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Improvements in Sand Mold/Core Technology: Effects on Casting Finish

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Note: any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Department of Energy.
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EXECUTIVE SUMMARY

Over $10.5 billion in metal castings are produced using sand molds/cores every year. In spite of the size of this market almost no predictive knowledge of how sand structure controls casting surface exists. In spite of the size of the castings market, almost no quantitative information about density variation within the molds/cores themselves is available. Unknown factors in components costing a few cents (the sand molds) impact the quality of components that can cost many hundreds of dollars (the castings). Undesirable surface finish leads to machining costs and substantial amounts of wasted metal. In this study, the development and impact of density gradients on metal castings were investigated using sand molds/cores from both industry and from in-house production.

Our experimental tools and our experience with them made us uniquely qualified to achieve technical progress. We undertook a study of the effects of mold/core uniformity by combining an advanced non-destructive X-ray analysis and an optical profiler. For the first time, predictive connections between the arrangement of sand grains within a mold/core and the resulting casting finish were made. This has significant energy implications for a series of operations within a typical foundry as well as the amount of CO$_2$ released.

The accomplishments of this project include: (1) First application of quantitative XRCT to industrial sand molds; (2) First correlation of variable sand mold density to cast metal surface finish; (3) Development of a simple optical technique allowing subsurface density gradients to be visualized directly; (4) Proof that acoustic stimulation can reduce the density gradients that are ubiquitous in metal casting and (5) Linkages between sand structure and chemistry and the surface roughness of the resulting casting.

It has become clear that density gradients exert considerable control over the surface finish of the associated metal castings. What is less clear is how density gradient lead to other more destructive phenomena such as veining. Commercialization of the optical technique required/requires the availability of a uniform light source. Surface chemistry has additional effects on metal casting finish in conjunction with those caused by low density areas.
CHAPTER 1: PROJECT INTRODUCTION

This final report summarizes the work done under U.S. Department of Energy (DOE) contract DE-FC36-01ID13984 for the period 11/1/00 to 10/31/03. This work was conducted as a part of the DOE Office of Industrial Technology’s (OIT) Industries of the Future (IOF) program through the Cast Metals Coalition (CMC). In this study, the development and impact of density gradients on metal castings were investigated using sand molds/cores from both industry and from in-house production. In spite of the size of the castings market, almost no quantitative information about density variation within the molds/cores themselves is available. In particular, a predictive understanding of how structure and binder content/chemistry/mixing contribute to the final surface finish of these products does not exist.

In this program we attempted to bridge this gap by working directly with domestic companies in examining the issues of surface finish and thermal reclamation costs resulting from the use of sand molds/cores. We show that these can be substantially reduced by the development of an in-depth understanding of density variations that correlate to surface finish. Our experimental tools and our experience with them made us uniquely qualified to achieve technical progress.
CHAPTER 2: BACKGROUND

Over $10.5 billion in metal castings are produced using sand molds/cores every year. In spite of the size of this market almost no predictive knowledge of how sand structure controls casting surface exists. Undesirable surface finish leads to machining costs and substantial amounts of wasted metal. Energy, labor and machine costs all partially derived from these variations.

Ohio State University proposes to undertake a study of the effects of mold/core uniformity by combining an advanced non-destructive X-ray analysis and an optical profiler. For the first time in foundry history, predictive connections between the arrangement of sand grains within a mold/core and the resulting casting finish will be available. This has significant energy implications for a series of operations within a typical foundry as well as the amount of CO$_2$ released. Current barriers are:
1) Penetration is currently difficult to anticipate and impossible to quantify before the casting is formed.
2) Much of the industry uses hand-applied coatings on those defects that are visible; this is not a ‘cure’ and does not prevent post-casting/machining rejection especially in convoluted internal cores.
3) Quantitative relationships between binder content, mixing procedures, sand density and their effects on surface finish do not exist.

The short answer to why these barriers still exist is that the data has not been available. While general information about the phenomena that occur at the metal-mold/core interface exists, there is no current connection of variable metal finish to sand structure. This is a barrier based solely on the historical absence of the experimental tools needed to quantify sand mold/core density and the resulting metal penetration.
CHAPTER 3. RESULTS

3.1 THE QUANTITATIVE CHARACTERIZATION OF INDUSTRIALLY-PRODUCED SAND MOLDS

3.1.1 ESTABLISHING A QUANTITATIVE XRCT BASELINE

X-ray computed tomography (CT) is a nondestructive technique that provides a unique means for the quantitative characterization of sand molds. Information relative to both the formation and performance of these molds can be gathered in a quantitative and reproducible way. The goal of the current study was to extend previous work to establish a quantitative correlation between the mass density of sand molds and scanned density as measured by CT. A quantified description of sand mold uniformity is critical to an improved understanding mold performance during casting operations. This requires that we develop appropriate procedures for accurate and repeatable quantification. We then sought the more aggressive application of this technique to a complex industrial molds used to produce millions of cast components every year. CT provided a clear, quantitative visualization of the distribution of low and high densities within these scanned volumes.

3.1.1.1 Introduction

X-ray computed tomography (CT) is a mature nondestructive technique that can detect internal variations in material density. Being non-contact, non-invasive and unlimited by the complexity of either internal or external surfaces, CT is appropriate for the inspection of a wide range of components including sand molds and their corresponding castings.

High-energy CT systems can penetrate large objects fabricated from the majority of the technologically useful elements in the periodic table. However, porosity, system noise and artifacts inherent to tomography can complicate the translation of CT numbers to absolute physical density (an absolute requirement in any manufacturing scenario). We were able to establish a quantitative correlation between the mass density of sand molds and scanned density as measured by X-ray computed tomography. A better understanding of sand mold uniformity is critical understanding mold performance during casting operations. This requires that we develop appropriate procedures for accurate and repeatable quantification.

During the early stages of our program, CT scans provided the first evidence that this technique had the potential to provide an in-depth understanding of such density variations\(^1\). However, procedures converting measured CT numbers to mass density have not previously been established for foundry sands. The goal of this chapter is to extend this previous approach to establishing physical densities\(^2\) in sand molds.

3.1.1.2 Quantitative Computed Tomography and Image Processing

All sand cylinders used as standards were scanned using a second generation CT scanner located at the Wright Laboratory/Materials Directorate at Wright-Patterson Air
Force Base near Dayton, Ohio. The scanner, known as LAM/DE\(^*\), is a moderate-energy CT system which was developed as a test bed for investigating laminography (LAM) and dual energy (DE) radiographic techniques. LAM/DE also serves as a research instrument for computed tomography and digital radiography applications.

The CT scanner used for this research is located at the Wright Laboratory/Materials Directorate at Wright-Patterson Air Force Base near Dayton, Ohio. The scanner, known as LAM/DE\(^*\), is a moderate-energy CT system which was developed as a test bed for investigating laminography (LAM) and dual energy (DE) radiographic techniques. LAM/DE also serves as a research instrument for computed tomography and digital radiography applications.

This second-generation system employs a conventional bremsstrahlung X-ray source. The Isovolt 420\(^*\) X-ray source, utilizes a tungsten filament and stationary tungsten target. The source is capable of delivering 420 keV peak energy at 5.0 mA with a 1.5 mm focal spot. The system's mean energy has been experimentally determined to be 225 keV. The LAM/DE CT system has a resolution aperture which is variable from 0.63 mm to 4.5 mm and a slice thickness aperture which is variable from 1.2 mm to 15 mm. LAM/DE has the capacity to handle objects up to 625 mm in diameter, 400 mm high and 100 kg.

The first step in working with this data is to eliminate noise and artifacts from the post-analysis\(^3\). Following this, the correct region-of-interest (ROI) must be specified. The most straightforward path of achieving this is to eliminate partial voluming or those regions of the scan that average the specimen with the surrounding medium. This is easily accomplished by "shrink wrapping" an ROI around the object but above a critical CT number. Once this range has been established, CT densities can be obtained from each individual sample based on this individual standard.

To correlate this with absolute density each of the cylinders was measured using the Archimedes method; less than 2% of moisture remained in each cylinder at the conclusion of the test. The equation for the relationship between density and CT number is as follows:

\[
\text{Density} = \text{CT#} \times 0.000055932 + 0.13255 \quad (R^2 = 0.95353)
\]

This is quite similar to the form previously derived for alumina\(^3\) which has successfully been employed elsewhere\(^7, 8\).

3.1.1.3 Application to Molds from GM PowerTrain (Defiance, OH)
Utilizing these quantitative procedures, we examined core molds fabricated by GM Defiance Powertrain group. All cores arrived at the WPAFB XRCT facility in one piece (thanks to personal transport by Jim Tyler). The cores were loosely held together in a tall box filled with polystyrene packing "peanuts". Cores were scanned perpendicular to the long axis of each mold. Scans took place along the vertical dimpled area identified as the location of veining during casting. All cores were immediately returned to Defiance after scanning was completed.

\(^1\) Manufactured by Advanced Research and Applications Corporation (ARACOR), Sunnyvale, California.
\(^2\) Manufactured by Advanced Research and Applications Corporation (ARACOR), Sunnyvale, California.
\(^2\) Manufactured by Seifert X-ray Corporation of Fairview Village, Pennsylvania.
Our observations are that these cores consistently increase in density from the upper end to the smaller ‘tail’ region. **Higher** (not lower densities as expected) densities were observed around the critical end that has historically experienced veining problems. The sand contains a few scattered metallic inclusions as expected.

Different groups were examined. Qualitatively, the appearance of density gradients is the same in each group. We used the quantification of density afforded to us by the work described earlier in this chapter to show that quantitatively the density of the ‘E5’ group cores appear to be higher. In both cases, the critical end leading to veining has a quantifiably higher density.

We can plot average values using all the E1 and E5 curves as shown in Figure XX. Our observations are that E5 cores are slightly higher density (about 2% on average) than the E1 cores. This density difference decreases about halfway up the core (from 4% to 1%). These density differences are not as dramatic as those we’ve seen elsewhere.
Figure 3.1-2. Quantitative variation in density from the bottom (left-hand side) to the top (right-hand side) of the parts shown in Figure 3.1-1.

Possibilities explaining the tendency of these cores to allow/undergo ‘veining’ at the denser end include:

1. Local surface densities are higher than what we can see w/this XRCT due to surface voluming considerations.
2. A critical value of density (~1.68 g/cc) is associated with a structure than cannot expand (a ‘locked’ structure) and this leads to cracking.
3. Metallic inclusions are present and these expand more rapidly than the surrounding grains nucleating a crack in these high density zones that are not as able to accommodate rapid expansion as low density zones.

3.1.1.4 Application to Molds from Alotech (Cleveland, OH)

Surface finish is a major concern in the production of aluminum castings at Alotech. We believed that variable density in the sand molds could account for much of these variations in surface finish. Low density areas in sand cores/molds could contribute to unwanted metal penetration/burn in/burn on etc. during the casting process. Scanning of and quantification of the molds and cores from this industrial collaborator allows us to determine a) if a problem actually exists and b) the severity of the problem. Components (Figure 3.1-3) were obtained from Alotech and scanned (Figure 3.1-4) to establish initial estimates of density.
Figure 3.1-3. An Alotech core on the XRCT table at WPAFB.
Figure 3.1-4 shows that the density gradients in the center of the core are extensive. This is not very surprising given that it is primarily just a loose fill that never sees hot metal. Of greater interest are the gradients in the outer ring area as these control critical surface finishes. The outer ring appears to exhibit some variations in density. Reconstruction artifacts (multitude of tangential lines originating from outer circumferences) made these difficult to ‘see’ with total certainty. To circumvent this we decided to section (using a band saw) the core and separate inner and outer components to eliminate these artifacts.
Figure 3.1-5. The sectioned core on XRCT table at WPAFB.
Figure 3.1-6. XRCT of sectioned core 2 mm below the top of the core.

Figure 3.1-7. Qualitative observations of density variation in the outer ring that very likely determine surface finish.

As Figures 3.1-6-3.1-7 show, density gradients do exist in the outer ring. These appear to be significant enough (in our experience) to contribute to surface finish inhomogeneities.
Using the density correlation developed for 1L5W Lake sand we can produce quantitative estimates of density variation (Figure 3.1-8).

![Figure 3.1-8](image)

Figure 3.1-8. Density gradient variation along the ‘arc’ of the core segment as quantified by XRCT.

These results show that significant density gradients do exist in critical sections of the Alotech core. These variations can be ‘mapped’ onto the surface of the corresponding casting by examining the as-cast surface via optical profilometry. Development of a visual tool allowing ‘early’ detection of density gradients will be beneficial as this would allow cores to be modified/replaced to increase the probability that the casting will appear visually ‘perfect’.

Areas for further research involve:
1) Investigation of different ‘filling’ conditions.
2) Probe finish variations versus vertical position along fill line; temperature - finish correlations?
3) Examine surface finish regularity; correlate to regularity of the sand structure in the core surface
4) Use of manufacturer-derived sand sand (approximately 10 pounds) to allow for development of more accurate density calibrations.
3.1.1.4 Application to Molds from Honda (Marysville, OH)

Surface finish is a major concern in the production of steel castings at Honda. We believed that variable density in the sand molds could account for much of these variations in surface finish. Low density areas in sand cores/molds could contribute to unwanted metal penetration/burn in/burn on etc. during the casting process. Scanning of and quantification of the molds and cores from this industrial collaborator allows us to determine a) if a density variation problem actually exists and b) the quantitative severity of the problem. Figures 3.1-9-3.1-11 show the qualitative variation in density for sand mold cores excised from much larger core assemblies. The lower density areas likely correspond to penetration and roughness generated during the casting process.

Figure 3.1-9. CT image of core #5.
Figure 3.1-10. CT image of core #6.
Figure 3.1-11. CT image of core #7.

Figure 3.1-12 provides a quantitative summation of the standard deviation in density within each of the small components in these cores. Within each of the core assemblies there are clearly individual cores that experience much wider variations in density and these are most likely to lead to problems with metal penetration and the associated decreases in surface finish and gas flow.
3.1.1.5 Conclusions

CT provides a unique means for the quantitative characterization of sand molds. Information relative to both the formation and performance of these molds can be gathered in a quantitative and reproducible way. These descriptions of sand mold density provide previously unavailable opportunities for quantitative process improvement at all stages of sand mold/core formation.

Figure 3.1-12. Quantitative variation in density expressed in terms of the standard deviation present in each of the individual molds in Figures 3.1-9 - 3.1-11.
3.2.1 NEED FOR A VISUALIZATION TOOL
Density gradients appear to be inevitable in all molds/cores formed using foundry sand. As a result, sand surfaces worth only a few cents control the quality of far more expensive metallic products. The best solution to the problem is to reject/repair the mold or core before casting takes place. Through X-Ray Computed Tomography (XRCT), we have acquired expertise in detecting and quantifying those gradients. However, XRCT is both too costly and slow for use in the average foundry. A simple indicator dye in the sand appeared to offer a means of detecting internal density gradients as they intersect the external casting surface. An inexpensive dye that fluoresces when present in very small quantities was determined to be the best choice. A series of sand molds were processed using the dye; no negative effects of the presence of the dye on the formation process were detected. XRCT images of the sand surfaces were obtained and provided good correlation to the results of dye incorporation and visual inspection. A series of issues were addressed: (1) source distance, intensity and uniformity; (2) dye absorption-reemission wavelengths and total content; (3) dye location and mixing; (4) visual image acquisition and post-processing; and (5) gradient sensitivity/’fit’ to XRCT data. We anticipate that the long-term use of this tool is in a stylus containing both an embedded fluorescence source and detector.

3.2.1.1 Introduction
Although sand cores/molds often appear uniform to the naked eye, experience tells us that density gradients – non-uniform distributions of sand and/or binder – are universal in products formed using standard foundry sands and processes. As a result, surfaces composed of sand and binder that are worth only a few cents control the surface quality of cast metal products costing hundreds of dollars or more. Instead of devoting time and resources to cleaning the most efficient solution is to detect quality-limiting density gradients beforehand and reject/repair the mold or core before casting occurs, thus avoiding the negative effects of density gradients on casting quality altogether.

Our program at OSU has relied on the quantitation and comprehension of sand mold/core problems afforded to us by utilization of X-Ray Computed Tomography (XRCT). However, we are familiar with the standard objections to it as an industrial tool for day-to-day operations: capital and operational costs, safety regulations and scanning speed. In response, we began a search for a technique that would allow shop floor personnel to ‘see’ density gradients in mold/core surfaces either with the naked eye or with minimal equipment. Our previous quantification of density gradients in sand molds [1] played a major role, however, as it provided the absolutely necessary validation of any visually-based method. Also, we now know that penetration is controlled by density in two distinct ways: (1) low density (LD) zones lead to generalized penetration and roughening and (2) high density (HD) zones lead to veining.
A simple dye that provided visual, concentration-dependent evidence of density gradients from a sand-binder surface was judged to be the simplest solution. In addition, however, this dye needed to be able to function with a variety of sand colors (especially darker recycled sands) without being impeded by competitive absorption. XRCT images of the sand surfaces were obtained and provided good correlation to the results of dye incorporation and visual inspection. A series of issues were addressed: (1) dye absorption-reemission wavelengths and total content; (2) source distance, intensity and uniformity; (3) dye location and mixing; (4) visual image acquisition and post-processing; and (5) gradient sensitivity/’fit’ to XRCT data.

3.2.1.2 SOURCE DISTANCE, UNIFORMITY AND INTENSITY
In attempting to obtain reliable optical data from sand surfaces containing the UV-active agent, one of the first difficulties we had to deal with involved finding a truly uniform light source. We evaluated several commercial, hand-held UV-emitting units; to the naked eye, each of these units emits a uniform light intensity. However, careful image analysis (Figure 2) shows that in fact these units each display a distinctive ‘footprint’ of intensity that decreases with increasing distance from the filament/tube source that provides the radiation. While this behavior has no negative consequences in examining castings for highly localized concentrations of dye, it completely obscures larger scale density gradients. Surprisingly, we found that simply relying on overhead fluorescent lighting (at a distance of approximately 10 feet) was more reliable and less likely to produce misleading indications of density gradients where none existed. Uniform commercial UV-emitting units can be purchased (http://www.execulink.com/~scitech/psitemap.htm) although these are expensive and are currently outside the scope of our program. In the end, we chose to work with sunlight, a freely available source of perfect uniformity. However, given that the sensitivity of this technique scales with intensity (and greater intensity requires less dye), more intense yet still uniform sources may be required.

Figure 3.2-2. Image analysis of the ‘footprint’ of light intensity produced by low-cost, commercial UV sources. The intensity on the surface of a sand block clearly drops off as a function of distance from the filament/tube, essentially superimposing an artificial density gradient across the surface and obscuring gradients in density.
3.2.1.3 GRADIENT QUANTIFICATION/'FIT' TO XRCT DATA
A critical test of this concept is comparison to quantifications derived from XRCT data. Our prior experience with the cylindrical molds showed us that distinguishing density gradients in flat surfaces will be easier, Figure 3.2-5 shows an image of a simple sand block into which 3 hand-rammed holes have been produced. This produces three HD zones on the opposite flat face that we define as the casting surface. Cross-sectional XRCT (Figure 3.2-4) was then performed to quantify the density gradients along a line bisecting two of these HD zones. Quantification utilizing a previously established routine [1] was then carried out and the results plotted in Figure 3.2-5, which shows how the density varies along a line running along the very bottom row of pixels in Figure 3.2-4. Figure 3.2-6 provides the optical output, quantified in terms of camera pixel intensity, across the same section. The results appear to be very encouraging: as the absolute density of the sand first increases and then decreases, the intensity of light output from that same surface first increases and then decreases. A comparison of the intensities corresponding to the two density regions also shows remarkably similar behavior.

The previous data involved the use of an XRCT cross-section; we reasoned that comparing a planar scan to the optical data would be more relevant and would provide more realistic information. To do this, a smaller 8-lb block was prepared and an ‘O’-shaped HD zone produced by ramming using a PVC pipe having an inner diameter of 6.9 cm and an outer diameter of 8.6 cm. Figure 3.2-7 shows the optical image of the as-fabricated block; Figure 3.2-8 is the same image following image processing to maximize the differences in intensity. While the ‘O’-shaped HD zone can be distinguished, a corresponding planar XRCT scan (Figure 3.2-9) suggests that the technique does not have equivalent resolution.

The lack of fine resolution may not be an issue for the majority of foundrymen. The two defects that concern most mold/core fabricators are a) swelling and b) veining. These are both due to the existence of either very low or very high relative densities in the surface. The current resolution is sufficient to detect defects of these relative magnitudes. However, we are currently attempting to improve resolution using:

1. A cutoff filter (Oriel Instruments, Stratford CT) that eliminates stray radiation above 480 nm and below 420 nm. This restricts the emission used for detection to only those wavelengths emitted by the dye itself.

2. Better mixing procedures. We have some concerns that the mixing of the dye with the sand may not be perfectly uniform. This could conceivably result in brighter and darker spots in the image, a feature we have seen in all of the optical images to date. Alternatively, these could be the result of more- versus less-reflective sand grains at the surface.

Finally, in discussing this technology with foundrymen it has become clear that the density gradients in large flat surfaces are of interest to those involved in the manufacture of components having large flat surfaces; here, swelling is a particular concern. However, many individuals are working with relatively small features (corners, fillets, grooves, etc.) where penetration can also be particularly troublesome and difficult to remove. For this reason we are pursuing the development of a stylus source-detector arrangement that would consist of a coil of optical fibers. Half of the fibers would
transmit UV light to the surface; the other half would detect the emitted radiance of the surface. The sensing bundle would be filtered to eliminate the original UV light and return only that associated with the dye. Such a bundle could be encapsulated inside a probe tip that could be shaped for a particular problem area; the bundle itself could be reused in a variety of probe tip shapes. As the technique would be purely quantitative it would produce data like that seen in Figure 3.2-5 and would eliminate image collection, processing and interpretation.

Figure 3.2-3. Image of three hand-rammed holes in a block made using 1L5W lake sand, pepset binder and 0.005 wt% Tinopal SFP. Use of hand-ramming provided both more gradual gradients than the previous images and guaranteed that the resulting HD zones would be more randomly-shaped.

Figure 3.2-4. The XRCT cross-section bisecting one of the hand-rammed holes in Figure 3.2-5. The “casting surface” for this block is located at the bottom of this image.
Figure 3.2-5. Quantitative data showing the density variation associated with the “casting face” of this block; two separate holes were sampled using XRCT.

Figure 3.2-6. The intensity data associated with the same areas as collected using a digital camera. The same general trends seen in Figure 3.2-5 are observed.
Figure 3.2-7. Optical image of an 8-lb square block fabricated to contain an ‘O’-shaped HD zone in the visible surface.

Figure 3.2-8. The same image seen in Figure 3.2-7 after treatment using image analysis to maximize pixel contrast across the surface. The HD ‘O’ is visible. The red rectangle is used to demarcate that section of the surface used for quantitative analysis of pixel intensity.
3.2.1.4 CONCLUSIONS
An optical technique has been developed that can provide substantial amounts of information regarding density variation in a sand mold/core surface without the need for XRCT. A series of issues were addressed to produce a technique is particularly useful for sensing the extremes of density (either relatively high or relatively low densities in a surface) that lead to surface defects such as swelling or veining. Without access to better, more uniform light sources it is still too soon to tell if the technique can be optimized to provide the same degree of density resolution as XRCT. We anticipate that the long-term use of this tool is in a stylus containing both an embedded fluorescence source and detector.
3.3 ACOUSTIC STIMULATION AND DENSITY VARIATION IN SAND MOLDS/CORES

3.3.1 NEED FOR ACOUSTIC STIMULATION

$10.5 billion in metal castings are produced using sand molds/cores each year. In spite of the size of this market, the ability of the foundry industry to control density variation in these sand bodies is limited. This has direct impacts on the amount of energy required to finish these parts as variable sand density is directly responsible for poor casting surface finish, metal penetration and veining. In this program we will target a large reduction in these problems and the associated energy costs by working directly with domestic companies in integrating a relatively new technology, acoustic stimulation that has been recently proven to minimize these internal variations. The experimental tools we use and our experience with them make us uniquely qualified to achieve rapid technical progress toward the following commercially goals:

1) Provide a predictive understanding of acoustic stimulation of sand mixtures inside mold cavities: source characteristics, sand characteristics, particle size, binder loading, and cavity size.

2) Determine the effects of acoustic stimulation on final core/mold quality: what maximum overall densities and minimum internal density variations can be achieved?

3) Continue to work directly with metal casting manufacturing operations to integrate this technology onto the manufacturing floor as rapidly as possible. X-ray Computed Tomography (XRCT) will be used to establish the effects of acoustic stimulation on density variations and optical profilometry will quantify the effects on roughness.

3.3.1.1 Technology Status

Penetration and metal veining are common occurrences in ferrous metal casting processes that use sand cores/molds to shape molten metal. Figure 1 shows the results of low-density zones on the roughness of as-cast metal surfaces. For both aesthetic and engineering reasons, these values of surface roughness must be reduced to a certain level prior to release of the casting to the customer. These machining operations can, depending on the level of penetration/roughness, require many hours of continuous hand grinding of large castings before an acceptable finish/dimensionality is produced. In an attempt to minimize this, the metal-casting industry applies specific surface coatings to the entire sand surface or on visible defects; this is far from a ‘cure’ and does not prevent post-casting/machining/rejection especially in convoluted internal cores.
Figure 3.3-1 showed how density controls casting surface finish. The casting surfaces of molds/cores in fact consist of a wide range of densities, not just a single value corresponding to the overall density. These internal variations lead to variable interactions between the metal and the sand and, when local values of density are low, excessive penetration into the sand as seen in the left-hand side of Figure 3.3-1. What is the extent of these internal density variations? Figure 3.3-2 shows the standard deviation of density within commercially produced, multi-part industrial cores as determined by the only technique capable of providing such information, X-ray Computed Tomography (XRCT). We can clearly see that density is not a constant value and can vary widely within a given core/mold surface.
Figure 3.3-2. Density variation in cores made by a prominent automotive manufacturer. While each core had an identical visual appearance, this XRCT data shows that the standard deviation in density (expressed as CT number) can be relatively small (cores 5 and 7) or much larger (cores 6 and 8). Cores 6 and 8 are more likely to produce castings that require machining to remove metal penetration.

Figure 3.3-3 is a profilometry image of an as-cast steel surface showing how sand and molten metal interact at a small scale. Metal penetrates in-between the sand grains that make up a casting surface. Lower density surfaces allow metal to penetrate further between the grains, resulting in greater roughness, increased likelihood of penetration and more post-machining.
Figure 3.3-3. Optical profilometry (Veeco NT 3300) analysis of a 1025 steel casting surface. The red-yellow areas are the ‘high’ spots on the surface that result from metal penetration. The blue areas are the ‘valleys’ in the surface that correspond to sand grains at the interface.

Mechanical or vibratory stimulation of the sand in a mold has been attempted as a means of homogenizing the sand structure to avoid the kind of part-to-part variation seen in Figure 3.3-2. Commercial examples of this technology include jolt tables and vibratory compaction tables. Neither of these technologies fully eliminates the problem of variable density and both can be very difficult to efficiently implement into core/mold production facilities. For example, to integrate a jolt table into a green sand production facility at the appropriate point during the process would require that the entire mold and press (hundreds if not thousands of pounds of metal) as well as the sand inside the mold be shaken.

During the Cold War, as the foundry industry continued to struggle with this problem, giant magnetostrictive lanthanide alloys were discovered and developed by the US Navy to provide higher performance than piezoceramics in sonar applications. Higher acoustic power, lower frequency and broader bandwidth were considered essential to next generation sonar. Many of the lanthanide (or rare earth) metals were discovered to exhibit "giant" magnetostriction, with strains of 1000 ppm or more. A metal known as “TERFENOL-D” was selected for commercial development because of its high power output, good temperature characteristics, and good magnetic properties, which allow reactively low drive current and high efficiency. The name comes from the metallic elements; terbium (TER), iron (FE), Naval Ordinance Labs (NOL), and Dysprosium-D. NOL developed and named the material, and is now known as Naval Surface Warfare Center (NSWC). The Navy developed TERFENOL-D for higher power sonar that would also have greater bandwidth and greater reliability.

TERFENOL-D is "magnetostrictive" meaning it changes shape in a magnetic field. TERFENOL-D has a greater shape change, or strain, than other common transducer materials, such as piezoceramics or nickel alloys. This means acoustic devices driven by TERFENOL-D have greater power, and actuators have more displacement and more force. Like other magnetostrictive alloys, TERFENOL-D does not change with time or number of cycles. TERFENOL-D allows electrical energy to be converted to mechanical energy in a solid-state fashion. The electrical energy is converted to a magnetic field through a coil wire wrapped around a cylinder of TERFENOL-D. The input of an alternating current, results in an oscillation of the TERFENOL-D. The material has garnered much attention because it can be used as a drive motor without any moving parts. Although life cycle testing continues, the material has been shown to withstand at least 100,000,000,000 cycles without performance degradation.

Over the past several years Furness- Newburge, Inc. (Versailles, Kentucky) has been working with ETREMA Products, Inc., Pennsylvania State University, TechSavants and Argonne National Laboratories to investigate the application of this range of acoustic energies in innovative remediation processes. Furness-Newburge has developed significant remediation technology, trademarked SonoperoxoneTM, which Pennsylvania
State University is researching. This technology uses high intensity ultrasound with advanced oxidants to chemically break down Volatile and Semi-Volatile Organic compounds (VOC’s and SVOC’s). The SonoperoxoneTM system sparges oxygen and ozone gas at the base of the tool into a sonic reaction chamber. There the gas dissolves into contaminated water and combined with ultrasonic energy creates very rapid oxidation reactions. Multiple species of oxygen and hydrogen radicals (advanced oxidants) have been identified when SonoperoxoneTM breaks down both chlorinated and unchlorinated organic compounds.

As the Sonoperoxone technology has already been successfully applied in the foundry industry, Furness-Newburge was interested in developing other applications of acoustic stimulation within this same industry. On March 11, 2002, a status report of OSU’s DOE-funded work entitled *A Visualization Tool for Predicting Mold/Core Penetration*, was presented by John Lannutti during EMTEC’s Casting Technology Update in Middletown, OH. As a result of that meeting, contact was made with Jim Furness of Furness- Newburge. On March 25th a demonstration of the acoustic stimulation technology for sand compaction was held in the foundry at the Ohio State University. In attendance were Jim Furness, Bob Bigge (ICRI), Carroll Mobley (OSU), John Lannutti and Zhijun Zhao (OSU). Subsequent XRCT analysis proved that these cores were more uniform than cores made by either blow molding or hand ramming operations (Figure 4). A presentation was made at the American Foundry Society 106th Casting Congress & Cast Expo (May 4-7, Kansas City MO) concerning the development of the visualization tool and this generated interest on the part of Neenah Foundry in applying acoustic stimulation in their mold/core processing.

![Figure 3.3-4. Density variation in cores made by standard hand ramming (“OSU HR”), industrial blow molding (from foundries ‘A’ and ‘B’), and acoustic stimulation.](image-url)
Sand density variations drop to the minimum amount when the sand is fluidized inside the mold using acoustic energy.

On May 15\textsuperscript{th} 2002, John Lannutti accompanied Jim Furness and Steve St. Vincent (Etrema Products) to the Neenah Foundry in Neenah, WI. There they met with Harvey Luebben (Plant 2 Manager), John Andrews (VP of Manufacturing) and Jeff Goudsward (Engineering Manager) and engaged in tests of the acoustic stimulation process as applied to core formation. As an enthusiastic user of the Sonoperoxone technology Neenah graciously donated production line time to study the integration of acoustic technology into mold/core manufacturing. Preliminary testing began using a bench-scale model of a TERFENOL-powered acoustic horn was used to examine two methods of acoustic stimulation: side stimulation of the cavity wall (Figure 3.3-5a) and direct stimulation of the sand itself (Figure 3.3-5b). Cores made using standard hand ramming and vibratory compaction were also produced for comparison. These cores were sent to OSU where they were scanned utilizing XRCT to determine their internal standard deviation in density. Figure 3.3-6 provides specific XRCT data showing that more work is needed to understand how acoustic energy can propagate inside a mold cavity. Key differences between this process and standard low frequency air powered vibration appear to be that acoustic stimulation produces higher sand densities. However, more controlled trials to determine optimum frequency and dose (time) are needed.

![Figure 3.3-5. Application of acoustic energy to a sand mold cavity at Neenah Foundry from the side (a) and from the top (b). The acoustic actuator (circled) is visible as a metal cylinder in both cases. In neither application is it necessary to vibrate the entire core box.](image-url)
Figure 3.3-6. XRCT images of hand-compacted as acoustically stimulated cores made at Neenah Foundry. White-red-yellow-green-blue represents the highest to lowest densities in these images. We can see the sand structure resulting from the filling process is still preserved in the hand-compacted core (a) while it is largely disrupted in the acoustically stimulated core (b). However, the acoustically stimulated core is not as uniform as those fabricated in the foundry at OSU. Propagation is clearly controlled by the length/diameter ratio of the mold cavity; we need to know more about how to successfully optimize this process.

Key to the success of these process improvements is the unique broad frequency response and high non-resonant amplitude of TERFENOL-powered acoustic actuators. As a result of forming a long-term strategic business agreement with Etrema, Furness-Newburge has specified this type of actuator for use in the sand compaction systems and several other energy saving foundry applications Furness-Newburge has developed.

An additional critical component of the project is the availability of an XRCT unit and the technical ability to convert these scans to quantitative measurements of density. Finally, optical profilometry is also available to us to evaluate surface roughness. In short, domestic industry or other commercial sectors cannot implement the proposed concept without this intersection of acoustic and analytical technologies. Without XRCT, compaction is largely a “black box” phenomenon and the quantitative effects of acoustic stimulation on density variation are completely mysterious.
3.3.1.2 Energy benefits

In this analysis we work extensively with the recent data derived from *Energy and Environmental Profile of the U.S. Metalcasting Industry*, by Energetics Inc., (1999). This document contains up-to-date information providing a general overview of the foundry industry that largely describes the energy justification for our investigations. The following analysis provides information regarding net energy costs to the foundry industry. In the following analysis we generally use conservative estimates. Our own expectation is that the actual impacts will be higher.

We begin by considering the energy costs associated with *surface finishing metal losses*. Out of 14,500,000 tons of metal cast/year in the US, 60% is cast against sand molds. This amounts to 8,700,000 tons/year requiring 15,000,000 Btu’s/ton. Of this, the report estimates that 0.5 to 1.0% is removed by surface cleaning and finishing (not the removal of gates and risers) operations associated with the use of a sand-based mold/core. We conservatively take only 30% of the average value (0.75%) of this (which amounts to 0.225%) as due to penetration preventable by a better control of variable internal density. On a per part basis the amount of metal removed will be highly dependent on the application and the desired surface finish. Our target seems easily achievable as the greatest/deepest penetration into the sand structure will be most affected. This produces a savings of 19,575 tons of metal or an energy savings of 293,625,000,000 Btu’s/year.

Next we consider the energy costs directly associated with the *surface cleaning and finishing operations* themselves. These operations require 1,000,000 Btu’s/ton; if only 20% of this is preventable by better control of internal density variation by the results of this project this will produce approximately 2,900,000,000,000 Btu’s of energy savings/year.

Reductions in the amount of binder used/year lead to direct reductions in the amount of energy needed to reclaim foundry sand. These energy costs associated with *thermal reclamation* are considerable and worthy of analysis. At 150 kWh/ton (511,821 Btu) of sand this amounts to 2,968,563,220,820 Btu’s/year. If we assume that binder (either organic or clay-based) content can be safely and conservatively reduced by a maximum of only 10% using acoustic stimulation the total energy savings will be 296,856,322,082 Btu’s/year.

Finally, we considered the effects of surface roughness on *casting yield* itself. Roughness constitutes the beginnings of more serious penetration that can lead to rejection (such as veining or swelling). This leads us to conclude that scrap rates due to mold/core density variations will also decrease if the origins of surface finish problems are controlled. If we examine the energy savings associated with small improvements in casting yield we find even just a 1% improvement in yield will produce significant energy savings (130,500,000,000 Btu’s).

For these four categories closely tied to sand mold/core technology, these conservative estimates produce a total energy savings of about 3,620,981,322,082 (3.6 trillion)
Btu’s/year. Of this metal losses are about 8%, casting yield 4%, thermal reclamation 8%, and cleaning and finishing 80%.

3.3.1.3 Economic and environmental benefits

The US foundry industry is suffering from foreign competition of their lower wage scales and relatively trivial environmental standards. Environmental constraints on the industry continue to grow in cost and complexity. Of greatest relevance to this proposal is the fact that the cleaning and finishing operations are the last step in the casting process. Up to 20% (on average) of the labor cost in foundries occurs at this stage in the process. In addition, this is probably the least appealing portion of the manufacturing process as it is very difficult to attract and retain workers in this area. Any technology that improves both profitability and the quality of the working environment in the foundry industry will bring immediate benefits to the industry as a whole.

If the US industry utilizes R&D efficiently it is generally predicted that the production of cast metals (14,500,000 tons/year) will remain relatively stable through 2010. Following that time, however, uncertainty over potential environmental regulations make predictions out to 2020 unreliable at best. However, relative to worldwide production the US industry will undoubtedly be able to cast metals with minimal emissions.

3.3.1.4 Environmental benefits

The contribution of greenhouse gases resulting from the casting process itself consists primarily of CO and CO$_2$ emissions resulting from gas fired melting furnaces; an average value is 300 kg/ton of molten metal. By eliminating 30% of the metal losses associated with variable densities, we estimate that 5,872,500 kg of CO and CO$_2$ emissions will be eliminated each year. Additionally, better compaction of sand can possibly allow a foundry to use up to 10% less organic resin in core production. As this resin is the source of approximately 50% of the VOC air pollution from pouring, cooling and shakeout of a casting operation, this could represent a 5% reduction in these emissions. Assuming an emission factor of 1.2 pounds of VOC per ton of iron poured and 15,500,000 tons poured per year, this could result in a reduction in emissions from better sand compaction of 870,000 pounds per year. Many of these emissions are targeted hazardous air pollutants such as benzene.
3.4 METAL PENETRATION IN SAND MOLDS: EFFECTS OF DENSITY AND SURFACE CHEMISTRY

3.4.1 INTRODUCTION

The production of high quality, net shape castings implies smooth surfaces free from visible defects. Preventing this are thirty-one documented casting defects that compromise the surface of an otherwise perfect casting [1]. Some produce a casting that is a total loss, where the cost of salvaging the casting is greater than its value. Others are minor and allow economic salvage/recovery but at a substantial yearly expenditures of cleaning room time. Whatever the source, casting defects represent a loss to the foundry industry.

Standard foundry knowledge often identifies variations in density and being the cause of undesirable penetration. Classic views of the behavior occurring at the sand-metal interface support this: as the distance between the sand grains increases so does the penetration [Lysachenko]. Hundreds of additives are mixed with various types of sands in the foundry industry. Approximately twenty are used more than all others combined. One category of these are the iron oxides. The principle forms used in the foundry are those ground from hematite, magnetite, limonite and siderite ores. The majority of iron oxide used currently is hematite ore (Fe$_2$O$_3$) in which the iron content varies from 30 to 55%. Hematite fine powders are very efficient in preventing casting defects. Foundries making gray and ductile iron castings find iron oxide useful in promoting easier cleaning. A good quality iron oxide, if used properly, should be able to (1) improve casting surface finish; (2) decrease veining and penetration; (3) reduce burn-on; (4) reduce or eliminate pinhole porosity and (5) decrease carbon pickup and lustrous carbon defects.

In the overall context of our work on the relationships between sand density and casting finish, including the effects of this additive provided an additional variable providing us with a more complete perspective of the metal-mold interface.

3.4.1.1 Background

It has been observed that the addition of hematite (Fe$_2$O$_3$) to a core/mold is effective in minimizing lustrous carbon defects in iron castings. It is believed that iron oxide helps to oxidize the carbonaceous residues resulting from binder decomposition and minimizes the reaction between FeO and carbon. Less carbon monoxide is produced and therefore the formation of lustrous carbon defects is significantly reduced. This mechanism should also apply to steel castings.

Veining occurs when a crack opens in the mold surface and molten metal fills it in. It is a serious casting defect characterized by metal ‘fins’ that can occur in inaccessible areas. Two variables known to contribute to veining includes uniformly-graded sands and high compaction density. The addition of iron oxide to the mold/core reduces the amount and severity of these defects. This is because iron oxide is believed to soften the sand mixture and allow it to deform without cracking. At the same oxygen content, raising the temperature favors the reduction of the higher order iron oxides to lower order iron
oxides, that is the conversion of hematite (Fe$_2$O$_3$) to wustite (FeO). Wustite (FeO) reacts with silica and form the FeO-SiO$_2$ eutectic known as fayalite. As the FeO-SiO$_2$ eutectic melts at 2150 ° F. (1178 ° C), one stated reason for the efficiency of iron oxide in softening the sand mixture and increasing hot compression strength and plasticity is that this iron oxide ‘glaze’ is compressed on a flat plane just beneath the core surface, thus lowering the possibility of crack formation. This glaze also prevents gas produced by binder decomposition from contacting the metal to reduce the frequency of pinhole defects.

Another use of iron oxide is the prevention of surface carburization or lustrous carbon formation. Lustrous carbon is formed by the decomposition of organic binders and can strongly affect the casting surface. Higher order iron oxides, e.g. hematite, in this hot reducing environment decompose to lower oxides and release oxygen into the mold atmosphere. The released oxygen reacts with excess carbon forming carbon dioxide. The hotter and more reducing the atmosphere is, the faster and more complete the reduction of the iron oxide.

It is widely believed that fine Fe$_2$O$_3$ (200 mesh or 74 microns) powders fill the interstices between the sand grains and thus not only produce a smoother mold surface but also increase the ferrostatic head required to initiate mechanical penetration. Also, the presence of Fe$_2$O$_3$ at the mold-metal interface affects melt interfacial surface energies and wetting angles. Experiments show that, to some degree, fines inhibit the onset of mechanical penetration, however, excessive fines can be detrimental because higher binder levels are usually required to maintain equivalent tensile strengths (due to greatly increased solid surface area), permeability may be reduced and blowholes might occur.

3.4.1.3 Optical Profilometry

A Veeco optical profilometer was used to provide characterization of both the sand mold and casting surface roughnesses. Such non-contact optical profilometers use two technologies to measure a broad range of surface heights. One is called Phase-shifting interferometry (or PSI mode) which allows measurements of smooth surfaces and small steps. The other is VSI mode (Vertical scanning interferometry) which works on rough surfaces and steps up to several millimeters in height. PSI mode is the classical technique for measuring relatively smooth surfaces. A white light beam is filtered (to obtain only red light) and passed through an interferometer objective to the test surface. The interferometer beamsplitter reflects half of the incident beam to the reference surface within the interferometer. The other half goes to the sample surface. The beams reflected from the test surface and the reference surface recombine to form interference fringes, which appear as alternating light and dark bands when the surface is in focus. During scanning, a piezoelectric transducer (PZT) linearly moves the reference surface by a small, precise amount to cause a phase shift between the test and the reference beams. The profilometer then records the intensity of the resulting interference pattern at many different relative phase shifts and converts the intensity to wavefront (phase) data by integrating the intensity data.

Relative to PSI mode, VSI mode is a newer technique better suited to our investigations. The principle of measurement is similar: light is reflected from a reference mirror and combines with light reflected from a sample to produce interference fringes. But in VSI
mode, a neutral density filter is applied for filtering white-light source and this preserves the short coherence length of the white light. The system thus measures the degree of fringe modulation, or coherence, instead of the phase of the interference fringes. The irradiance signal is sampled at fixed intervals as the optical path difference is varied by a continuous translation of the vertical axis through focus. Low frequency components are first removed from the signal; the signal is located and the vertical position that corresponds to the peak is recorded. The interferometric objective moves vertically to scan the surface at varying heights. Since white light has a short coherence length, interference fringes are present only over a very shallow depth for each focus position. Fringe contrast at a single sample point reaches a peak as the sample is translated through focus. The fringe contrast or modulation increases as the sample is translated into focus, then falls as it is translated past focus. The system scans through focus (usually from above focus) as the camera captures frames of interference data at even-spaced intervals. As the system scans downward, an interference signal for each point on the surface is recorded. The system uses a series of advanced computer algorithms to demodulate the envelope of the fringe signal. Finally the vertical position corresponding to the peak of the interference signal is extracted for each point on the surface.

In this project, surface roughnesses of up to one or two millimeters in height are the major concern. Two amplitude parameters are used for characterizing the surfaces of these samples: average roughness ($R_a$) and average maximum profile height ($R_z$). The roughness average $R_a$ defines the arithmetic mean of the absolute values of the surface departures from the mean plane. The digital approximation for three dimensional $R_a$ is:

$$R_a = \frac{1}{MN} \sum_{i=1}^{M} \sum_{j=1}^{N} |Z_{ij}|$$

where $M$ and $N$ are the number of data points in the X and Y direction, respectively, of the array, and $Z$ is the surface height relative to the reference mean plane. $R_a$ is generally used to describe the roughness of machined surfaces and is an easily implemented parameter, useful for detecting general variations in overall surface height characteristics and for surveillance of an established manufacturing process.

The other roughness parameter we use is $R_z$, the average maximum height of the profile, and is the average of the ten highest and ten lowest points in the dataset. $R_z$ is calculated using the following expression:

$$R_z = \frac{1}{10} \left[ \sum_{i=1}^{10} H_i - \sum_{j=1}^{10} L_j \right]$$

Where $H_j$ are the highest points and $L_j$ are the lowest points found in the dataset. $R_z$ is useful for evaluating surface texture on limited-access surface such as small valve seats and the floor and walls of grooves, particularly where the typical presence of high peaks or deep valleys is very significant. In the context of our investigations $R_z$ plays a significant role as it provided the most direct linkage to our modeling work.
3.4.1.4 Variations in Sand Chemistry

As a simple ranging experiment, blocks containing small plugs having different concentrations of carbon black and iron oxide (Fe₂O₃) were fabricated to quantify the effects of interface chemistry on casting surface finish. Instead of being mixed throughout an entire block, the additives were added into plugs that were then inserted into the mold surface. This produced a sand mold in which an internal standard (the ‘normal’ sand around the plug) was present and provided a casting finish baseline for profilometry. This required manually placing a small plug of sand mixture into the surface of a mold. The preparation of this sample is described as follows. A five inch long, one inch in diameter plastic cylinder was machined at one end to the appropriate shape and placed on the top of the pattern as shown in Figure 3.4-1. The normal sand mixture was then filled in around the pattern to a depth of 2 inches. The plastic cylinder was then removed and the sand mixture containing additive was added to the cavity resulting from the removal of the plastic cylinder. After the area around the cylindrical cavity is filled, the regular sand mixture is then added to fill the rest of the frame (Figure 3.4-2). The mold is then allowed to set for at least 10 minutes to attain normal hardness and strength.

Three concentrations, 0.01 wt%, 0.05 wt% and 0.1 wt%, each of carbon black and iron oxide in sand plugs were prepared and embedded into mold drag portions. Molten 1025 steel was then cast against these mold surfaces*. After the casting solidified and slowly cooled to room temperature, the profilometer was used to scan the majority of the casting surface (a 4 mm by 4 mm area) that corresponded to the mold plug surface. Rₐ and Rₗ were determined to quantify surface roughness.

Sand cylinders fabricated using plastic cylinder with curvature matching the pattern

Figure 3.4-1 Schematic Illustration of how plugs of controlled chemical composition are physically incorporated into the drag surface prior to casting.

Sand molds produced by these routes were scanned using a second generation CT scanner located at the Wright Laboratory/ Materials Directorate at Wright-Patterson Air Force Base near Dayton, Ohio. The CT images of the samples show (Figure 3.4-3) that the casting surface of the plugs have densities similar to those of the surrounding surface.
As this initial experiment verified the beneficial effects of iron oxide on casting finish, additional experiments were called for to determine the effects of higher concentrations. More iron oxide was added to each plug to produce concentration of 1 and 2wt%. The average size of these iron oxide powders is 200 mesh (74 microns) which is much finer than the size of the sand grains (fineness number = 62). However, non-uniform mixing could potentially occur when the sand and the iron oxide are mixed together. This might cause certain density gradients on the sand mold surface and result in varied casting surface roughness. To minimize this and eliminate the possibility of interstitial filling, the iron oxide was added to the sand surface in the form of a ‘nanoscale’ coating. This required direct hydrothermal synthesis of iron oxide powders on the surface of the foundry sand. Ultrafine alpha-Fe₂O₃ oxide powders were produced under hydrothermal conditions by the decomposition of iron nitrate. The particle size for this technique ranges from 25 to 700 nanometers. Hydrothermal synthesis is conducted at 150-250 °C. High temperature hydrolysis of aqueous iron (III) nitrate solution leads to the intensive formation of hematite. The particle size of the synthesized hematite powders increases with the concentration, temperature and time of hydrothermal treatment.

0.027 mol iron nitrate (formula Fe(NO₃)₃·9H₂O) was dissolved in 0.3 liters deionized water. One pound of sand is then added to the solution and stirred to ensure complete wetting. The sand–iron nitrate mixture is then heated from room temperature to 250°C, held for 2 hours and cooled to room temperature. All iron nitrate is converted to iron oxide particles in the form of coating around the sand grains. Since the iron oxide particle
size is below 1 micron, the sand grains were coated with this nanoscaled iron oxide. The
calculation show that the percentage of iron oxide based on the weight of sand is 1%.
This sand was then used in the fabrication of mold plugs.

Molten steel 1025 was cast against these molds at (Ashland Chemical, Dublin, OH) containing into which these iron-oxide containing plugs had been incorporated. Casting roughness was determined using the profilometer.

Figure 3.4-3 Optical profilometry output resulting from analysis of the as-fabricated sand mold surface. Red is used to denote the elevated sand grains; blue refers to the sand grains below the overall plane of the surface.
3.4.5 Effects on Roughness

The averaged values of $R_a$ and $R_z$ are plotted in Figures 3.4-5 and Figure 3.4-6 respectively.
Figure 3.4-5 Surface roughness $R_a$ in terms of different concentrations of additives. Additive concentrations are in weight percent. Each data point and standard deviation represent 10 different scanned areas.
Figure 3.4-6 Surface roughness $R_z$ in terms of different concentrations of additives.

By simple repetitive grinding steps alternated with profilometry, we established that a desirable surface finish would have an $R_a$ of approximately 5 microns or less.

$R_a$ and $R_z$ for the iron oxide containing plugs vs. the surrounding areas are plotted in Figures 3.4-7 and 3.4-8.
Figure 3.4-7 Surface roughness $R_a$ in terms of different concentrations of additives in new sand mold. The roughness of the sand surface outside the area of the casting facing the mold was also determined to provide a better standard for comparison. Six data points are used to produce the average and the standard deviation.
Figure 3.4-8 Surface roughness $R_z$ in terms of different concentrations of additives in new sand mold. The roughness of the sand surface outside the area of the casting facing the mold was also determined to provide a better standard for comparison. Six data points are used to produce the average and the standard deviation.

3.1.6 Roughness-chemistry correlations

Increasing concentrations of these additives should improve the resulting surface finish and therefore both $R_a$ and $R_z$ should decrease. However, the initial summary of surface roughness (Figure 3.4-5 and 3.4-6) does not match these expectations. The castings made from the molds with different concentrations of carbon display values of surface roughness similar to the unmodified sand. The amount of carbon may be too small, so that upon contact with the molten metal, the burning of the carbon doesn’t produce a gas cushion sufficient for prevention of metal penetration.
An example of this can be observed in any carbonated beverage in a PET bottle: after shaking, if the bottle is partially (and carefully) vented the interface between the foam and the slowly escaping gas is cup shaped. Even though the evolving gas is actively escaping sufficient pressure is maintained to shape the interface. When the foam is spread out in the wide portion of the bottle, the interface is curved but not severely. As the foam is allowed to advance toward the neck of the bottle, the radius of curvature becomes relatively small and more hemispherical. In metal castings, the gas is generated by the rapid pyrolysis of the binder to CO, CO₂ and H₂O.

At the same additive content however, iron oxide causes definite improvements in roughness. Careful examinations of Figure 3.4-7 and 3.4-8 lead to the finding that surface finish generally becomes better as the usage of Fe₂O₃ although the effects on Rₐ are not as obvious as those on Rₐ. When the usage of Fe₂O₃ is 1% or higher, the castings show obvious improvement compared to those made from lower concentrations. But 2% usage and the 1% “Nano-coated” molds do not produce significantly better castings than those made from molds with 1% Fe₂O₃. It is reasoned that for this specific pepset sand mold system, the addition of 1% Fe₂O₃ is high enough to obtain good surface castings.

These results cast doubt on the idea that interstitial filling of the sand molds is necessary to prevent localized metal penetration. Surface roughness is decreased when the iron oxide is present only on the sand grains themselves. These results say nothing about the penetration of more catastrophic veining. However, the initial stages of veining may be influenced by localized wetting phenomena before progress to more severe forms of penetration.
3.5 MODELING TO PREDICT CASTING SURFACE ROUGHNESS

3.5.1 NEED FOR QUANTITATIVE MODELING OF PENETRATION

Besides the experimental work to correlate the mold density gradients to casting surface finish, a numerical approach has been used to predict the casting surface roughness based on local information about mold density. It has been found that after using profilometry to scan the mold and the casting, the casting surface roughly matches the mold surface micro-configuration. However, the as-cast surface is not an exact replica of the sand surface because the gases trapped at the interface appear to act as elastic physical bodies preventing the intimate penetration of molten metal into the pores and depressions in the sand surface. This leads to the idea if localized pressure can be taken into account, a numerical model could be constructed that uses information about localized density to predict casting surface finish.

3.5.1.1 Introduction

Direct study of the mold surface shows that the grains composing the surface layer of the mold are in fact not close together and that there are substantial gaps between them. A simple description of the structure of mold surface consists of individual sand grain and three basic assumptions:

1. All the sand grains can be represented as spheres with radius $R_s$ [Lysachenko]. The influence of trapped gas at the interface only improves the validity of this assumption.

2. All the sand grains are equally separated with packing coefficient $\Psi$ that describes the packing of the sand grains. Therefore, the centers of neighboring grains in the mold are at a distance of $2\Psi R_s$ from each other.

3. Suppose a new sand grain of radius $\Psi R_s$ replaces the original sand grains of radius $R_s$. Further assume that these new sand grains are ideally hexagonal close packed.

\[
\frac{4}{3}\pi R_s^3
\]

In each hexagonal cell, there are 6 six sand grains. Each sand grain having the volume of

The total volume of all 6 sand grains is $8\pi R_s^3$. The lateral length of the cell is $2\Psi R_s$. The requirement of ideal close packed hexagonal is that the height should be 1.633 times that or $3.266\Psi R_s$.

The sand that is used for this project has its specific density of 2.76 g/cm$^3$. All other lengths are all in the unit of cm. The density of the mold can be obtained by calculating the density of the hexagonal cell, which is the ratio of the weight of 6 sand grains to the volume of the hexagonal cell.

The weight of the 6 sand grains is $2.76 * (8\pi R_s^3) = 69.366 R_s^3$;

The volume of the hexagonal cell is
The density can be described by:

\[ \rho = \frac{\text{Weight}}{\text{Volume}} = \frac{69.366 R_s^3}{33.94 (\psi R_s)} \]

\[ \psi = \frac{1.2688}{3 \sqrt{\rho}} \]

Reorganizing the equation results in the form:

Assuming only mechanical penetration occurs, the irregularities of the surface can be written in the following equation [Lysachenko]:

\[ h = R_s + R_m - \sqrt{R_s^2 + R_m^2 - 2 R_s R_m \cos \theta} \]

\[ \psi R_s \]

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Carbon dioxide can react with steel to produce wustite (FeO) that wets on silica sand. It has a wetting angle of 21° which is low compared to the 154.5° nonwetting angle of pure iron on SiO$_2$. Therefore, wustite wets the sand and remains around the sand surface. Under favorable thermodynamic conditions, FeO may react with and dissolve silica, resulting in the formation of fayalite (Fe$_2$SiO$_4$). It is assumed that the molten steel slightly wets the sand and that the dynamic wetting angle is 70°.

Therefore cosθ = 0.342. So the equation can be written as:

$$h = R_s + R_m - \sqrt{R_s^2 + R_m^2 - 0.684 \times R_s \times R_m - (\psi R_s)^2}$$

(9-1)

In his paper, N.N. Lyashchenko obtained by deriving through a serial of equation where

$$\phi = \frac{2\sigma}{\sqrt{\rho g R_m}}$$

and $H_p$ is the pressure developed in the mold (for ordinary pouring $H_p$ is, in fact, determined by the geometric dimensions of the casting and of the casting mold). $\sigma$ is the surface tension of molten iron and $\rho$ the density of iron.

Molds were made in the procedure described previously. The molds were scanned using XRCT and thus the density was obtained. Here there are 6 squares with different densities. Plain carbon 1025 steel was poured against these molds. Optical profilometry was used to obtain the surface roughness parameters $R_s$ and $R_z$.

1L5W lake sand was used in the tests. It has a fineness number around 50 or a mean sand size of 0.295 mm. So $R_s$ is 0.15 mm. Plain carbon 1025 steel has density of 7.5 g/cm3 and surface tension of 1450 dynes/cm. Therefore

$$R_m = \frac{\phi^2}{H_p} = \frac{0.63^2}{22} = 0.01804 \text{cm} = 0.1804 \text{mm}$$

$$\phi = \sqrt{\frac{2\sigma}{\sqrt{\rho g}}} = \sqrt{\frac{2 \times 1450}{7.5 \times 981}} = 0.63 \text{cm}$$

Substituting the above data into the equation 9-1 produces

$$h = R_s + R_m - \sqrt{R_s^2 + R_m^2 - 0.684 \times R_s \times R_m - (\psi R_s)^2} = 0.33 - \sqrt{0.0365 - (0.15\psi)^2}$$

$\Psi$ is determined by the density of the square in the mold surface. The density is incorporated to the equation and the surface irregularity $h$ obtained. This irregularity is calculated by assuming penetration occurring between two sand grains. Careful
examination of the profilometry images of the casting surface leads to the discovery that the average penetration between three sand grains is approximately 1.7 times this value. This irregularity is named as $h_1$. The irregularity $h_1$ derived from the model is compared directly to the surface roughness $R_z$ (Figure 3.5-2).

This calculation was also performed on the new sand: Wedron washed silica sand which has the fineness number of 70. The average grain size is 0.208 mm. So $R_s$ is 0.104 mm and the surface irregularities is

The measured surface roughness data and the calculated irregularities is shown in Figure 9.4.

$$h = R_s + R_m - \sqrt{R_s^2 + R_m^2 - 0.684 \times R_s \times R_m - (0.104 \psi)^2} = 0.2844 - \sqrt{0.0305 - (0.104 \psi)^2}$$
Figure 3.5-3 Comparison of surface irregularities from modeling and surface roughness $R_z$ from profilometry for the new sand.

3.5.1.2 Discussion
This model is built through a series of equations utilizing several important parameters such as the density of the mold, the contact angle between the steel and the sand grains and the size of the sand grains. Comparison of the initial data from the model and that from the profilometer provides a poor match. Surface finish improves as mold surface density increases. The surface irregularity predicted by the model is much lower than the actually measured surface roughness.

The real sand used in the experiment has a size distribution rather than a single size. The penetration through the interstices between the larger grains would be more severe than that calculated in the model.

One of the advantages of optical profilometry is its ability to describe the roughness of relatively large areas compared to previous methods. This should provide more accurate values of $Ra$ having greater statistical validity. However, we realized that to connect the measured roughness to the modeling we had to reduce the sampling area. This seems counterintuitive but makes sense if the definition of $R_z$ is examined more closely. In other words, the average value of $R_z$ should increase as the range of allowed maxima and
minima increase. Figure 3.5-4 shows that for a specific casting that the surface roughness R\textsubscript{z} decreases as the sampling area decreases.

This model predicts the surface irregularities of the local region on the mold, however, the measured R\textsubscript{z} represents an area that is much larger. We then realized that decreases in the scanning area should make both the predicted and the measured data more comparable.

![Rz in terms of scanning size](image)

Figure 3.5-4 Surface roughness R\textsubscript{z} in terms of the size of the scanning area.

Also in Figure 3.5-3 the predicted surface roughness R\textsubscript{z} does not decrease significantly with increasing density. The slope of the curve is not as obvious as the measured data and the calculated roughness for the old sand. This is because the new sand particles are finer than the old sand grains and are not as easily compacted to produce large density gradients. Therefore, the model gives relative smaller packing coefficients and penetration depth.
3.6 ACCOMPLISHMENTS

The accomplishments of this project include:
1. First application of quantitative XRCT to industrial sand molds.
2. First correlation of variable sand mold density to cast metal surface finish.
3. Development of a simple optical technique allowing subsurface density gradients to be visualized directly.
4. Proof that acoustic stimulation can reduce the density gradients that are ubiquitous in metal casting.
5. Linkages between sand structure and chemistry and the surface roughness of the resulting casting.

Publications resulting from this work:

The following patent was granted to us:
“Method for Detecting Density Gradients,” U.S. Patent No. 6,598,663 was issued on July 29, 2003. Some discussions with Ashland Chemical regarding the licensing of this technology have taken place. At this writing they appear to prefer a previously developed technology into which they have invested considerably over the past decade.

3.6.1 CONCLUSIONS
It is clear that density gradients exert considerable control over the surface finish of the associated metal castings. What is less clear is how density gradient lead to other more destructive phenomena such as veining. Commercialization of the optical technique required/requires the availability of a uniform light source. Surface chemistry has additional effects on metal casting finish in conjunction with those caused by low density areas.

3.6.2 RECOMMENDATIONS
We recommend that the optical technique be further investigated by obtaining a more uniform light source. As we have demonstrated, any such technique will require comparison to XRCT data in order to have any quantitative validity.
References / Bibliography

References