Steel Foundry Research

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ABSTRACT

Steel casting research has progressed dramatically in the past twenty years. Casting users identified reducing inclusions, better dimensional control, weld repairs, and soundness in fluid handling components as critical quality issues for casting producers. By developing research partnerships, significant effort has been directed at improving steel foundry technology. Past projects have reduced inclusions, improved yields, and reduced process variations. Future work will use advanced modeling to create high performance cast components.

INTRODUCTION

Significant changes hit the steel foundry industry from 1979 to 1983 with production falling from over 2,000,000 tons to 720,000 tons, a 65% decline in market demand. In response to this steep drop, the industry formed a Quality Assurance Task Force that interviewed important customers. They reported in 1983 that changes in machining practices caused steel castings to be undesirable. The variability in quality of the castings caused cutting tools to break and often gave unacceptable parts after the cost of machining had been incurred (Parana). Inclusions were identified, as the number one concern of customers. Other issues of note were dimensional control, metal penetration, soundness, and weld quality. While the sharp drop in demand was not directly the result of industry performance but an economy wide response to excess capacity and supply, these technical issues drove the direction of steel casting research for the past twenty years.

The steel foundry industry has been a leader in casting technology development. Major strides were made under the stewardship of Charles Briggs through the Steel Founders' Society. Feeding distance rules, design strategies to avoid hot tears, dimensional control, gating system approaches, the use of specialty sands to reduce penetration, and improved ladle refractory materials to reduce inclusions are just a sample of the work he directed (Conway). The research led by Briggs was funded entirely from member dues.

As a result of the steep drop in production in the early 1980's, it was no longer possible to support research with internally generated funds. Using the needs identified by the Task Force, projects were begun initially through a partnership with the Department of Commerce in the area of clean steel. The research program has received the bulk of its support from consortia such as the Cast Metals Coalition partnered with the Department of Energy-Office of Industrial Technology and the American Metalcasting Coalition partnered with the Department of Defense-Defense Logistics Agency. These partnerships provided the resources needed to achieve breakthroughs in inclusion elimination, improved soundness, dimensional control, surface quality and inspection. The future planned research is model-based design and processing to enable high performance steel castings to be designed, produced, inspected, and used with safety and reliability.

CLEAN STEEL-ELIMINATING INCLUSIONS

Inclusions, that resulted in poor machining., broken tools, and porosity on machined surfaces, were the most troublesome feature of steel castings. Customers were concerned that high speed machining lines were being crippled by steel castings containing inclusions. Significant progress in understanding inclusions had been made in the development of minimills for steel long products (Heaslip). Leveraging the improved understanding of inclusion formation, support from the Department of Commerce and trials by steel foundries, significant improvement has been possible.

In steel foundries, inclusions were thought to be entrained materials such as refractories, sand, slag, or coatings. There were constant disagreements over whether they resulted from poor molding practices or melting practices. Identification of the source of inclusions was problematic. Earlier work had shown that melting practice, molding materials, refractory quality in ladles and deoxidation products all contributed. Chemical analysis of inclusions did not provide much help, inclusions were typically a mixture of alumina, silica, manganese and iron oxide. The aim of the first “clean steel” project to reduce inclusions was to identify the source of inclusions.

Since the common belief was that inclusions were entrained materials, premium materials should dramatically reduce inclusions. Cast test plates produced by steel foundries were used to evaluate inclusion formation. The plate quality was rated using radiography, the inclusions were then removed and characterized by scanning electron microscopy, SEM. Production castings were included in addition to the test plates. It was thought that plates made from basic arc melted steel, AOD refined, bottom poured from newly board lined ladles into ceramic molds would produce the least inclusions while acid melted steels lip poured into green sand molds would produce the most inclusions. Contrary to the expectation, the least inclusions were poured from small lip poured ladles from an acid furnace into green sand molds.

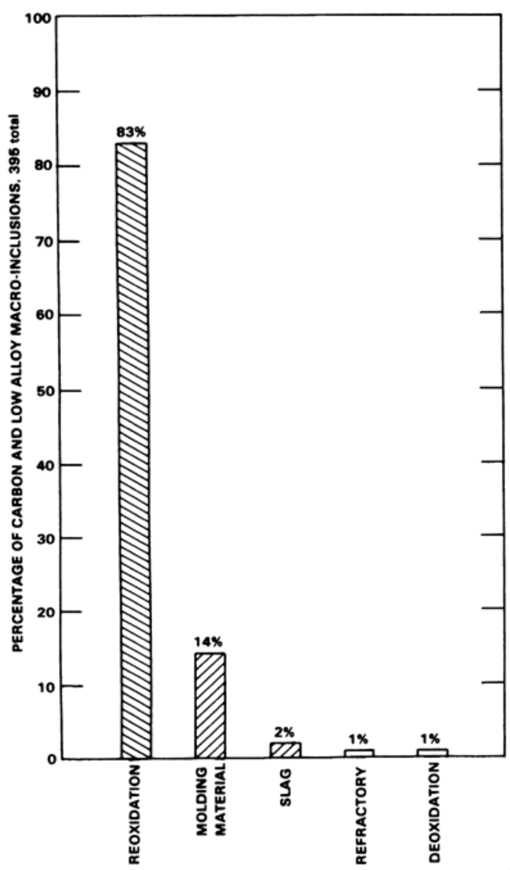

Fig. 1. Distribution of macroinclusion sources in carbon and low alloy steel castings

Inclusions were classified by the SEM. Since sand and refractory dissolves slowly, these materials can be readily identified from their appearance. Slag has certain trace elements which can be picked out with electron dispersive X-ray analysis, EDAX. Based on the analysis of almost 500 inclusions, reoxidation was identified as the cause of more than 80% of the inclusions. As can be seen in Figure 1, molding materials come in a distance second, at 14%. This overstates the influence of molding and understates reoxidation since sand containing reoxidation inclusions were counted as a half point for each. The sand in the reoxidation inclusions was unlikely to be trapped if the reoxidation inclusion was not present (Svoboda).

Reoxidation was recognized by the minimills as a major factor in inclusion formation (Heaslip). This work allowed a series of breakthroughs. Reoxidation and not entrainment was accepted as the cause of most inclusions. Reoxidation includes reactions with the slag or refractories so it is caused both by reactions with the air during pouring and melting and ladle practice.

One early effort was to try and reduce air entrainment during pouring through an innovative bottom pour nozzle design. Using a cross-shaped nozzle eliminated the rotational velocity transferred from the ladle into the stream causing stream flaring. Visually the improvement in stream shape was dramatic. Since air entrainment was thought to be controlled somewhat by stream quality, this nozzle was expected to improve casting quality. With the support of the manufacturer and a foundry, an extensive trial was conducted. Contrary to the improved stream shape, the new nozzle design showed no benefit. This trial consisted of six different castings from over 80 heats producing more than 400 castings. This result was confirmed in water modeling trials where the cross-shaped nozzle showed only a slight reduction of air entrainment when throttled and no reduction when fully open, Figure 2 (Blair 1991).

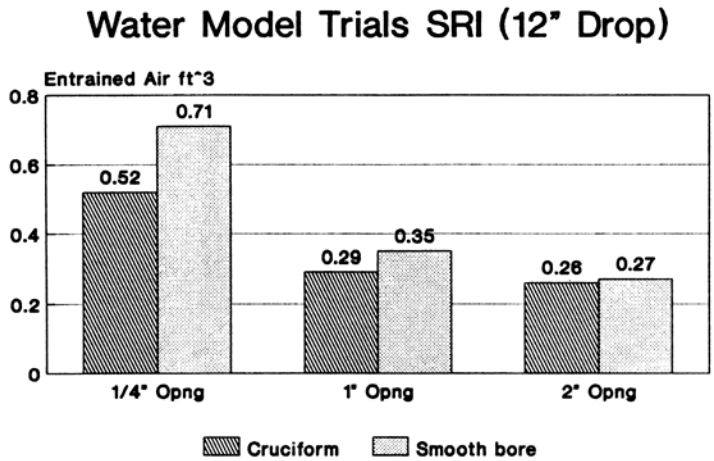

Fig. 2. Average air entrainment

Water modeling proved to be valuable step in understanding pouring and gating (Beckermann, 1993). Traditional gating system design frequently failed to appreciate the link between pouring practice and gating design. Lip or teapot pouring systems linked well with the traditional tapered sprue-well basin-drag runner-cope gate design widely taught as standard. The systems were intended to allow flotation to eliminate entrained material not to prevent exposure to reoxidation. Bottom pour systems most often used tile runners that allowed un-choked pouring from a full ladle. This requires the tile diameter used for the sprue to be larger than the nozzle diameter and the runner-gate system cross-section to be even larger and enter at the lowest part of the casting. Traditional gating systems do not function as envisioned; they do not fill or establish the planned flow patterns until pouring has nearly been completed. Water modeling of pouring and gating systems showed the lack of expected behavior.

Examples of the insights gained through water modeling are shown in Figure 3 (Wanstall). Full ladles had more air entrainment than half full ladles. Not surprisingly, throttled pouring gave greater air entrainment than fully opened nozzles. Taller sprues and nozzle extensions both increased entrainment. The use of full factorial experimental designs and water modeling gave a clear indication that air entrainment was controlled to some extent by the pouring and gating system.

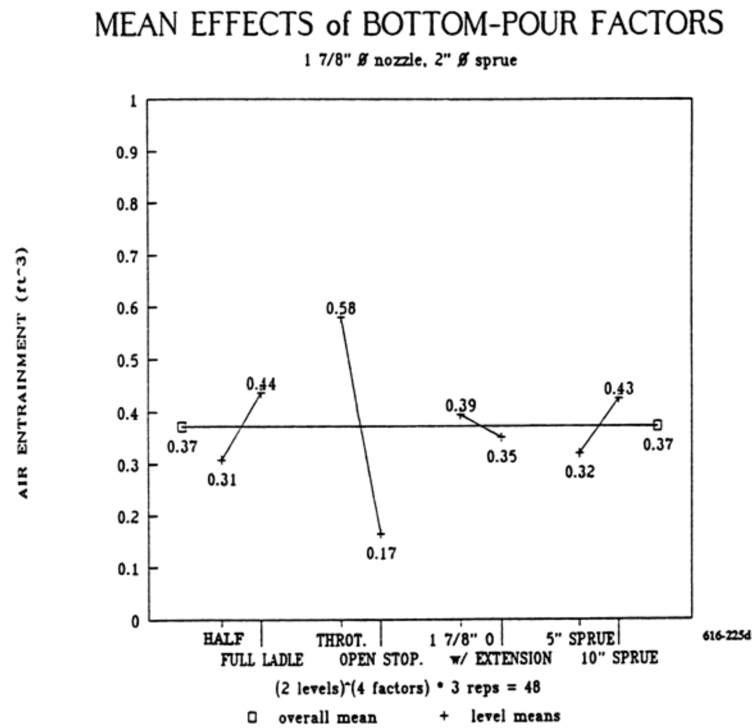

Fig. 3. Mean effects diagram for bottom pouring factors in water modeling series 1

Higher total pouring heights seemed to always give higher rates of entrainment. In practice, pouring times were often used to control pouring operations. Since pouring times in un-throttled bottom poured ladles were the result of nozzle size and height of fluid in the ladle, an analysis was carried out to try to relate pouring time and air entrainment. Using the engineering relationships from the literature (Beckermann 1991) and the results of water modeling pouring systems (Wanstall), a relationship was developed for air entrainment, Air Entrainment is proportional to Pouring Time times Head height to the five halves power, AE=K*PT*Ht^5/2. All pouring systems were consistent with this relationship as seen in Figure 4 (Blair 1993). This included lip pour, teapot, bottom pour with standard nozzles, bottom pour with cross-shaped nozzles, throttled pouring, and irregular pouring. Head height was the total drop in the system from the highest level of liquid in the system to the lowest point of impact. This was consistent with individual heats reanalyzed from the nozzle trials (Monroe 1994). This is consistent with the results of the first project that larger ladles gave more inclusions (Blair 1993) since larger ladles have greater head heights. Lip pour and teapot ladles have lower head heights than the same size bottom pour and larger ladles tend to be bottom pour. Ladles normally have a height to diameter ratio of one to two.

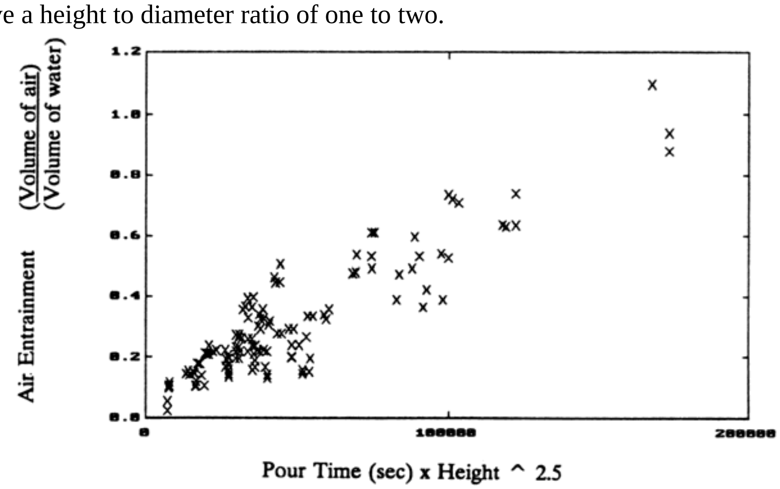

Fig. 4. Equation H plotted for water modeling results

Bottom pour ladles were thought to be better at preventing inclusions since they retained the floating slag and poured from the bottom. Consistently, bottom pour ladles give the poorest quality when near full and the fewest inclusions when almost empty. This can be seen in the graph of pouring order and casting quality rating in Figure 5 (Griffin). This defies the conventional understanding but confirms the results of the water modeling. Reducing the total head height in the pouring system has a significant effect.

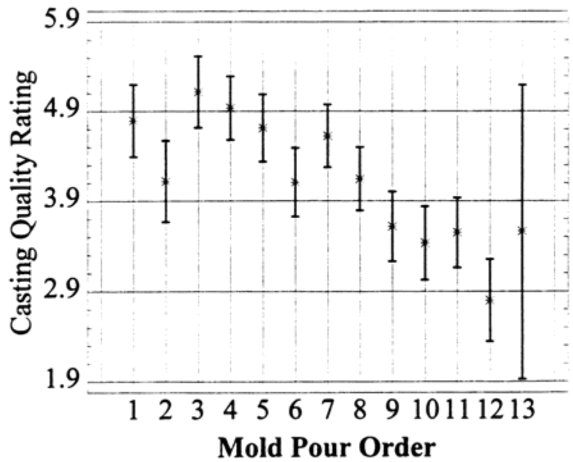

Fig. 5. Effect of head height on casting quality at basic foundry

An alternate successful approach is to shroud the stream from reaction and reoxidation. Inert gas approaches have been tried without success. Ceramic shrouds sealed to the ladle nozzle have been used to achieve a dramatic reduction in inclusions. The results are shown in Figure 6 (Hartay). Shrouds have shown beneficial in other plants but they have not been adopted widely. They are most likely to be successful in the production of larger castings from bottom pour ladles.

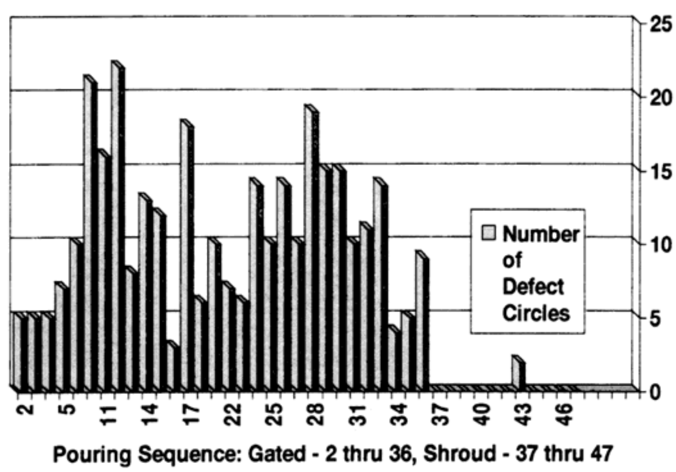

Fig. 6. Pouring shroud test #1

The dominance of head height in air entrainment suggested that flow-modeling velocity in pouring and gating systems would predict casting quality. Significant efforts have been made to predict gating performance without success. Filter trials show a fifty percent reduction of inclusions when filters are applied but the reduction due to filters was less than the heat to heat variation. Refractory type, acid or basic, the use of calcium wire injection, and the control of the oxygen blowing melting process are shown to have an effect (Carpenter). Gating systems were shown to have an effect on particular castings. Pouring through filters may be the best solution for smaller castings. The use of counter gravity pouring may also be a future development.

DIMENSIONAL CAPABILITY

Tolerance grades for steel castings were formulated by the industry by an evaluation of the process capability (Aubrey). Six tolerance grades were developed based on a large number of castings measured. These tolerance grades were permissive and did not reflect the improving practices in operations, especially the shift to chemically bonded mold and core production. They were also limited because the measurement systems used were not evaluated for their capability prior to obtaining the measurement data. Six tolerance grades were promulgated and used by industry.

Based on customer feed back and market pressure to more accurately describe the process capability, the industry developed new guidance for tolerances. This effort used gage repeatability and reproducibility evaluations to qualify measurement system prior to collecting data. Based on an analysis of the resulting data, new tolerance grades based on ISO 8062 were developed (Voigt, 1997) and are available (Voigt, 2003). A comparison of the older tolerance grades and the industry capability is shown in Figure 7.

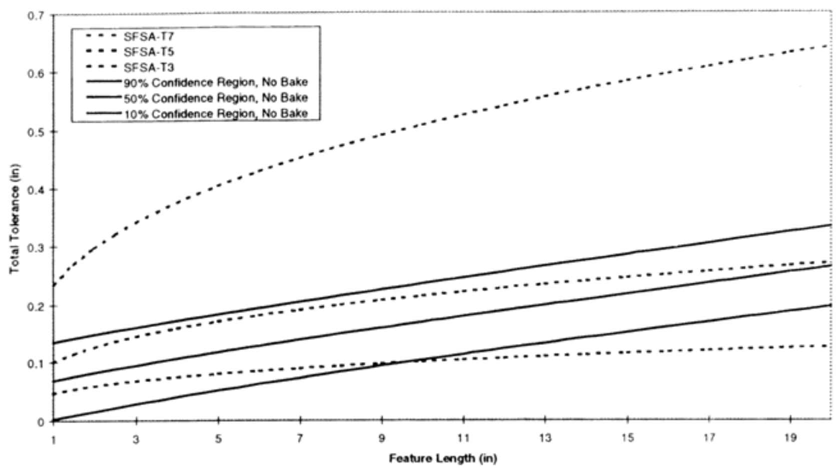

Fig. 7. Long series production – No bake dimensional capabilities compared to SFSA T-Grades

An interesting analysis of sampling and pattern adjustments was done as a part of this project. Because of limited production of castings in development, pattern adjustments are made after measuring a small sample of production. The uncertainty from the small sample compounds the uncertainty from process variation to enlarge the tolerance band achievable. If 3 or fewer castings are sampled, the tolerance ranges must be enlarged by 20 to 30% to accommodate the sampling problem (Voigt, 1997)

In addition to the development of casting tolerance bands, additional work was done to reduce the amount of reverse engineering required to meet dimensional requirements. While the traditional shrink rules adequately account for the majority of required dimensions, certain casting features may vary significantly from the target. This leads to the production of a pattern, the measurement of results, the adjustment of the pattern, the re-measurement of the castings, etc. It may take a year after the successful production of a quality casting to tune in the pattern to the required dimensions.

The pattern advisor package allows the more accurate prediction of pattern dimensions to achieve the desired casting dimension. Green sand and chemically bonded sand molds with cores and dimensions which crossed the parting line were included. It was found that unrestrained features, those casting features that were not prevented from shrinking due to an included core or mold feature, fully restrained features, those casting features that were prevented from full shrinkage by a core or mold, and partially restrained features required different shrink rules.

SOUNDNESS, SHRINKAGE, AND SOLIDIFICATION

The application of computer simulation to solidification has revolutionized steel casting design. The industry has used casting trials and solidification modeling as a method of re-evaluating riser sizes and feeding distances. The feeding distance relationship for radiographically sound plates is shown in Figure 8 (Carlson, 2003). Changes in mold conditions such as binders or chills, changes in alloy, and changes in superheat can all be accounted for by the use of a simple scaling factor.

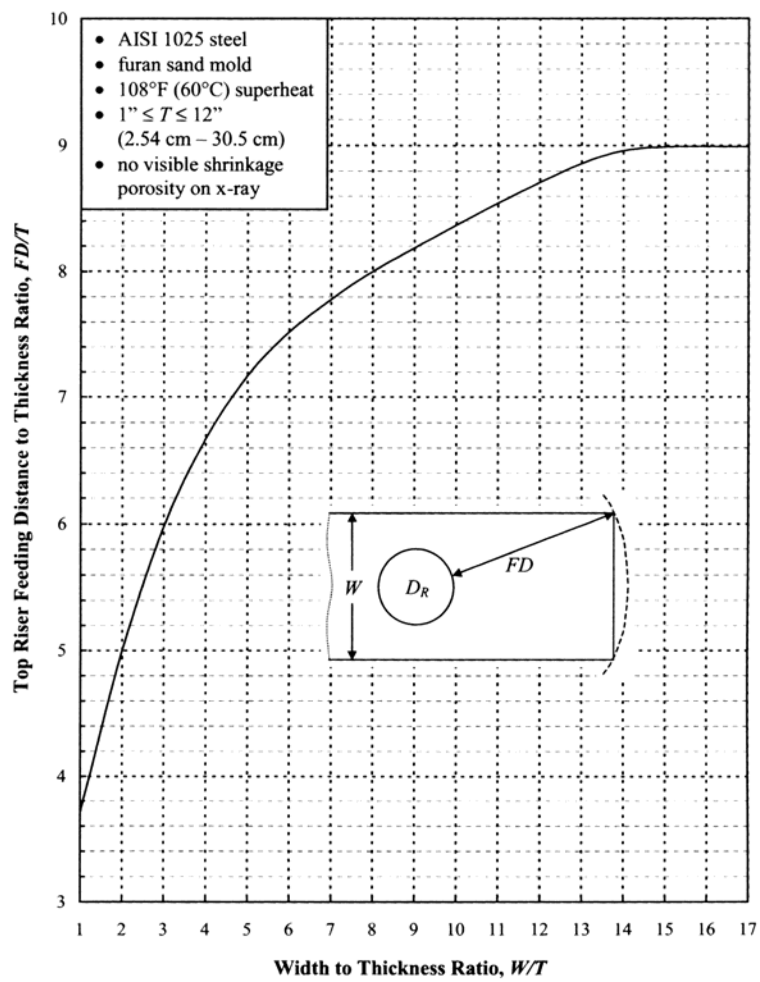

Fig. 8. Feeding distance (FD) as a function of width and thickness for top-risered sections cast with plain carbon steel

Developing the feeding rules required the use of radiographic standards. The lack of correlation of solidification modeling results and radiographic evaluation led to a closer investigation of the standards. An effort was undertaken to use the films of the test plates cast for feeding distance in a gage repeatability and reproducibility study. The results of this effort were revealing. The standards were unable to be repeatably applied even by the most experienced professionals. A sample of the results is given in Figure 9 (Carlson, 2000). The scaling of the standard to the film is an irresolvable issue in the evaluation.

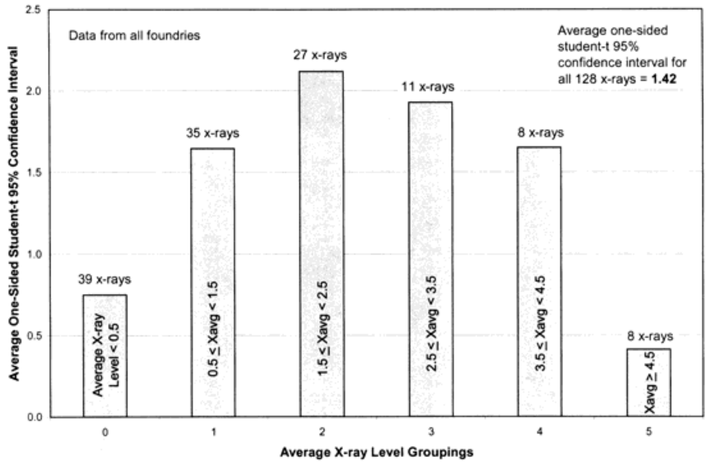

Fig. 9. Average one-sided confidence intervals of x-ray level ratings, grouped by average x-ray level.

Penetration of steel into the mold prior to solidification was troublesome and an effort was made to better understand control of this condition. The historic models of mechanical, chemical and vapor penetration pointed at alloy changes, deoxidation, head height in the mold, etc. that were not often effective in preventing penetration. Instead, foundry practice was to use coatings and specialty sands in hot spots in the mold to prevent penetration. Careful examination of this condition led to the observation that mold areas that are heated above the solidus temperature are prone to metal penetration. Coatings can prevent the occurrence so the condition depends on coating failure. Coatings can fail if applied too thickly or dried too rapidly. Reoxidation inclusions are able to cause coating failure. Damage to the coating in handling can be a source of failure. The use of specialty sands lowers the thermal expansion of the mold surface, reducing the strain on the coating. It also reduces the temperature at the mold metal interface. The toughness of the coating is a key factor in rating coating performance (Richards).

QUALITY AND PRODUCTION

Production of high quality steel castings is not efficient when compared with other manufacturers. In assessing the current production facilities and management of the process, the industry has been unable to resolve this inefficiency. Part of the problem is due to the systemic overcapacity that limits profitability and the resources for new investment. Stagnant markets do not provide the impetus for new technology. The lack of growth and resources are a significant barrier to progress. The layout and production practices of steel casting production have not been adequate. Sorting, handling, and inspection add to the time and cost of production (Rolling).

FUTURE TECHNOLOGY

The success of solidification modeling and stress analysis with the continued rapid development of computerized engineering tools suggest that modeling the casting process will be key to service performance and production. Process modeling the casting operation offers hope of significant improvements in steel casting quality.

For example, current solidification models predict thermal conditions which may result in unsound areas. The recent work used the Nyama criteria to develop feeding distances. Further work has developed a prediction that allows the size and shape of the porosity formed in solidification to be modeled (Carlson 2002) The porosity prediction is being used with traditional stress analysis to predict life in fatigue environments (Hardin). Modeling has also been developed to simulate the formation of reoxidation inclusions (Carlson 2004), hot tears (Monroe 2004) and predict dimensional changes (Ou), It may be possible to use thermal criteria to identify areas prone to penetration in heavy section castings (Richards)

The implementation of modern lean or other manufacturing philosophies along with strong market demand and a lack of domestic capacity may allow steel foundries to reinvest, modernize and dramatically improve quality and productivity. One area identified as a problem is in finishing operations. The welding and grinding required to comply with customer requirements is costly and inefficient. The variability of casting quality due to antiquated equipment and difficult to control processes makes this a challenging management issue. It has been shown that typically 80% of the grinding is unexpected, that is not at the gate, riser or parting line. Small welds to improve surface quality are common. The variability of surface inspection is shown dramatically in Figure 10 (Harwood). Other new efforts are underway to assess surface inspection techniques such as magnetic particle and liquid penetrant.

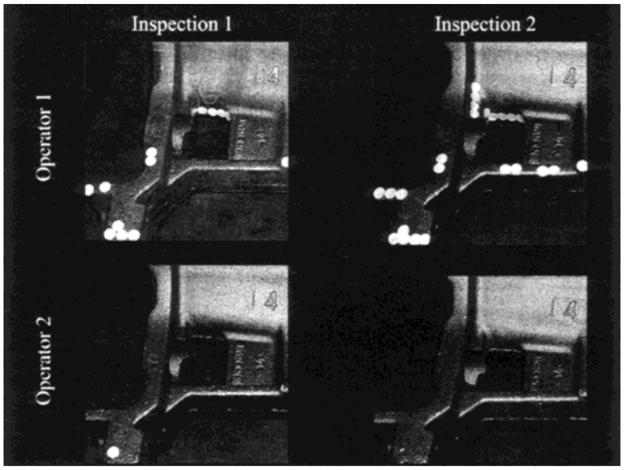

Fig. 10a. Pictures of defects marked on a specified location on one casting four different times. Two inspectors each inspected the same part twice.

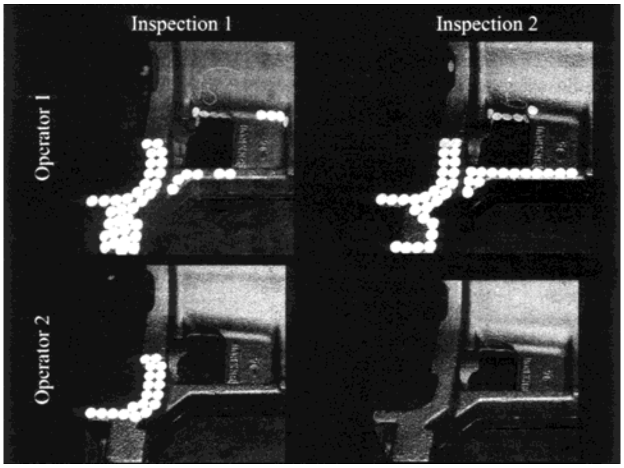

Fig. 10b. Pictures of defects marked on the same specified location on a second casting four different times. Same method used; two inspectors each inspected the same part twice.

In addition to modeling providing tools for dramatic product design and quality improvement and new investment based on new technology offering improved productivity and quality, new markets are being sought for steel castings. For example, building construction uses steel extensively but steel castings sparingly. Steel castings offer a great opportunity to make complex connections in high profile buildings and inexpensive quick connections for more common applications. The performance of steel castings in these types of applications has been shown dramatically in a seismic connection (Poweleit). Steel castings are also finding applications in transportation offering high performance weight reductions (Mikkola).

New markets, advancing technology, and improved production promise a bright future for steel castings

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