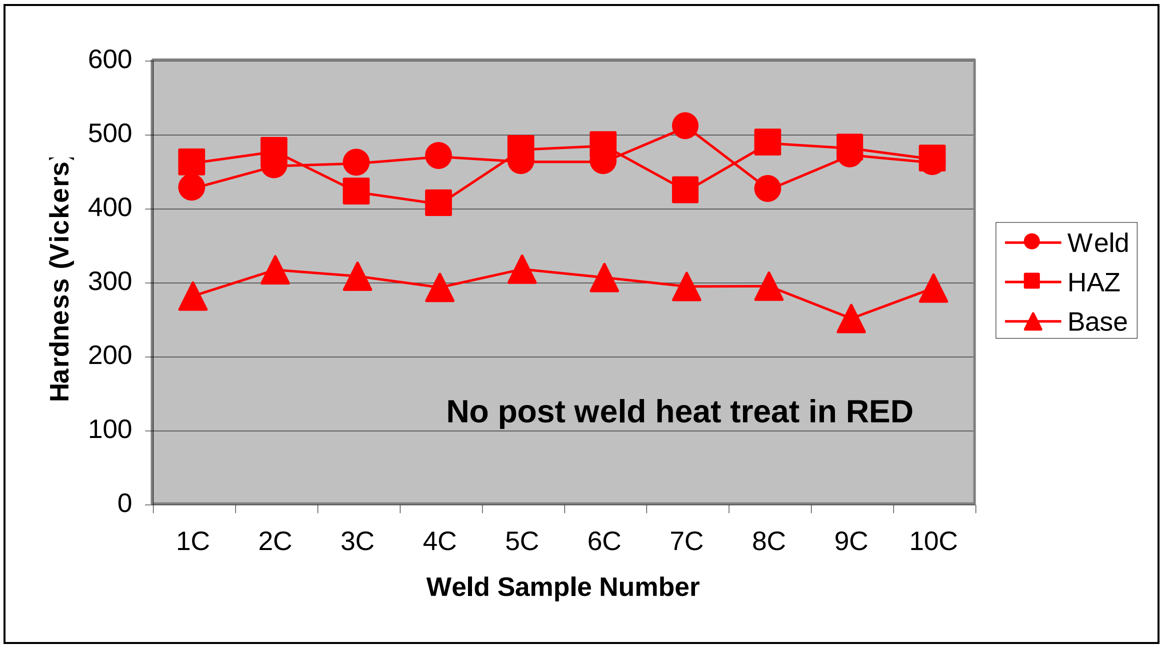

Figure 45 Plot of a sample's hardness in the weld, HAZ, and base metal for alloy C12A with normalize and temper and without PWHT. The weld size increases with increasing weld sample number.

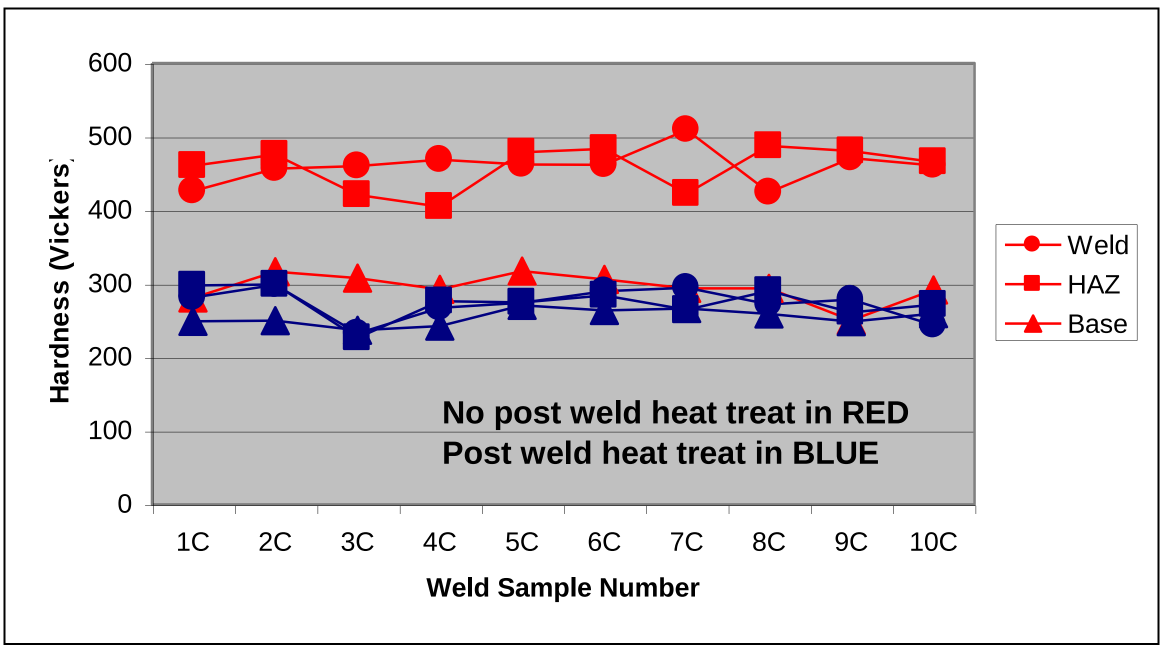

Figure 46 Plot of a sample's hardness in the weld, HAZ, and base metal for alloy C12A with normalize and temper and with and without PWHT. The weld size increases with increasing weld sample number.

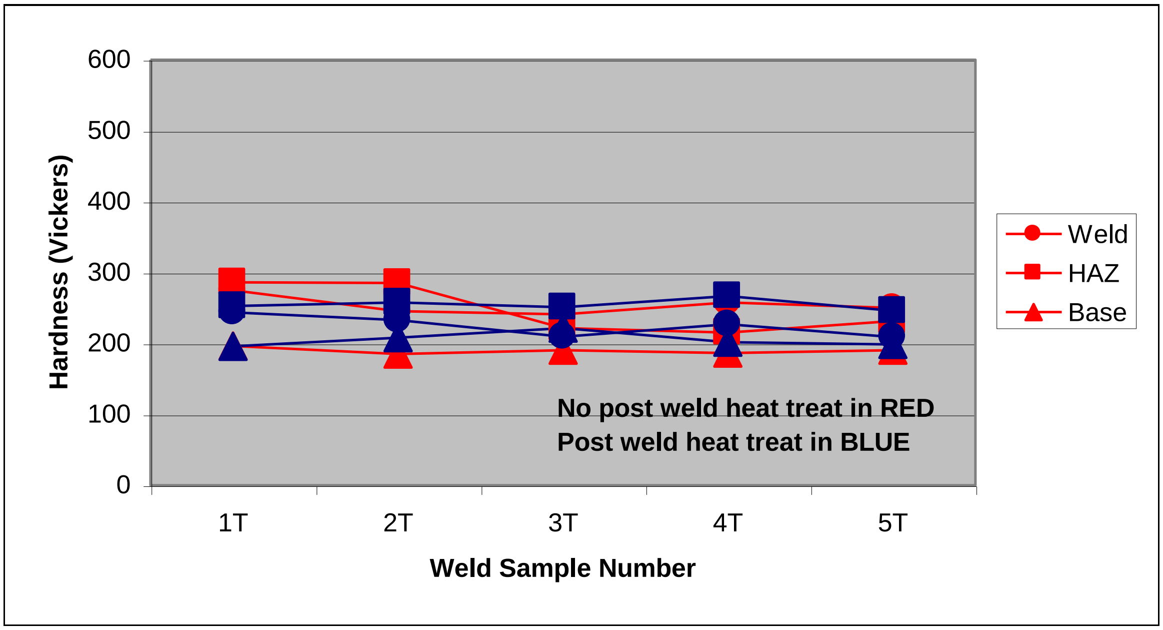

Figure 47 Plot of a sample's hardness in the weld, HAZ, and base metal for alloy 1030 with normalize and temper and with and without PWHT. The weld size increases with increasing weld sample number.

The focus of this experiment was to investigate the metallurgical effect that is caused by different size welds on common steel casting alloys with various initial heat treatments, and with and without the use of post weld stress relief. The data suggests that small welds do result in higher hardness for the base metal in 8620, 8630, and 8630m. Specifically, the spread between the hardness of the base metal and the HAZ is greater for small welds, because of the faster cooling rate.

The weld metal used to perform the repairs on the 8620 and 8630m saw only slight decreases in hardness from the post weld heat treatment. The HAZ decreased in hardness to values equivalent to the weld metal when stress relieved, to a value slightly above the weld or base metal.

The unwanted increase in hardness from welding can be lowered with a post weld heat treatment to a uniform hardness near or slightly higher than the base metal hardness. This suggests that if a post weld heat treatment is done, then any size weld is acceptable. If no post weld heat treat is performed, then small welds should not be made. Additionally, the initial heat treatment condition (Q&T and N&T) of the workpiece before welding has little to no effect on the results.

The C12A alloy performed differently than the 8620 and 8630m alloy. The increase in hardness from welding was independent from weld size. The reason for the uniform hardness increase in the weld and HAZ is a result of the material being easily air hardened, regardless of the weld size. The similarity in chemical composition led to similar hardness values for the base, HAZ, and weld after a post weld heat treat.

For the 1030 alloy samples that were initially normalized and tempered, the post weld stress heat treatment had little effect on the hardness in any of the areas. Size also had little influence.

The metallurgical effect of different size weld was investigated with various initial and post process heat treatments. For 8620 and 8630m, smaller welds lead to higher hardness. The high hardness can be eliminated with a post weld heat treat. Weld size has no effect on the C12a alloy. Initial heat treatments had no effect on the hardness values of the welds. However, the lack of initial heat treatment was a factor for the 1030 alloy.

3.5 Rapid Pattern Making Machine

The system presented here is a combination of an additive and subtractive process (Figure 48). This methodology can utilize most of the traditional machinable sheet materials used for pattern making, but can be fully automated. This process stacks a new slab onto the build platform, and then the unneeded material is removed via machining. On many layers, much of the material is actually removed; however, the need for a time consuming process planning step is avoided and the system can run unattended. Moreover, by machining only one layer at a time, very deep and complex patterns can be machined using very short cutting tools. Short tools can be used in very small diameters to create small features avoiding deflection of the tool and any collision conditions that often warrant the use of multi-axis systems (i.e. 5-axis CNC routers).

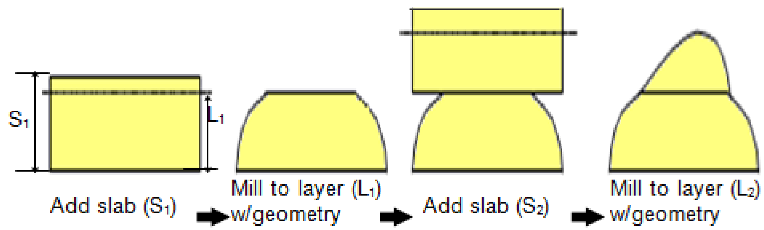

Figure 48 Basic steps in the Additive/Subtractive rapid pattern manufacturing process. Source: [13]

This process only considers the most recent layer added to the pattern, as the machining on previous layers has already been completed. All of the machining operations can be reduced to 2- and 2 ½ D machining using a lower cost 3-axis CNC mill/router. The first step in the process for each layer is to fully face machine the entire new "slab" to a particular "layer" height. Most often the depth of the face milling cut is the minimum necessary to ensure the layer is flat. However, there are some special geometry considerations that dictate that more than a minimal depth be removed, which will be discussed below. After the face milling of the layer, the subsequent machining entails flat- and ball-milling operations using waterline toolpaths to generate the 3D surface geometry, as illustrated in Figure 48.

The machining accomplished here may initially appear similar to some common industry methods which involve machining of slabs to produce more complicated pattern shapes. However, these techniques often rely on 3 or even 5 axes CNC cutting to machine the geometries. The difference is that others use larger slabs, blocks, stacks of stock material and the CNC machine much if not all of pattern at once. This often requires more extensive process planning than our 2 and 2 ½ D machining. The other advantage of our system is the ability to create deep pockets with fine detail using a small tool, as illustrated in Figure 49.

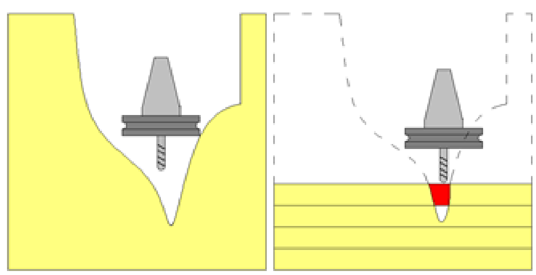

Figure 49 Deep cavity machining example (a) large slab or solid block approach causes collision, (b) Layer based approach avoids collision. Source: [Luo 2009]

It is anticipated that the typical nominal slab thickness will be ~0.75 or 1 inch. Some of each slab will be removed during the initial face milling operation to ensure that the subsequent layer is parallel with respect to the X-Y machine axes. This nominal thickness range is chosen based on the availability of material, and so that relatively short tools could be used. If there were large sections void of fine details that required small diameter tools, then larger layer thicknesses could be utilized along with larger diameter and longer tools.

Luo and Frank more thoroughly explored the choice of layer thickness (Figure 50) [Luo 2009]. The specific problem they addressed is choosing the thickness based on slab thickness and part geometry. There are some instances in which a uniform layer thickness could lead to situations where the pattern quality would be diminished. Some examples are illustrated in Figure 51. Areas in which there is an extremely small amount of material remaining in a particular area need to be avoided because they would result in chipped or rough surfaces and/or would not survive during the subsequent molding operations. The algorithms discussed in [Luo 2009] will determine where these situations will exist, and optimize the layer thicknesses to avoid them.

The varying layer thickness could be accomplished by utilizing raw material of varying thicknesses or by simply removing more material during the initial face milling operation.

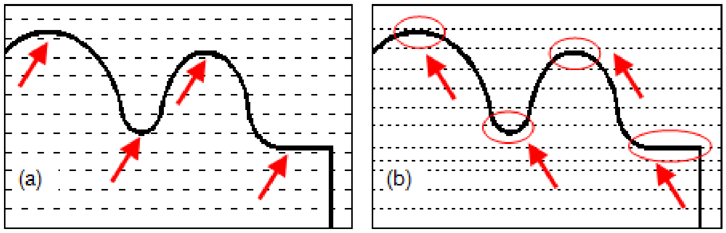

Figure 50 Layer thickness approaches (a) uniform layers do not locate effectively at peaks, valleys and flats, and (b) adaptive layers based on locations of features. Source: [Luo 2009]

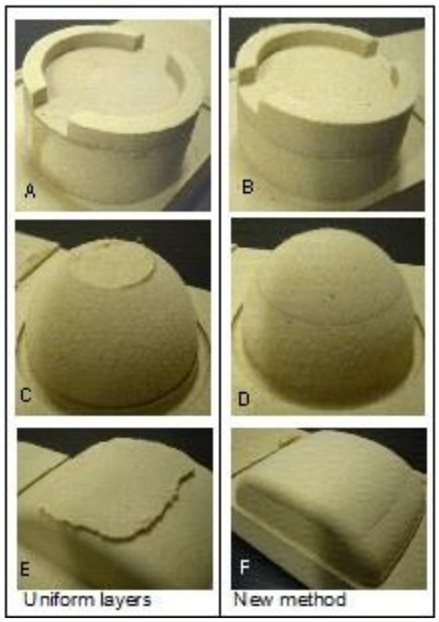

Figure 51 Illustrations of uniform (A, C, E) versus new (B, D, F) layer placement methods. *Source: [Luo 2009]*

Figure 51 provides an example of a test piece that was produced with uniform layer thickness contrasted with one that had optimized layer thickness. In this figure, Example A shows a large area of very thin wood that was generated due to having a layer transition occur too close to the upfacing flat surface. This issue is that this thin section may de-laminate when sand is pulled from a mold. Examples C and E illustrate thin areas which were easily damaged. The layer determination algorithm successfully avoided these issues.

To produce the toolpaths, the preferred file format is the native CAD file, if available, to reduce the chance for inaccuracies. The algorithms to determine the thickness of the layers utilize data in STL formats. This was chosen because the input models provided potentially could be in several formats but all can be converted to STL format. Furthermore, the potential inaccuracies are not a factor when determining the thickness of the machining stock; in addition to the fact that layer based analysis is facilitated by the polygonal STL file format.

A rapid pattern manufacturing machine has been constructed at Iowa State University. The system has six major components. The first is the material feed component, pictured on the right side of Figure 52. This has a capacity to hold a 4’ stack of 4x4’ sheet materials. The second component is the material handling system which will pick up a sheet from the feed stock, transport it to the build platform, and hold it while the sheet is glued and compressed to the build stack. The third component is the automated gluing station which is located between the feed and build stacks. The next component, the build platform, will index down as the pattern is built up; the build platform is the same size as the feed stock platform. The fifth component is a commercial 3-axis CNC router which is located above the build platform. Finally, a dust collection system picks up the cutting chips at the tool. The build platform is capable of 3800 pounds-force to compress the existing pattern into the new sheet to complete the layer bonding step. NC code for each layer and the requisite slab sequencing and facing to layer height data is output from MasterCAM and then processed using customized control system software to drive the machine elements. In all, there are seven controllable axes to completely automate the pattern manufacturing process. Currently, all of the components are functional except the gluing system which is still being implemented and optimized. After this is completed, the entire system will be capable of working unattended through the entire build volume.

Figure 52 Additive/Subtractive Rapid Pattern Manufacturing Machine in Rapid Prototyping & Manufacturing Lab at Iowa State University

The capabilities of the rapid pattern making system should be able to meet most of the needs of the steel casting industry for the production patterns required for sand molds. The system constructed at Iowa State has a 4x4x4' build volume. If larger patterns are needed, it would be possible to build them in modular fashion. Of course, a machine with a larger build volume could also be constructed using the same system design and using a larger capacity CNC router.

There are few geometric limitations which are relevant to sand molding. Since the mold has to draw off the pattern, undercuts in the pattern are not typical. The only undercut that could be created in this system is one which is planar and parallel to the X-Y cutting plane. This is made possible in the layer determination algorithm by starting a new layer at the level of the undercut.

Surface roughness of the resultant pattern is controlled by the stepover and stepdown during the finish machining operations. Except for the planar surfaces parallel to the X-Y cutting plane, all of the surfaces are created using a ball end tool. A reduction in surface roughness would require additional machining time. The patterns produced to date were able to be successfully used with only minimal hand finishing to clean up some areas.

4. Benefits Assessment

This task consisted of five separate projects aimed at improving steel casting processes. The goals of this project were to develop better tools and strategies to collect and manage process and product information. Working with the steel casting industry, five areas were selected based on the amount of variation caused by this source or the potential for improvement in terms of energy, emissions and competitiveness. The five areas were:

1. Heat Treatment Control Strategies
2. Semi-Automated Grinding
3. Surface Mapping Software
4. Study of Impact of Repairs via Weld Gouges
5. Rapid Pattern Making Machine

These process improvements will provide the steel casting industry with improved process tools that will lead to energy savings as a result of a reduction in scrapped castings and re-work/repair. Heat Treatment Control Strategies utilized new sensors and control strategies that better assess the temperature of castings during heat treatment, more accurately controlling the temperature instead of relying on several iterations of heating and delays. Semi-Automated Grinding, Surface Mapping Software, Impact of Weld Repairs, and the Rapid Pattern Making Machine reduce the amount of scrap, and thus the amount of re-work required.

These new technologies were predicted to result in an average energy savings of 3 trillion BTU's/year over a 10 year period.

For Heat Treatment Control Strategies, current (Dec 2013) annual energy saving estimates based on commercial introduction in 2013 and a market penetration of 60% by 2024 is 0.16 trillion BTU's/year. Along with these energy savings, reduction of scrap will result in a reduction of the environmental emissions associated with the melting and pouring of the metal which will be saved as a result of this technology. The average annual estimate of CO2 reduction per year through 2024 is 0.003 Million Metric Tons of Carbon Equivalent (MM TCE).

For Semi-Automated Grinding, current (Dec 2013) annual energy saving estimates based on commercial introduction in 2014 and a market penetration of 20% by 2024 is 1.3 trillion BTU's/year. Along with these energy savings, reduction of scrap will result in a reduction of the environmental emissions associated with the melting and pouring of the metal which will be saved as a result of this technology. The average annual estimate of CO2 reduction per year through 2024 is 0.02 Million Metric Tons of Carbon Equivalent (MM TCE).

For Surface Mapping Software current (Dec 2013) annual energy saving estimates based on commercial introduction in 2013 and a market penetration of 50% by 2024 is 4.5 trillion BTU's/year. Along with these energy savings, reduction of scrap will result in a reduction of the environmental emissions associated with the melting and pouring of the metal which will be saved as a result of this technology. The average annual estimate of CO2 reduction per year through 2024 is 0.07 Million Metric Tons of Carbon Equivalent (MM TCE).

For Impact of Repairs via Weld Gouges current (Dec 2013) annual energy saving estimates based on commercial introduction in 2013 and a market penetration of 25% by 2024 is 1.1 trillion BTU's/year. Along with these energy savings, reduction of scrap will result in a reduction of the environmental emissions associated with the melting and pouring of the metal which will be saved as a result of this technology. The average annual estimate of CO2 reduction per year through 2024 is 0.02 Million Metric Tons of Carbon Equivalent (MM TCE).

For Rapid Pattern Making current (Dec 2013) annual energy saving estimates based on commercial introduction in 2013 and a market penetration of 20% by 2024 is 0.9 trillion BTU's/year. Along with these energy savings, reduction of scrap will result in a reduction of the environmental emissions associated with the melting and pouring of the metal which will be saved as a result of this technology. The average annual estimate of CO2 reduction per year through 2024 is 0.01 Million Metric Tons of Carbon Equivalent (MM TCE).

For the entire project, by 2024 the average annual energy savings estimate is 7.96 trillion BTU's/year and the average annual estimate of CO2 reduction per year 0.123 Million Metric Tons of Carbon Equivalent (MM TCE).

5. Commercialization

There were different commercialization plans for the different technologies.

The heat treatment control was utilizing different sensors as well as an innovative control strategy to better control the heat treatment operation. This approach was demonstrated via a case study at two steel foundries by the researchers, and furthermore assisted another company in implementing this strategy. The results were publicized via conference proceedings and presentations at two different venues. One company, Falk Corporation reported their implementation in 2006. [Nitz 2006].

A proof of concept system was developed for the Semi-Automated Grinding system which demonstrated that the approach and algorithms were workable for the semi automation of grinding operations. The results were published in conference proceedings and being reworked for a journal publication. There was some interest in commercializing the approach, but the large investment into a full scale system was a hindrance.

The Surface Mapping Software has been provided to several industry users and their input has been very useful in improving the product. The results of using the software have not only been reported via conference presentations, proceedings and workshops by the project team, but an industry user has also presented their results at a conference. Initial requests through Iowa State University to fund the next commercialization steps have not been successful, but the project team has been receiving advice from a software entrepreneur on how to better secure funding to take this product to market. Funding to take the software to full scale commercialization remains the final hurdle. Another commercialization option that is being explored is to part with a solidification software company as this tool could be used to interface with their solidification results (in particular the inclusion and hot tear prediction).

The results of the weld gouge analysis study were well received by the industry via a conference presentation and publication. These results have been requested by industry personnel since the publications. The true benefit of these results is in the producer's ability to better demonstrate to their customers on the importance of adequately and appropriately specifying the surface quality necessary.

The rapid pattern making machine has been updated and made more reliable through this project. At the time of this report, case studies to demonstrate the use of the technology are underway with industry. Talks are also underway with economic development officials to help jumpstart this technology. One of the research team is seriously considering taking this technology to found a startup company.

6. Accomplishments

This project worked to improve the operations of metalcasting facilities by equipping them with methods and tools to reduce process variation, rework, scrap and ultimately energy utilization. Heat treatment control strategies were readily picked up by industry, implemented and further implementation was spurred by industry representatives reporting on their implementation success. A prototype system for the semi-automation of the grinding process for large castings was developed and demonstrated in the laboratory. While there was some initial interest from industry, commercialization has stalled because of the risk and investment threshold. A robust software system for the collection, management and analysis of casting surface data was taken from a prototype stage to a beta rollout to several industrial users. Industry is beginning to reap the benefits of the software in terms of providing them with readily accessible data they can utilize to make informed process control decisions. This is further supported by a conference presentation by industrial personnel on their use of the software. The consequences of making weld repairs on the casting surfaces was investigated via a study conducted at three steel casting producers. The report on this work was presented at an industrial conference and published in the proceedings. This information is now available to help producers educate their customers on the implications of excessive surface requirements. Finally, an automated system for rapid pattern making was advanced to the point of conducting case studies to demonstrate its effectiveness with industry. Commercialization through state economic development routes is currently under investigation.

Graduate students thesis based on the project work

- Danni Wang, Ph.D. Thesis, "A general material removal strategy based on surface sampling and reconstruction on unknown objects," 2007.
- Brian Harwood, M.S. Thesis, "Improving productivity and energy efficiency in the heat treatment of steel castings," 2006.

- Greg Saveraid, M.S. Thesis, “Cast data matrix symbols quality characterization”, 2009.

Other products:

- *Surface Mapping Software* system for collecting, managing and analysis of 3D surface information
- *Semi-Automated Grinding System* – control algorithms and prototype hardware system to demonstrate the effectiveness of semi-automated grinding of large castings
- *Rapid Pattern Making Machine* – improved hardware and software to allow for the automated manufacture of large pattern tooling for metalcastings.

7. Conclusions

This project made inroads in tackling some particular areas of the metalcasting process that can help the industry reduce variability of their operations, and hence, reduce the labor and energy inputs needed and be more responsive to their customers' needs. The heat treatment control efforts were immediately adopted by some casting producers as there were no commercialization hurdles. The grinding automation system, while successfully demonstrated via a laboratory prototype, has the largest chasm to cross before it can be commercially viable because of the risk of investment in the system development. The analysis of the metallurgical effects of the weld gouges was well received by industry; it remains to be seen if this information will be adopted by their customers, who ultimately have the say on the product requirements. Given the advances credited to this project, the Mapping software and rapid pattern making system are initially being adopted by industry, and further commercialization efforts are ongoing.

8. Recommendations

The heat treatment control strategies were the first of the technologies developed here that was adopted by industry users. It is expected that this work will enable further improvements as technology devices are more prevalent and less expensive.

The Grinding Automation System was successful as a laboratory prototype, but failed to gain acceptance from industry because of the risk and investment hurdle. The opportunity still exists for a machine builder to pick up the control strategies and system architecture to build a full scale system.

The Surface Mapping Software continues to gain success. The researchers are continuing to work on a full scale commercialization plan.

The study on the material effects of the weld gouges on the casting surface was essentially a standalone study. This work should be used in conjunction with ongoing efforts to look at the effects of defects to develop a more robust casting surface specification strategy that would better serve the casting user.

The Rapid Pattern Making Machine has been advanced to the stage that commercialization is possible. Efforts to this regard are ongoing.

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