To Promote the production and application of ductile iron castings

Metals and Alloys for the Foundry and Steel Industry

FEATURES
• Carbidic Austempered Ductile Iron (CADI)
• K.D. Millis Scholarships Awarded
• Dotson Foundry Virtual Tour
• Factors that Affect Compactability and Consistency in Green Sand
• Comparative Machinability Evaluation of Ferritic Ductile Iron Castings
• Porosity Defects in Gray and Ductile Iron Castings from Mold Metal Interface Reactions
• Purchasing Quality Ductile Iron
• Casting Process Simulation
• Comparison of Clarifier Drives
• Ashland Introduces ExactCalc

DEPARTMENTS
• News Briefs
• Associate Member Profile - ASI International
• Associate Member Profile - Odermath
Carbidic Austempered Ductile Iron (CADI)

Presented at DIS Meeting on November 14, 2000

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ABSTRACT
Carbidic Austempered Ductile Iron (CADI) is a family of ductile cast irons produced with carbides, (both thermally and mechanically introduced), that are subsequently Austempered to exhibit adequate toughness and excellent wear resistance.

INTRODUCTION
Since about 1990 industry has discovered various material/process combinations that exhibit surprisingly good wear resistance but defy classification as either white irons or Austempered Ductile Irons. They combine various thermal and mechanical means for introducing carbides in, and on ductile iron components. They are subsequently heat treated by the Austempering process.

This paper attempts to define this class of Carbidic Austempered Ductile Irons and to define for the reader the state of the art to date.

CARBIDIC AUSTEMPERED DUCTILE IRON (CADI)
Since the early 1990's several manufacturers have been using various techniques to exploit the advantages of the wear resistance of carbides and the toughness of the Ausferrite matrix produced by the Austempering process.

What is Austempering?
Austempering is a high performance isothermal heat treatment that imparts superior performance to ferrous metals. The classic definition describes that as an isothermal heat treatment. Figure 1 compares and contrasts conventional “quench and temper” heat treatment and Austempering in a generic ferrous material.

In conventional quench and tempering (red line) the component is heated to red heat and a fully Austenitic condition. It is then quenched rapidly to a temperature below the Martensite start line. At this point the face centered cubic Austenite transforms to a taller, body centered tetragonal Martensite. This untempered Martensite is very hard and brittle. This can cause difficulty as the exterior of the part transforms first. Moments later, the inside of the part transforms to Martensite and forces the exterior to “move”. This non-uniform transformation can result in severe distortion or cracking. (Cast irons are particulary vulnerable to cracking during quenching). The Martensitic structure is subsequently tempered to produce the desired combination of strength and toughness.

The Austempering process (green line) begins similarly with austenitization followed by rapid cooling to avoid the formation of Pearlite. However, there the similarity ends. In the Austempering process the quenching media is held at a temperature above the Martensite start temperature. This results in the FCC austenite cooling to the quench temperature. The quenched material is then held at that temperature for a time necessary to produce the desired acicular structure. In steels, that structure is bainite, a structure of acicular ferrite and carbide. In cast irons, with their higher silicon content, an intermediate structure called Ausferrite results. Ausferrite consists of acicular ferrite and carbon stabilized Austenite. This isothermal transformation results in uniform transformation of the structure throughout the part. Thus cracking during quench transformation is virtually eliminated.

In Austempered cast iron, this Ausferrite has very good abrasive wear properties because of its tendancy to “strain transform” on the abraded surface. Austempered Ductile Iron (ADI) can compete with much harder materials. However, even ADI can be bested by materials containing carbides. But, carbidic irons tend to be very brittle.

What is Carbidic ADI (CADI)?
CADI is a ductile cast iron containing carbides, (that are either thermally or mechanically induced), that is subsequently Austempered to produce an Ausferritic matrix with an engineered amount of carbides.

Methods of carbide introduction include:

- As-Cast Carbides
  - Internal (chemical or inverse) chill
  - Surface chill (limited depth, directional)

- Mechanically Introduced Carbides
  - Cast-in, crushed M_xC_y carbides
Carbidic Austempered Ductile Iron (CADI)

- Cast-in, engineered carbides (shapes)
- Welded
  - Hardface weldment
  - Weldment with $M_xC_y$ grains

**As-Cast Carbides**

**Internal (chemical or inverse) chill**

Iron created as ductile iron and treated with magnesium and/or rare earths to result in spheroidal graphite can be induced to produce a carbidic microstructure by a variety of methods. These include alloying with carbide stabilizers such as chromium, molybdenum, titanium and others, controlling the cooling during shakeout or adjusting the carbon equivalent to produce a hypoeutectic iron chemistry. The carbides produced from this technique can be “dissolved” to a controlled extent by subsequent Austemper heat treatment.

Figure 2 shows a CADI sample with as-cast carbides that was subsequently Austempered at 500°F with 65% carbides remaining. This sample has a continuous carbidic matrix that would limit its toughness. Figure 3 shows a similarly produced iron Austempered at 500°F. However, in this sample the carbides were further “dissolved” during austenitization, resulting in 45% carbides and a continuous Ausferritic matrix. This microstructure would be slightly less wear resistant than the iron in Figure 2 but with greater toughness. Figure 4 shows a similar iron with carbides further dissolved to 30%. Figure 5 shows the wear resistance of a typical CADI vs as-cast gray and ductile iron and various grades of ADI. Table 1 shows a table of typical unnotched Charpy impact values including CADI.

**Directional Surface Chill Carbides**

These carbides are produced by placing media with high thermal conductivity and thermal capacity adjacent to the surface of the solidifying iron. As the molten iron contacts this surface the solidification rate is sufficiently high to create carbides perpendicular to that surface and extending into the body of the part. These components may/or may not be free of carbides in the thermal center of the part. Depth of chill can, and is, controlled by controlling the chill scheme and the chemical analysis of the iron. These carbides can be “dissolved” to a controlled extent by subsequent Austemper heat treatment.

**Mechanically Introduced Carbides**

**Cast-in, crushed $M_xC_y$ carbides**

This process, to the authors’ knowledge is only practiced by license to Sadvik Corporation. In this process, crushed $M_xC_y$ carbides are strategically placed in the mold cavity at the desired location. The metal then fills in around the carbides resulting in a continuous iron matrix with discrete carbides mechanically trapped in it. The specific method used to contain the carbides “in place” during mold filling is not known to the authors. This method allows the engineer the option of placing carbides only where needed resulting in a traditional ductile iron matrix throughout the rest of the casting. These particular carbides are essentially unaffected by subsequent austemper heat treatment.

**Cast-in, engineered carbides (shapes)**

This process requires the setting of engineered carbides into the mold with special core prints or other techniques. These engineered carbides may have back drafts or keyed features that allow them to be mechanically locked into the metal once it solidifies. These carbides are then unaffected by subsequent austemper heat treatment.

**Carbidic Weldments**

**Hardface Weldment**

This process starts with a conventional ductile iron casting, typically with a fully, or mostly ferritic matrix. The casting is then hard-face welded in the area of greatest wear. This results in a carbidic weld and a heat affected area at the weld/casting interface as shown in Figure 6. Subsequent Austemper heat treatment has little or no effect on the weld structure (depending on the chemical analysis of the weld material chosen) but the heat affected zone is eliminated and a fully Ausferritic matrix results in all areas other than the weld itself as shown in Figure 7. In some weld applications powdered metal carbides can be purged into the molten weld to provide additional wear resistance.

**Table 1:** Typical un-notched Charpy impact values (ft-lbs). Tested at 72°F (22°C).

<table>
<thead>
<tr>
<th>Material</th>
<th>Impact Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-45% Carbine 500 CADI</td>
<td>10</td>
</tr>
<tr>
<td>Carburized 8620 Steel</td>
<td>13</td>
</tr>
</tbody>
</table>

**Back to Article**
POTENTIAL APPLICATIONS FOR CADI

The current applications for CADI are limited, but growing. Agricultural components have been produced in CADI with as-cast carbides since the early 1990s. A Sandvik licensee has produced limited production quantities of CADI parts with cast-in, crushed carbides as well. Research into chill-carbide CADI camshafts is ongoing. However, the visibility of CADI has been greatly increased of late with the public launch of CADI in programs at John Deere.

In the February 2000 issue of SAE Off Highway Magazine John Deere announced the use of CADI elements in its revolutionary new rotary combine (Figure 8). Then, in John Deere’s Owners Circle Magazine (March 2000) they publicly announced the use of CADI in their Lazer Rip ripper points. These two events accelerated ongoing efforts in the industry in both research and production.

CADI presents some intriguing product possibilities. Potential applications in vehicles include camshafts and cam followers. Agricultural applications may include rippers, teeth, plow points, wear plates and harvester, picker and baler components. Possible railroad applications include contact suspension components and railcar/hopper car wear plates. In construction and mining potential applications include digger teeth and scarifiers, cutters, mill hammers, flails, guards, covers, chutes, plates, housings, transport tubes and elbows, rollers and crusher rollers. General industrial applications could include pump components, wear housings and plates, conveyor wear parts, skids and skid rails, rollers and blast parts.

WHAT ARE THE RISKS / DISADVANTAGES OF CADI?

- CADI exhibits only limited machinability (possibly grinding only)
- If alloying is used the returns must be segregated
- Additional operations and costs may be incurred if carbides are welded on or cast-in

WHAT ARE THE ADVANTAGES OF CADI?

- CADI is more wear resistant than Grade 5 ADI with acceptable toughness.
- CADI is less expensive and tougher than 18% chrome white iron.
- No capital investment is required for the metal caster to add this new product line.

WHAT MARKET OPPORTUNITIES DOES CADI PRESENT TO THE DUCTILE IRON PRODUCER?

- Replaces Mn steel at equal or lower cost
- Replaces 18% Cr white iron at lower cost
- Sells as a premium, engineered iron with longer life
- Creates new markets for ductile iron

SUMMARY

CADI is a relatively new engineering material. This paper attempted to summarize the state of knowledge at the time of this writing. Ongoing research and market developments will be reviewed in subsequent reports.

ACKNOWLEDGMENTS

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- John Deere
- Carroll Ag
- Federal Mogul
- Terry Lusk
- SAE Off Highway Magazine
- The Team at AP Westshore

ADDITIONAL RESOURCES

- SAE Off Highway Magazine February 2000
- John Deere Owners Circle Magazine March 2000
- Applied Process Inc. internal research
- www.appliedprocess.com
- www.ductile.org / associated links / DIMG / Ductile Iron Data, Chapter 4, ADI
**Carbidic Austempered Ductile Iron (CADI)**

**Figures**

Figure 1: Compares the quench and temper and austemper processes for a ferrous material.  
[Back to Article](#)

![Figure 1](image1.png)

Figure 2: CADI with 65% carbide and a 500F ADI matrix. (These carbides were produced as-cast).  
[Back to Article](#)

![Figure 2](image2.png)
Figure 3: CADI with 45% carbide and a 500F Ausferrite matrix (These carbides were produced as-cast).

Figure 4: CADI with 30% carbide and a 500F Ausferrite matrix. (These carbides were produced as-cast).

Figure 5: Abrasive wear resistance of CADI vs. as-cast and Austempered gray and ductile irons.
Carbidic Austempered Ductile Iron (CADI)

Figure 6: Microstructure of hard-face welded ductile iron showing the Carbidic weld (light) and the pearlitic heat affected zone (dark).

Figure 7: (Right) Microstructure of hard-face welded ductile iron that has been subsequently Austempered at 700°F showing the Carbidic weld (light) and the Ausferrite matrix (dark).
Figure 8: John Deere’s new, high performance, rotary combine uses CADI in its critical thrashing elements. (Courtesy of SAE Off Highway Magazine)
K.D. Millis Scholarships

**K.D. Millis Scholarships Awarded**

Keith D. Millis Scholarships were awarded at the November College Industry Conference in Chicago.

The following students received awards of $2000 each:

- Lazaro Beltran-Sanchez  University of Alabama
- Andrew J. Herring  Pittsburg State
- Matthew J. Mroczek  Ferris State University
- Hans R. Vanden Berg  Wisconsin Platteville

Congratulations students!
Dotson Foundry Virtual Tour

At the Ductile Iron Society Annual Meeting in Las Vegas, Dotson Company, Inc. presented a virtual tour of their company.

For a more complete description of their facilities, click on the image at the right.

The Dotson Company History 1876 - 2000

The business that is today called The Dotson Company was founded 123 years ago in Mankato by the Mayer family. Lawrence Mayer and his three sons, Louis, Lorenz and Conrad, began their business as a blacksmith shop on Vine Street in 1876. Louis and Lorenz started the foundry in 1894.

In 1895, Louis invented the trip hammer which was sold under the Little Giant name. The trip hammer, manufactured in five sizes, is used as a mechanical blacksmith in machine shops and manufacturing operations.

During the early 1900's, the Mayers drastically expanded their product line with items such as boilers, gasoline and steam engines, hoists, steel beams, manifolds, ditching machines, clotheslines, traffic directors, road signs, woodworking equipment, lathes, band saws, circular saws, drill presses, tractors and road graders. Most of these products were produced for only a short time period before being discontinued.

In 1907, Louis Mayer invented a V-8 engine, one of the first in the country. He used this engine in a car which he assembled over a period of four years. The Mayers built the chassis and engine, but sent to Detroit for a wooden body, which they carefully gave 20 coats of black paint. The car ran superbly, and even was able to easily go up the Main Street hill (Agency Hill at the time). In 1916, due to financial problems within the company, the Mayer brothers were asked by their stockholders to step down.

The company, now run by the banks, carried on as Little Giant for the next few years. In 1923, L.J. Fazendin was brought in to manage the company. He discontinued the tractors (over 500 had been made since 1914) and other unprofitable products and began manufacturing plumbing parts. In 1924, Little Giant began producing potato pickers, but these too, did not work out.

In 1937, Little Giant went bankrupt, and L.J. Fazendin bought up the assets and became the owner. In 1943, Fazendin's son-in-law, Jerry Dotson, joined the company. At this point, the outlook was good. Because of the war, trip hammers were necessary, and Little Giant's was the best. In its specification, the government required: "Little Giant or equal." Under Jerry Dotson's leadership the foundry grew from a very small captive foundry to a relatively large jobbing foundry. Jerry was instrumental in persuading several foundries to close down and transfer their business to Dotson. The first union contract was signed in 1944 and started a close working relationship that has continued for 50 years. When Mr. Fazendin died in 1955, Jerry Dotson continued on as president of The Dotson Company and Fairview Corporation.

During the next few years, the foundry continued to grow and expand into new areas. While small amounts of aluminum and bronze were poured by Dotson Company in the 1940's, aluminum and bronze were first produced in large quantities in the 1950's by a sister company Fairview Corporation. In 1967, a ductile iron foundry was started on a new site just north (across the tracks) from the original Rock Street foundry. Fairview started steel foundry in 1976.

In 1973, Jerry Dotson's son, Dennis joined the company. After Jerry's death in 1978, Dennis became the president. Dennis continued the expansion and modernization of the new iron foundry. During a slow down in business in 1977, and with the expansion of the new foundry, there was enough capacity to permanently close the Rock Street iron foundry.

The 1980's were tough years for all manufacturers and particularly those that concentrated in the agricultural and energy markets as Dotson did. With the collapse of the Midwest markets in 1981 and 1982, The Dotson Company was faced with some very difficult decisions. Sales dropped more than 80% during this period and losses threatened the survival of the company. To make matters worse, exchange rates and cheap labor gave foreign foundries an opportunity to take customers away from Dotson.

The decision was made in 1983 that The Dotson Company would close the brass and aluminum foundry, the steel foundry, the machine shop and stop making the Little Giant trip hammer. At the same time, the company would invest in new melting and molding equipment for the iron foundry. In order to convince the banks that the foundry was a worthwhile risk, the company asked the employees and their molder's union to take cuts in pay and to postpone some wages until the company was profitable. While the dept from the new equipment almost bankrupted the foundry in 1985, the increased productivity and strong employee support gradually led the way back to profitability.

Major equipment purchases and expansions were completed in 1989, 1991, 1995, 1997, 1999 and 2000. The operating capacity of the plant is now at 120 melt tons per day. A 1996 partnership with the Enterprise Division of Machine Power set up a complete, on-site CNC machining operation.

Today, The Dotson Company is one of the major Midwest ductile and gray iron foundries and certified to the ISO 9002 quality standard. We are fortunate to have a great workforce, equipment that takes advantage of the newest technology and customers that want long term partnerships. As we look to our future, we understand that the challenges never go away. These future challenges are expressed in our mission statement and quality policy: "Our long term survival and growth is based on providing continuous improvement in quality, service and value to our gray and ductile iron customers; achieved through a process of
committed employee involvement and recognition; and, accomplished in a safe environment."

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Foundry Virtual Tour

Dotson Company, Inc. Virtual Tour at October DIS Meeting

Statistics

- Recycle 8,500 Tons of Steel Per Year
- 180,000 lbs. Melted Daily
- 500,000 lbs. Sand Mixed Daily
- 1,000,000 Molds Per Year
- 3,000,000 Castings Per Year
- $100,000 Monthly Energy Costs
- 120 Employees
Factors That Affect Compactability and Consistency in Green Sand

By George DiSylvestro, DiSylvestro Videography Service

Green sand molding is a process that combines the advantages of versatility, productivity and low cost for the production of quality castings of any metal that is castable. Because of the advent of high pressure, high density, automated molding machines, improved casting dimensions are obtained consistently.

A simple test that has replaced the “hand feel test” is the compactability test. Compacted mold uniformity is a vital factor in achieving net shape casting production. Correct interpretation of this test can help reduce mold wall movement that could be a prime cause of apparent shrinkage. The test is reported as a percentage and indicates the relationship among molding sand compaction characteristics, composition, sand preparation and transportation through the mold cycle.

The compactability simply indicates the degree of temper or relative wetness of a molding sand mixture. It provides a percentage number that can be used in auditing sand consistency for quality control and automation. The compactability test determines the percentage decrease in height of a loose mass of sand under the influence of controlled compaction. The compactability molding values are directly related to the performance of a molding sand mixture. With control of some of the major conditions that affect the test, it’s use can yield excellent casting finish and reduce cleaning cost.

Essentials affecting compactability

In the past only a few factors were researched and reported as important factors to control.

These factors were:

- Moisture content
- Length of mulling time
- Clay content
- Carbonaceous material
- Inert fines (water absorbing)

However, in the past 30 years since the introduction of the test, extensive production experience has been gained along with research studies. The quantitative measurement of the process allowed foundry personnel to respect compactability as a meaningful tool to achieve consistency in green sand molding production.

This report was developed to better define and further share knowledge and refinement of these and other factors with a much greater detailed explanation. The importance of controlling compactability and consistency in molding sand can be summarized as follows:

<table>
<thead>
<tr>
<th>High compactability could result in -</th>
<th>Low compactability could result in -</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved dimensions</td>
<td>Friable edges</td>
</tr>
<tr>
<td>Gas/blow/pinholes</td>
<td>Crushes - inclusions</td>
</tr>
<tr>
<td>Better casting finish</td>
<td>Hard to lift pockets</td>
</tr>
<tr>
<td>Brittle mold surfaces</td>
<td>Mechanical penetration</td>
</tr>
<tr>
<td>Expansion problems</td>
<td>Apparent shrinkage</td>
</tr>
<tr>
<td>Difficult shakeout</td>
<td>Cuts and washes</td>
</tr>
<tr>
<td>Hard mold penetration</td>
<td>Cope drops</td>
</tr>
<tr>
<td></td>
<td>Oversize castings</td>
</tr>
<tr>
<td></td>
<td>Rough surfaces</td>
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</tbody>
</table>

Effects of sand additives on compactability
Bentonite

* Western (sodium type)
  Sodium bentonite when wetted has a pronounced effect on the compactability of molding sand. This is due to their physical and chemical characteristics. The following factors are most conducive to changes in compactability and the amount can vary with the composition and physical properties of the prepared molding sand.

  Listed below are significant characteristics of western bentonite -
  
  - Swelling capacity
  - Water holding capacity
  - Air set strength
  - Change with temperature
  - Percent activation

* Southern (calcium type)
  Calcium bentonite mixes easier than sodium and has a very minimum of swell and viscosity compared to sodium. Calcium bentonite contributes more green compression strength at lower moisture levels. Since green compression strength affects compactability, the amount of calcium bentonite used will impact compactability.

* Cereals and Starches
  The following is a list of the most popular semi-bonding additives used that affect compactability in order of bonding strength. They all contribute to green compression strength similar to bentonite.

  A. Dextrine
  B. Corn flour
  C. Wheat flour
  D. Rye flour
  E. Oat flour
  F. Ground oat hulls

  Of all of these, dextrine and corn flour are very effective in developing sand toughness and green deformation. They rate as high as sodium bentonite in affecting the change in compactability at much lower additions. They are most preferred in casting steel and heavy weight or thick section castings. The high toughness that these additions develop, render the measuring of compactability impracticable. The inconsistency of compactibility is also influenced by the higher affinity for water absorption during mulling. Adding water to the sand in the muller first, improves the efficiency and consistency of cereal starches and bentonite. If this practice is not followed, the development of clay balls can occur, especially with an increase in fines. Understanding these conditions, reproducibility of compactability readings becomes difficult. The existence of clay balls in molding sand causes non-uniform mold compaction.

* Cellulose additives
  Non-bonding filler additives mostly used to accommodate sand expansion, such as wood flour, ground corncobs, ground oat hulls, and similar ground cellulose fibers, have an opposite effect on compactability. They absorb moisture, and increase compaction by reducing the resistance developed by the bonding agents used. Cellulose additives contribute to more drying and effect continual change in compactability, reading, especially true with higher return sand temperatures and time. These additives contribute to brittleness and require careful auditing and control to prevent sand inclusions.

* Variations in water
  There are four conditions that have a major effect on compactability, that are caused by water. Use of (1) hard water, (2) water temperature, (3) reused water from other sources, (4) water from wet dust collectors, “black water.”

  (1) Effect of hard water - The condition of the water and its source can influence the development of bonding agents and their characteristics in use. Use of hard water reduces the activation of sodium bentonite. The use of electrolytes and additives that enhance bentonite development or deactivate its toughness (mostly acidic) can be used but are least recommended. They are very difficult to test for and to control the amount used and retained.
(2) **Water temperature** - The temperature of the water has an effect on the development of the bentonite and starches during mixing. Use of cold water at below 45F makes bentonite activation more difficult. As mixing time increases the internal friction heats the sand. More energy is consumed and mulling time should be increased.

(3) **Recycled water** - Recycled water from cooling furnaces etc., is usually warm and poses no problems of significance. The water quality should be monitored for PH. If the water becomes acidic, it has a major effect on deflocculating sodium bentonite. These variations affect compactability readings.

(4) **Black Water** - Black water is recycled water from wet dust collectors and is recycled for environmental reasons. It usually contains a percentage of the bonding additions plus fines. The problem in its use, is the assurance of consistency. This must rely on the dust collection system and its maintenance. The problem that accelerates is the variation of fines put back in the molding system unknowingly. Although we have not discussed the molding sand fineness as related to compactability, a major deviation can occur as fines develop. The addition of water described can provide the catalyst to develop the cohesiveness of the clay bond and additives. Thus it has the greatest influence on the development of the compactability reading at the same MB clay level. Likewise, as moisture evaporates during the transporting, the compactability level is constantly changing. This condition is greatly accelerated with hot returned sand and the cooling of the sand prior to mold compaction.

The controlling of moisture and or additions of bond are key variables that are used for automatic compactability control equipment. The equipment effectiveness is based on monitoring return sand temperature fluctuations. By consistent adjustments made for returned sand, these automatic controllers can produce consistent compactability.

* **Mulling and mixing**

  Compactability increases steadily as calibrated mixing and mulling energy is applied to a sand mixture. Since the return sand temperature is an important factor, (based on mold/metal weight fluctuations and shake out time) the evaporation of water is the main reason for the variation of compactability. This is important enough to repeat. There is constant change in molding sand mixtures from the reduction of sand temperature during transport and handling from shakeout, mulling and return to the molding machine. In some cases with high intensity mixing or mulling, the friction causes heat. In other cases with high intensity mixers the excess energy and increased time can actually create fatigue in the bentonite, which renders the sand more brittle and friable. This lowers the compactability reading. This condition is detrimental and can affect casting quality by an increase in sand inclusions. This is due to a mold surface dryness. Aerators can be used to improve the consistency of compactability. The sequence of additions to the muller if not consistent, can affect the compactability readings. If the formulas are added as a premixture, the variability is reduced.

* **Conclusions**

  All conditions that contribute to the development of green compression strength and air set strength affect the variability of compactability readings. All of the raw materials used in the green sand formulation have some effect on the variability of compactability. The following are the largest contributors in order of most influence:

  1. Moisture content
  2. Starch and cereals
  3. Sodium bentonite
  4. Activated bentonite
  5. Mixing and mulling
  6. Hot returned sand
  7. Calcium bentonite
  8. Electrolytes/polymers
  9. Sea coal (S content)
  10. Cellulose materials
  11. Fines and finer sand
  12. Coarse sand

  In the light of repeated successes foundry men have adopted, improved, computerized, and automated the compactability-
testing concept. They have proven its effectiveness for stabilizing and controlling automated green sand systems, with improved production rates.

It is very important to know and specify the raw materials being used, control the sand composition, temperature and processing methods. These all in synergism, control compactability and ultimate consistency of green sand molding. The success has been confirmed in the field where over 90% of green sand foundries have made it a production test necessity.

References

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2. Testing Molding Sand for Compactability, George DiSylvestro, DIS News Issue #2, 1993
5. Sulphur in Molding Sand, DIS Research Report #17, 1993

Critical Molding Factors Affecting Net Shape Castings
Raw Materials and Molding Sand Control
High Density Molding Technology
ABSTRACT
The evaluation of the machinability of a material is usually a lengthy process. However, some indices, namely drilling thrust force and torque, may be used to rank the machinability of several materials considered for a given application. This method was used to characterize the machinability of ferritic Ductile Irons. The results were then compared to those obtained for several competitive materials. It has been shown that ferritic Ductile Iron is easier to machine than most competing alloys. The results also indicated that the structural characteristics of a material play a major role in its machining behavior.

1. Introduction
Although the machining of Ductile Iron components is minimized by the casting process itself, secondary operations such as drilling, milling, turning, etc. are often required. In some cases, machining may represent a significant fraction of the total cost of the component. Therefore, understanding the machinability behavior of Ductile Iron is instrumental in maintaining and improving its competitiveness.

The evaluation of tool life is certainly the most accurate method to assess the machinability of materials. However, the time required to fully characterize a material is often a major obstacle. A rapid characterization method might be sufficient for the foundry man to evaluate the machining characteristics of his product or for a casting user to approximate the machining behavior of a material as a function of its mechanical properties and/or structural characteristics. For instance, the measurement of the drilling thrust force and torque at constant feed rate and rotating speed provides sufficient qualitative information to judge on the quality of the material or to carry out a preselection amongst many candidate materials\(^1\).

In this paper, a machinability evaluation technique using drilling thrust force and torque as machinability indices is described. The relationship of these properties to tool wear is discussed for ferritic Ductile Irons and compared to those obtained for other engineering materials, namely wrought steels, powder metal steel, and gray iron.

2. Machinability Evaluation Procedure
Figure 1 presents a schematic of the experimental set-up designed to measure the drilling thrust force and torque. It consists of a high-powered drill press with automatic feed rate control. The apparatus is equipped with a specially designed specimen holder capable of monitoring the torque applied on the tool and the thrust force transmitted to the test specimen. The feed rate and the rotating speed are continuously recorded during the operation. The acquisition system enables the measurement of the four parameters nine times per second. The data is then transmitted to a computer for processing. As shown in Figure 2, the rotating speed and feed rate do not significantly vary during a test.

Typical thrust force and torque curves obtained when drilling a hole with this set up are shown in Figure 3. As the drill penetrates the work piece, the thrust force and torque quickly increase to reach a steady state. In most cases, both the thrust force and torque remain at relatively constant levels and then drop when the feed is interrupted. Occasionally, the torque may increase towards the end of the test probably because of an increased difficulty to expel the chips from the hole. The average thrust force and torque in the steady state portion of the curves are then calculated for each hole. The drill is removed at regular intervals to evaluate qualitatively the land wear and the accumulation of the machining debris on the tool. Drilling chips are also examined.

When different materials are characterized, one drill is used per material. In order to minimize the impact of the variation of the drills characteristics on the measurements, a qualification process was established. The method consists in drilling two holes to a depth of 2.5 cm in a standard material at a feed rate of 0.12 mm/rev and a cutting speed of 2220 rpm. To be accepted, the thrust force and torque measured on a drill must be within ±5% of the average values of a lot of twenty drills minimum. In this study, the cutting tools were high-speed steel drills with a helix angle of 118° and a diameter of 6.35 mm. The cutting speed and feed rate were 2220 rpm and 0.12 mm/rev.

Figure 4 presents an example of curves that can be obtained with such an evaluation method for materials with different machinability levels\(^2\). The thrust force obtained for material B resembles a typical tool wear curve\(^3\), with three different stages. During the first stage, the thrust force increases rapidly which corresponds to the first stage of wear, i.e., the breakdown of the initial cutting edge and the development of a finite land wear on the tool. This is followed by a region of linear progression of the thrust force (or torque) similar to the steady state of the wear process during which a uniform wear rate is noticed. Then, the thrust force increases very rapidly and reaches a level at which the drill fails: this is the final accelerated wear stage. If the machinability of the material is marginal as for material A, the thrust force (or torque) rapidly reaches a high value at which the tool is exhausted without apparent steady-state stage. On the other hand, however, it may happen that a material exhibits excellent machinability, which makes the determination of tool life a lengthy procedure, such as for material C. In such a case, the thrust force (or torque)
measured can be used as a relative indicator of machinability. In the example of Figure 4, material C, which exhibits the lowest thrust force, is the most machinable alloy followed by materials B and A.

3. Materials Characterization

As stated earlier, this study was aimed to the comparison of the machinability of various materials competing with Ductile Irons on the same applications. As shown in Tables 1 and 2, the test matrix was divided into two series of experiments. In the first one, the effect of structure and composition on the machinability of materials (two Ductile Irons and one steel) of comparable hardness was investigated. The objective of the second series was to compare the machinability of the best Ductile Iron to that of competitive materials, namely gray iron, wrought steel and powder metal copper steel.

The first group of materials (Series A) includes two Ductile Irons with a hardness of 152-156 BHN. However, as seen in Tables 1 and 2, the composition and structure of these materials are different. Material D-1 was based on HPI added with FeMn and cast in RIT-Technology pilot plant according to procedures described elsewhere. The samples consisted in 2.54 cm keel blocks whose structure is described in Table 2. The second set of Ductile Iron specimens consisted in commercial castings with a section size varying between 1.5 and 3 cm. The casting was fully ferritic, Table 2, due its high silicon content (2.8% Si) and exhibited a high ferrite micro hardness (Table 2). For comparison purpose, the machinability of a steel of comparable hardness was also investigated. This material was a 11L17 steel in which lead and MnS particles act as machinability enhancers. The composition of the steel is listed in Table 1 and its structure shown in Figure 5.

The second series of materials, which are also described in Tables 1 and 2, consisted in alloys (P/M steel and gray iron) competing for applications similar to the one for which material D-2 was used. The gray iron material was a class 40 commercial casting (same type of parts as D-2) whose structure consisted in type A flake graphite embedded in a fully pearlitic matrix. The castings had a Brinell hardness of 197 BHN. For comparison purpose, 1045 steel with the same hardness as the gray iron castings was also included in the test matrix with the objective of identifying the role of graphite as machinability enhancer. Finally, powder metal steel whose structure is shown in Figure 6 was also tested. Such a FC-0205 material is typical of a P/M alloy competing for parts currently made of cast irons. The P/M specimens were pressed to a density of 6.8 g/cm³ and sintered at 1120°C for 20 minutes under a controlled atmosphere.

4. MACHINABILITY CHARACTERIZATION

4.1 Series A Materials

Figure 7a presents the change in average drilling thrust force as a function of the drilled depth for the materials of Series A, i.e. for the Ductile Irons and the 11L17 steel with hardnesses of 152-156 BHN. The three materials display curves of similar shape. With these materials, the initial increase shown for forged P/M steel in Figure 4 is less pronounced implying that the initial breakdown of the tool probably occurs over a long period of time in these materials due to their relatively good machinability. However, the torque curves shown in Figure 7b exhibit the typical behavior of the wear curves, i.e. a rapid increase followed by a steady state. This indicates that the torque applied on the tool is more sensitive to the initial change of the cutting surface (sharpness or build up of debris on the tool) than the thrust force.

It is a common practice to relate the machinability of a material to its hardness, i.e. the harder the material, the more difficult it is to machine. However, as shown in Figure 7, although the materials of series A exhibit the same bulk hardness, their machinability as measured by drilling thrust force and torque is different. The comparison of the curves obtained for the two Ductile Iron materials reveals the following:

i) the drilling thrust force and torque required to machine the fully ferritic Ductile Iron (D-2) are larger than those needed for the Ductile Iron containing about 15% pearlite (D-1). After a drilled depth of 80 cm, the difference is about 100 N (20%) for the thrust force and 0.6 N-m (40%) for the torque.

ii) the rates of increase (slope) of the drilling thrust force and of the torque are higher for the fully ferritic iron (D-2) than for the D-1 iron.

Such differences are related to the following factors. First the production of the fully ferritic casting D-2 required to alloy the iron with 2.8% Si. The solid-solution hardening effect of Si resulted in a harder ferrite, which requires higher thrust force and torque. Second, because ferrite is a ductile phase, it tends to deform rather than break during machining. The occurrence of a limited amount of brittle pearlite dispersed in the intercellular regions of the D-1 alloy resulted in the rupture of the chips during their formation. It then limits the adhesion of debris on the tool face and reduces the friction force induced by long chips. This is illustrated in Figures 8 shows that more long curled chips are formed in the fully ferritic D-2 material than in the D-1 Ductile Iron. This phenomenon is mainly responsible for the higher torque measured when drilling the fully ferritic material.

iii) A larger nodule count in Ductile Iron should be a positive factor vis-à-vis machinability, the dispersion of graphite particles in the structure ensuring a more continuous lubrication at the tool/chip interface. However, during these tests, such an effect has probably been dominated by the previously discussed factors. It nevertheless indicates that a nodule count of 75 is sufficient to ensure a continuous lubrication at the tool/chip interface.
It is seen in Figure 7a that the 11L17 steel requires the highest thrust force of this series of materials but the lowest torque. The absence of soft graphite nodules in the steel probably makes more difficult the penetration of the matrix by the drill and results in a higher thrust force. However, the dispersion of the machinability enhancing compounds in the steel matrix ensures a better lubrication at the tool/chip interface and during the removal of the chips, which results in a lower torque value. It is nevertheless worth noting that the machinability of Ductile Iron competes with that of a steel specially engineered for applications requiring substantial machining.

4.2 Series B Materials

The machinability results obtained on the materials of series B are presented and compared to those of Ductile Iron D-1 in Figure 9. The lowest thrust force is displayed by the D-1 material followed by the gray iron (G-1), the P/M steel (PM-1) and the 1045 steel (S-2). As in Series A, the characteristics of the phases present in the material control the level of thrust force required to drill the materials:

i) D-1 material, which is significantly harder than the PM-1 material, is found easier to drill. As seen in Figure 6, a P/M steel with a density of about 6.8 g/cm³ contains 10 to 12% porosity. Under the stresses applied by the drill, the pores collapse which results in the densification of a layer of material under the tool, Figure 10, and in the strain hardening of the material(5). Micro hardness of this densified layer can be as high as 283 VHN(5) which exceeds the hardness of the 1045 steel. The occurrence of graphite in Ductile Iron further contributes to ease the cutting of the material by acting as a solid lubricant and as a chip breaker. Note however that the addition of solid lubricants such as BN(6) or MnS(5) to P/M steels improves their machinability. For example an addition of 0.3% MnS to the PM-1 steel would reduce the thrust force by 40% or to 450 N after 80 cm drilled depth under the drilling conditions used in this study(5), which is closed to that of the D-1 material. However, PM-1 steel would have UTS and elongation values significantly lower than those of the D-1 material (450 vs. 550 MPa, 2 vs. 15%).

ii) The pearlitic G-1 gray iron requires a higher thrust force than the Ductile Iron D-1 material. However as the drilled depth increases, the thrust force for G-1 increases at a significantly larger rate than for D-1(1.1 vs. 0.5 N/cm), resulting in a higher wear rate of the cutting tool. This is confirmed by the examination of the cutting edge of the tools which reveals a land wear approximately double on the tool used for drilling in G-1, Figure 11.

iii) Although displaying the same hardness as the G-1 material, the 1045 steel (S-2) exhibits a thrust force 40-50% higher than the one observed for G-1. The rate of increase of the thrust force as a function of the drilled depth is about the same for both materials, implying comparable wear rates. However, as seen in Figure 12, drilling debris tend to adhere on the cutting face of the tool used in the S-2 material while this phenomenon is minimal when drilling in the gray iron, Figure 11b. The build-up of debris, which is prevented in gray iron by the occurrence of graphite, is responsible for the higher thrust force measured for the 1045 steel.

The ranking of Series B materials using the torque curves shown in Figure 10 is slightly different than the one obtained with the thrust force curves. The gray iron (G-1) required the lowest torque followed the Ductile Iron (D-1), the PM steel (PM-1) and the 1045 steel (S-2). Figure 13 compares the chips generated when drilling the first and fiftieth (80 cm) holes in the gray iron and the 1045 steel. As expected, the gray iron chips are small and non-oxydized; no significant difference is seen between the chips from the first and fiftieth holes. Those generated in the steel are long and their level of oxidation increases significantly as the number of holes increases. Graphite in G-1 material plays a two fold role: it contributes to chip breaking while being also an efficient lubricant that eases the evacuation of the chips. This limits the heating of the tool as indicated by the absence of a detectable amount of oxide on the chips. Nodular graphite in Ductile Iron plays a similar role although being a less efficient chip breaker than flake graphite.

5. CONCLUSION

The machinability of Ductile Iron was characterized using the forces generated during drilling under controlled conditions as machinability indices. The results were compared to those obtained on various other engineering materials competing with Ductile Iron on many applications. Within the limits of this study, the following conclusions can be drawn:

1. For materials of similar hardness, the micro structural characteristics may significantly influence the machinability.

2. A fully ferritic Ductile Iron casting containing a high silicon concentration is less machinable than a casting of similar hardness containing about 20% pearlite. The softer ferrite and the chip breaking effect of pearlite are responsible for such an effect.

3. Drilling in ferritic Ductile Iron requires lower thrust force than in 11L17 machinable steel with a slightly higher torque. Nodular graphite in Ductile Iron plays a role similar to that of lead and MnS in the 11L17 steel to improve machinability.
4. Ferritic Ductile Iron with pearlite at cell boundaries machines significantly better than a FC-0205 P/M steel containing no machinability enhancer; the addition of such additives to the P/M steel makes the two materials competitive machinability wise.

5. Ferritic Ductile Iron machines better than class 40 gray iron or 1045 steel although the torque measured when drilling in gray iron is slightly lower.

6. Flake graphite is a more efficient machinability enhancer than nodular graphite.

7. Drilling thrust force and torque are indices that can be used to characterize the machinability of materials.

References


List of Figures

- Figure 1 - Schematic of the Machinability Evaluation Set-up.
- Figure 2 - Recordings of Rotating Speed and Feed Rate during a Drilling Test.
- Figure 3 - Recordings of Thrust Force and Torque during a Drilling Test.
- Figure 4 - Examples of Thrust Force Curves Obtained in Powder-Forged Materials as a Function of Drilled Depth (Reference 2).
- Figure 5 - Unetched Structure of the 11L17 Steel (Material S-1).
- Figure 6 - Typical Etched Structure of the FC-0205 P/M Steel (PM-1).
- Figure 7 - Change in a) Thrust
- Figure 8 - Drilling Chips Obtained when Drilling the First Hole in a) Material D-1 and b) Material D-2. Force and b) Torque as a Function of Drilled Depth for Materials of Series A.
- Figure 9 - Change in a) Thrust Force and b) Torque as a Function of Drilled Depth for Materials of Series B.
- Figure 10 - Densified Layer under the Tool after Drilling in the PM-1 Material.
- Figure 11 - Land Wear Developed after 80 cm Drilled Depth on Tools Used for a) Ductile Iron D-1 and b) Gray Iron G-1.
- Figure 12 - Land Wear and Build-up of Debris on the Cutting Edge of the Tool Used for Drilling in the 1045 Steel (S-2) after 80 cm Drilled Depth.
- Figure 13 - Drilling Chips Obtained when Drilling in Material G-1 ( a) 1st Hole, b) 50th Hole) and in Material S-2 ( c) 1st Hole, d) 50th Hole).

Table 1 - Description and Chemical Composition of the Materials

<table>
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<th>Series</th>
<th>Material Code</th>
<th>Composition, wt %</th>
<th>Description</th>
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<tr>
<td>A</td>
<td>D-1</td>
<td>C 3.52  Si 2.49   S 0.012  Mn 0.30  Mg 0.041</td>
<td>Charge: Sorelmetal</td>
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### Table 2 - Structure and Hardness of the Materials

<table>
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<th>Series</th>
<th>Material Code</th>
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<th>Structure</th>
<th>% Ferrite</th>
<th>% Pearlite</th>
<th>Hardness</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bulk BHN</td>
</tr>
<tr>
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<td>D-1</td>
<td>75 (11)</td>
<td>71</td>
<td>18</td>
<td></td>
<td>156</td>
</tr>
<tr>
<td></td>
<td>D-2</td>
<td>155 (11)</td>
<td>89</td>
<td>0</td>
<td></td>
<td>152</td>
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<tr>
<td></td>
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<td>77</td>
<td>20</td>
<td></td>
<td>152</td>
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<td>0</td>
<td>40</td>
<td>60</td>
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<td>102</td>
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</table>

* ferrite  
** ferrite-pearlite.
Comparative Machinability Evaluation of Ferritic Ductile Iron Castings

Figures

Figure 1. Schematic of machinability evaluation setup. Back to Article

Figure 2. Recordings of rotating speed and feed rate during a drilling test. Back to Article

Figure 3. Recordings of thrust force and torque during a drilling test. Back to Article
Figure 4. Examples of thrust force curves obtained in powder-forged materials, as a function of drilled depth.²
Back to Article

Figure 5. Unetched structure of 11L17 steel (Material S-1).
Back to Article
Figure 6. Typical etched structure of FC-0205 P/M steel (PM-1).

Figure 7a. Change in thrust force as a function of drilled depth for materials of Series A.

Figure 7b. Change in torque as a function of drilled depth for materials of Series A.
Figure 8a. Drilling chips obtained when drilling the first hole in material D-1
Back to Article

Figure 8b. Drilling chips obtained when drilling the first hole in material D-2.
Back to Article

Figure 9a. Change in thrust force as a function of drilled depth for materials of Series B.
Back to Article
Figure 9b. Change in torque as a function of drilled depth for materials of Series B.
Back to Article

Figure 10. Densified layer under the tool after drilling in the PM-1 material.
Back to Article

Figure 11a. Land wear developed after 80cm drilled depth on tools used for DI D-1.
Back to Article
Figure 11b. Land wear developed after 80cm drilled depth on tools used for gray iron G-1.

Figure 12. Land wear and buildup of debris on the cutting edge of the tool used for drilling in the 1045 steel (S-2) after 80cm drilled depth.
Figure 13. Drilling chips obtained in Material G-1 and S-2.

Back to Article
13d. S-2, 50th hole
Porosity Defects in Gray and Ductile Iron Castings
from Mold Metal Interface Reactions

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October 21, 2000

Introduction: Surface and subsurface gas defects have always been common and troublesome defects in gray and ductile iron castings poured in green sand molds. During the past 30 years, innovations in synthetic binder technology have resulted in movement away from green sand molding and toward total no-bake molding and core making processes and accompanying new types of casting defects. In the year 2000, it is estimated that phenolic urethane binders, in both the cold box and no bake versions, will account for over 60% of all chemical binders used by the U.S. foundry industry. Although millions of tons of gray and ductile iron castings are cast using these resins for both core and mold binders, casting defects stemming from mold-metal reactions continue to pose problems for foundry men.

Generally speaking, there are three major sources that may contribute to porosity formation in gray iron castings. These are: 1) high initial gas content of the melt originating from either the charge ingredients, melting practice or atmospheric humidity, 2) reaction of carbon and dissolved oxygen under certain melt conditions, and 3) mold-metal reactions between evolved mold and core gases at the solidifying casting surface. In addition, any combination of these three sources may have a cumulative effect on promoting porosity formation. However, the gases normally held responsible for subsurface porosity defects are nitrogen and hydrogen.

The appearance of the subsurface porosity defects resulting from the preceding sources may take numerous shapes but usually form as either small, spherical holes (sometimes elongated or pear-shaped) and called pinholes, or larger, irregularly rounded holes or irregularly shaped fissure type defects. The internal surfaces of the resultant holes may be 1) oxidized, 2) lined with a shiny graphite film, or 3) contain slag or manganese sulfide inclusions.

The phenolic urethane resin system consists of no-bake and gas cured resins; both systems consisting of two resin components. Part I is a phenolic resin (poly-benzylic-ether-phenolic resin) diluted approximately 50% by solvents. Part II is a polymeric di-isocyanate resin diluted with approximately 25% solvents. The solvent can be either aliphatic and aromatic in composition. The primary purpose of the solvents is to reduce binder viscosity. Typically, the viscosity of the Part I and Part II resins are adjusted to 200 cps or lower to provide good pump ability, rapid and efficient sand coating qualities and good flow ability of mixed sand. A second purpose of the solvents is to enhance resin reactivity. An amine-based catalyst is used as the curing agent for the no-bake binder while a gaseous amine (triethylamine or dimethylethyl amine) is used for the gas-cured binder.

The general chemistry of phenolic urethane binders remains essentially the same as when the binders were developed in the late 1960 to early 1970's. There have been some changes in basic resin formulations involving the solvent systems as well as base phenolic resin system. The Part I phenolic resin has been modified to reduce odor by reduction in the level of free formaldehyde, and this becomes especially apparent when hot foundry sands are used. In addition, because of efforts to reduce solvent vaporization into the atmosphere, the solvent systems have been modified extensively to incorporate higher boiling point solvents or new solvents systems having improved environmental properties.

Being organic based systems, the phenolic-urethane family of binders are composed of only four basic elements: 72% carbon (C), 8.5% hydrogen (H), 3.9% nitrogen (N) and 15.5% oxygen (O).

With phenolic urethane systems, the nitrogen component is associated solely with the polyphenyl polyisocyanate (Part II) binder component. Part I, or the hydroxyl containing phenolic binder component, contains no nitrogen. The gases typically responsible for subsurface porosity in iron castings are nitrogen and hydrogen; carbon and oxygen from binder decomposition usually present no problem because the high silicon content of gray iron acts to suppress the formation of carbon monoxide porosity.

Hydrogen, nitrogen, oxygen and carbon, may react or combine in numerous ways to provide the necessary conditions that favor porosity formation. The following gaseous reactions are thermodynamically possible and under the right conditions may occur at the mold-metal interface:

\[
\begin{align*}
\text{Binder} & \rightarrow H \text{(nascent)} \rightarrow H_2 \text{(g)} \\
\text{Binder} & \rightarrow N \text{(nascent)} \rightarrow N_2 \text{(g)} \\
Fe + H_2O \text{ vapor (binder)} & \rightarrow FeO + 2H \text{(nascent)} \\
3 H_2 \text{ (binder) } + N_2 \text{ (binder)} & \rightarrow 2NH_3(g) \rightarrow 6H\text{(nascent)} + 2N\text{(nascent)} \\
FeO + C \text{ (binder)} & \rightarrow CO \text{ (g)} + Fe
\end{align*}
\]

While the first four reactions are likely to provide both surface and subsurface porosity defects, the last reaction usually results only in surface defects, such as pock marking or more frequently, lustrous carbon laps and surface wrinkles. When an organic binder thermally degrades, hydrogen and nitrogen are liberated in the nascent or atomic form. In this mono-atomic state, they are
Porosity Defects in Gray and Ductile Iron Castings

readily soluble in molten iron, and if present, dissolve quite easily in both molten gray and ductile irons. If ammonia forms, it also may dissociate into both nascent hydrogen and nitrogen. Since the solubility of hydrogen and nitrogen in liquid iron is far greater than in solid iron, these gases will precipitate out of solution as gas bubbles during solidification if they are present in amounts greater than the solid solubility limits. The shapes of the resulting gas holes may vary from small, widely dispersed spherical shaped holes lying just under the surface to numerous fissure type holes, often resembling shrinkage defects and are usually perpendicular to the casting surface. In either case, absorption of nitrogen and/or hydrogen by the molten iron, either individually or jointly, may result in subsurface porosity defects.

Clearly, many factors are involved in the development of binder-associated defects; neither they nor the various core making parameters and foundry melting variables that have a direct influence on the occurrence of such defects were well understood in the early 1970's. Recognizing this situation, the object of this investigation was aimed at determining how such variables influence the occurrence of porosity defects. Also, the development of remedial techniques to alleviate these problems was also extensively studied.

Experimental Procedure

The experimental program used in this investigation was divided into two phases. The first phase was devoted to 1.) the development of a suitable test having the capability to produce porosity defects and 2.) the delineation of core making and metal processing variables having an effect on porosity generation. The cylindrical test casting shown in Figure 1 was developed for these tests to observe the extent of porosity formation under various test conditions. This "stepped cone" configuration was selected because its design was such that core decomposition gases would be generated rapidly while the casting was still in the molten state. Also, this design easily lent itself to the study of section size, re-entrant angle (hot spot) and other geometric effects (see Figure 2).

The majority of molds used for the production of test castings were made with a zero nitrogen no-bake furan binder. The base core sand mix used for most of the experimental work consisted of the phenolic urethane no-bake binder (PUN) mixed with a high purity, washed and dried, round grained, silica (W/D) sand. The core making procedure used throughout most of this work consisted of adding the phenolic polyol resin component (Part I) and the catalyst to the sand and mixing for two minutes, followed by the addition of the polysiocyanate component (Part II) and mixing for an additional two minutes. The mix was immediately hand rammed into the core box and the stepped cone cores were stripped within five minutes.

Gray and ductile irons of the compositions shown in Table I were utilized in the investigation, although the bulk of the experimental work was conducted with a high carbon equivalent iron (4.3 C.E) inoculated with standard foundry grade (0.75% minimum calcium) ferrosilicon in the ladle. Inoculant addition levels were 0.25% silicon, based on the pouring weight. All heats were prepared with virgin charge materials to insure low initial gas content and were poured at selected temperatures as measured with a Pt-Pt 10% Rd immersion pyrometer and a high speed, strip chart recorder. Variables studied during this phase of the investigation included binder ratio, binder level, pouring temperature, sand type and permeability, mixing effects, metal composition and core age. Within each series of tests, the conditions were controlled as carefully as possible and individual variables altered to determine their effect on porosity.

The second phase of the experimental work was devoted to developing remedial techniques to prevent porosity. To a great extent, this effort was very dependent upon the first phase of the work in that conditions that were found to promote porosity were used exclusively. Therefore, it was a prerequisite to develop the capability to produce binder-associated gas defects at will. The same melting and core making procedures previously described were likewise used at this time. Techniques studied in attempt to eliminate defects included 1.) Investigation of various grades of iron oxide, 2.) Ladle additions of ferrotitanium, as well as titanium and zirconium based ferroalloy inoculants, 3.) Use of core sand additives, 4.) Core baking, and lastly, 5.) A study of experimental core coatings. During this phase of the work, variables found responsible for porosity formation were held constant during the preparation of test castings.

The extent of porosity formation in all castings was determined by careful sectioning at several locations. To determine whether any metallurgical changes resulting from porosity formation had occurred, metallographic investigations of the cast structure in the mold-metal interface area were also carried out. To observe the nature of the internal surfaces of gas porosity defects, a scanning electron microscope was utilized.

Results

Parameters Affecting Formation of Binder Related Porosity Defects

It is of great importance to the foundry man to fully understand the nature of and fundamental chemistry of no-bake binder systems in order to assure their correct usage. This is particularly true with phenolic urethane no-bake (PUN) systems. Generally, any one of a number of minor operating variables can exert a cumulative effect on the performance of no-bake binders. Some of these factors which contribute to binder misuse are: 1) infrequent calibration of binder pumps and sand flow rates on continuous mixers, 2) general equipment malfunctions related to binder pumps, worn mixer auger screws or blades, poor housekeeping practice, etc, 3) intentional unbalancing of binder components to facilitate stripping, or 4) general misunderstanding of possible potential consequences resulting from any of the preceding. To determine how these effects and other variables may affect porosity formation, numerous experimental heats were poured to study their effect on casting integrity.

Effect of Binder Part I to Part II ratio -- The effect of the ratio of Part I to Part II resin components for PUN binders on porosity
propensity is shown in Table 2.

Binder ratios of 60 : 40 (Part I : Part II) provided sound test castings in every case under the test conditions used. As this ratio became balanced (50 : 50), trace amounts of porosity were found in a few test castings but the majority of test castings made with balanced ratios were sound. In those cases where porosity was found, a substantial portion was as surface porosity or semi-rounded holes (pock marking). As the binder ratio was unbalanced again in favor of excess Part II (40 : 60 and 35 : 65), greater amounts of subsurface porosity formed in the test casting. The types of defects observed and described as varying in intensity from nil to very severe are shown in Figure 3. Although the recommended ratio for running PUN binders varies between a 55:45 to 60:40 ratio, in actual practice, extreme ratios favoring excess Part II or polyisocyanate are often encountered. Such problems often arise from worn or defective binder pumps, air in binder lines, changes in binder viscosity from temperature, inefficient mixing, and numerous other less incidental, but often overlooked sources. For example, in the early 1970's, it was not unusual to foundries to run binder ratios favoring excess polyisocyanates to facilitate the stripping of difficult cores or to increase fully cured core strengths.

New resin formulations (1998 versions) showed very little difference in casting performance compared to early 1970 versions. Binder ratios in which unbalanced ratios of 60 : 40 were employed produced sound castings. Unbalanced binder ratios favoring excess Part II or the isocyanate component once again were very susceptible to severe subsurface porosity.

**Effect of Binder Level** -- To determine the effect of binder level on porosity susceptibility, test castings were poured with test cores made with binder levels ranging from 1.25% to an extreme of 3.0%. At some of these levels, the ratio of Pt I : Pt II was again varied to determine effect on porosity formation. (It should also be noted that although these higher levels may never be encountered in actual practice, they were intentionally selected to magnify the effect of binder level or the effect of reclaimed sands having high "LOI" values.) The results obtained from these tests showed that as the binder level increased at the same Pt I : Pt II ratio, the severity of the porosity defects likewise increased. At the highest binder level tested, porosity tended to form at even balanced ratios as shown in Table 3.

These results show that if sufficient amounts of evolved hydrogen and/or nitrogen decomposition gases are made available to the solidifying iron, porosity will generally occur even with favorable binder ratios and using relatively high pouring temperatures. These same phenomena can be extrapolated to include what the consequences will be when using reclaimed core or molding sands having high loss on ignition values. Excessive amounts of dissolved gases stemming from inappropriate charge materials or liquid metal processing will likewise be more susceptible to core gas defects from absorption of hydrogen and/or nitrogen.

**Effect of Casting Temperature** -- Although the previously reported results have shown significant effects of both binder ratio and level on porosity formation, their effect was very temperature dependent. Results obtained from test castings poured at several casting temperatures and incorporating unbalanced binder component ratios favoring excess Part II are shown in Table 4.

These results demonstrate the temperature dependency of porosity formation with PUN binders. Pouring temperatures of 2700°F and higher (as measured in the pouring ladle) produce severe subsurface defects when unbalanced ratios are used. Such pronounced behavior is not observed when these ratios are balanced or when excess Part I is used. Reducing the pouring temperature at both binder levels resulted in lesser amounts of porosity until at the lowest temperature sound castings were achieved.

Pouring temperature effects were further demonstrated by pouring experimental test step cores that were coated with the polyisocyanate binder component (Part II). For these tests, pouring temperatures of 2500°F were employed and test cores were bonded with an unbalanced (35:65 ratio) binder system containing 3.0% total resin. Sectioned test castings obtained under these conditions were entirely sound.

The porosity-temperature dependency can best be illustrated in Figure 4. In this figure, pouring temperature is plotted against binder ratio. It is interesting to note that there appears to be a definite region in which porosity seems to form and also another definite region where sound castings are obtained. In between these two areas, porosity may or may not occur depending on other liquid metal processing factors. Similar findings on the effect of pouring temperature with other binder systems have been reported by other investigators.4, 16

**Effect of Section Size** -- In those castings containing porosity, it occurred in preferential locations. Deep seated, subsurface porosity was usually located adjacent to the 90° re-entrant angle or "step" and most often occurred in section thickness' ranging between 7/8 in. and 1-3/8 in. These locations act as localized hot spots since a small volume of the core is heated from both sides by the solidifying iron. In thinner sections, varying degrees of surface porosity or pock marking were often found. From the appearance of these defects, it appears probable that they were formed late in the solidification process by gaseous decomposition products pushing away the semi-skinned over casting surface.17 Since these bubbles are formed late in the solidification process at the mold-metal interface, not enough time was available for their dissolution. Consequently, a depression is left in the surface when final solidification commences. The extent of this surface porosity varied between somewhat large, semi-rounded holes extending at most only 1/8 in. into the surface to very small surface pores having no appreciable depth.

**Sand Effects** -- The type of sand used in experimental test cores had a significant effect on porosity formation. Some results obtained with typical lake sand and washed and dried silica sand are listed in Table 5.

Although several castings were poured under identical conditions and also from the same ladle, severe subsurface porosity was
Porosity Defects in Gray and Ductile Iron Castings

very prevalent with washed and dried silica sand while castings made with the Michigan lake sand were entirely sound. The behavior of lake sand in eliminating gas defects may possibly be attributed to either its significantly larger quantity of surface impurities, bulk impurities or greater permeability.

To determine the effect of surface purity on influencing gas porosity, an acid treatment was administered to the lake sand to remove trace surface impurities. The acid treatment consisted of soaking the sand in a 10% solution of sulfuric acid for 24 hours followed by a 24-hour water wash and drying. Such treatments have been shown to be very effective in removing these impurities.\(^1\)

Comparisons of casting results obtained with acid-treated versus untreated Lake Sands are shown in Table 6. The results in Table 6 showed that removal of surface impurities by acid leaching was not effective in promoting porosity and no porosity was observed in the test castings.

Because of the known effect of permeability on porosity defects and the potential chemical effect of sand type, several other sands having a wide range of compositions, permeabilities and AFS grain fineness distributions were selected for testing. These tests were run to determine relative porosity susceptibilities of common core and molding sands. The results of casting tests all run under identical conditions along with the physical properties and resultant porosity sensitivities are summarized in Tables 7 and 8.

Based on the preceding, even though the sands tested had a wide range of AFS grain fineness and permeabilities, there doesn't appear to be any correlation between these parameters and porosity sensitivity. The trend in Tables 7 and 8 is such that the lower the impurity level, and particularly the iron oxide content of the sand, the greater the sensitivity of the system for promotion of porosity defects. Hence, although very pure, round grained sands offer outstanding core and mold making properties, they may not produce the best castings, as less impure sands seem to do.

The intentional addition of impurities such as iron oxide to sand mixes is widely recognized as an effective means of controlling porosity, veining, improving hot strength and other less incidental properties. However, the presence of such a small amount of iron oxide as a bulk impurity associated with the sand mineralogy appears to have a significant effect on retarding or inhibiting porosity formation. In addition, the type and purity of iron oxide will be shown to have an overriding effect on porosity formation.

Binder Dispersion or Mixing Effects -- Proper dispersion of the liquid binder components on sand surfaces is a necessary prerequisite in the production of high quality cores and molds. Mixers which were prevalent in the early to mid 1970's often provided relatively poor blending of binders and subsequent coating of sand grain surfaces. This was especially true of slow speed screw or auger types, which left something to be desired where high mixing efficiency is desired. Also, if the screw blades or paddles and trough are not cleaned regularly to remove resin buildup, are poorly designed or wide clearances exist due to wear, then poor mixing action will result. If proper dispersion of the binder components is not realized, many areas of the core surface will essentially contain varying ratios of binder components even though the bulk core may contain the proper total amount of each component. Although high speed, high efficiency sand mixers along with advanced resin metering systems, often with computerized controls, have been developed in the 1990's and have resulted in dramatically improved mixing, consideration must still be given to properly maintaining the equipment.

To determine the effect of proper binder dispersion on mixing efficiency, several core mixes were made in a laboratory high intensity batch mixer and mixed for various times to simulate mixing conditions ranging from very poor to excellent. Experimental test cores were made using mixing times of 5, 10, 20, 30 and 60 seconds for each component (double for actual total mix cycle). All of these cores were prepared with balanced ratios of Pt. I : Pt. II (50 : 50) on the standard washed and dried silica sand. Cores prepared with total mixing times of 10, 20 and 30 seconds exhibited pronounced non-uniform binder dispersion and were spotty in appearance. This was found to be most pronounced with the 10 and 20 second mix cycles. Longer mixing times of 80, 120, and 240 seconds provided very uniform results. Physical properties such as scratch and tensile strengths of mixes mixed for total times of 40 seconds and longer were not impaired even though traces of inadequate mixing were apparent on the 40-second mix.

The results obtained from casting tests using test cores prepared in the described manner are listed in Table 9. To briefly summarize these results, short mix cycles of 10 to 40 seconds total time tended to promote the formation of both surface and subsurface porosity. Only trace amounts of subsurface porosity, probably better described as microporosity, were found in the remaining castings made with cores mixed for intermediate times of 60 to 80 seconds total. In castings containing pronounced defects, these defects were obviously formed where the solidifying casting was in contact with binder-rich areas and particularly those containing excess polysisocyanate. Sound castings were obtained when total mixing times ranged from 2 to 4 minutes.

Effect of Metal Composition -- The type and composition of the castings poured had a significant effect on porosity formation. Results of these tests are shown in Table 10. The porosity forming tendencies seemed to be greatest for the low carbon equivalent iron and least for ductile iron. Porosity defects in all gray iron castings formed readily when unbalanced binder ratios favoring excess polysisocyanate were employed. Porosity defects that formed in low carbon equivalent irons were predominantly fissure type defects, although some rounded and irregularly shaped holes also formed. Ductile iron castings seemed to be far less susceptible to defect formation than either composition of gray iron. Results obtained with a high carbon equivalent iron as used throughout this investigation have been previously reported and remain unchanged.

Although it is commonly accepted\(^2\) that ductile iron is more susceptible to porosity defects, the present investigation tends to show just the opposite. However, most of these previous findings or observations have been with ductile irons containing...
appreciable amounts of aluminum and poured in green sand molds. 8,15 It is also generally held that ductile irons are more prone to hydrogen defects arising from interactions with water vapor and magnesium. This is probably related to the fact that the residual magnesium is influencing hydrogen solubility 15,20,21 or is assisting the reduction of water vapor. However, Dawson and Smith also showed that although high residual magnesium contents increased hydrogen solubility in ductile iron castings poured in green sand molds, pinholes still did not form.20 Since the chemistry and gaseous thermal decomposition products for PUN binders are obviously more complex than those interactions with green sand molds, the performance of ductile iron with these binders may in actuality differ considerably. However, one would expect porosity formation in ductile irons to be much more difficult due to the higher melt interfacial surface energy. Other investigators have also reported a relationship between porosity and surface tension in ductile irons. 9,22,23 Lastly, the bubbling of magnesium vapor through the metal during the nodularizing process effectively purges most dissolved gases from the metal, allowing for possible absorption of core gases without super saturation. 23, 24

**Effect of Core Age** -- The effect of test core age within the first 24 hours after strip had no effect on porosity formation. Test castings poured with cores used immediately after strip or after overnight aging performed in a similar manner. Results obtained from aging tests poured at three pouring temperatures are listed in Table 11.

If test cores made with unbalanced systems were aged over several days under ambient conditions, the severity of the defects increased slightly. This phenomenon appears to be related to moisture from atmospheric humidity combining with unreacted NCO groups in the polyisocyanate and forming urea structures. 25,26 The porosity forming tendencies of this latter group of substances is well known. 1,2,8 They are reported to readily break down into ammonia derivatives at high temperatures that later dissociate into nascent hydrogen and nitrogen, 1,2,8 both of which are highly soluble and dissolve very readily in molten irons.

**Elimination of Porosity Defects**

Numerous methods, both metallurgical and chemical, were investigated as potential remedial techniques to eliminate defects in castings poured under somewhat adverse conditions. Most of these techniques were straightforward in approach; however, those techniques that may have resulted in reduced melt quality, such as trace element additions of tellurium, selenium or bismuth, were not examined in the original research work since it was felt that these methods would not be very feasible. Any potential gains in porosity elimination may have been overshadowed by chilling and/or poor metal quality. New techniques incorporating the use of proprietary inoculants containing carefully controlled additions of surface active elements as well as elements that neutralize nitrogen (by forming stable nitride compounds) were examined and are reported herein.

**Effect of Titanium and Zirconium Additions** -- Additions of titanium have long been recognized as helpful additives in reducing subsurface porosity defects related to nitrogen. 1,3 To determine if such additions were effective in controlling porosity in test castings poured with PUN test cores, varying levels of 70% ferrotitanium (20 mesh x down) were added in the ladle prior to pouring. Besides using 70% FeTi, two commercial gray iron inoculants containing titanium were also examined. The effect of zirconium on porosity reduction was evaluated by adding 0.05% zirconium as ferrosilicon zirconium as well as incorporating zirconium into a high potency proprietary inoculant. The casting results obtained from these tests are listed in Table 12.

In almost all cases, the addition of small amounts of titanium as a ladle addition was effective in eliminating subsurface porosity in castings made with cores bonded with excessive Part II polyisocyanate levels. In the case of 70% ferrotitanium additions, titanium additions of 0.05% were effective in removing subsurface porosity defects, a considerable amount of surface porosity or small pores remained. Since it is well known that 70% ferrotitanium may be difficult to dissolve at temperatures below 2,700°F, resulting in erratic recoveries and results, two proprietary titanium containing gray iron inoculants were also investigated. Proprietary Inoculant A was effective in eliminating porosity when the titanium addition level was 0.03%. Inoculant B is based on 75% ferrosilicon, and since inoculants based on 75% FeSi dissolve more rapidly than those based on 50% FeSi 28. Inoculant B appeared to be more effective at somewhat lower titanium addition rates.29 No porosity was found when titanium addition levels of 0.025% were employed with Inoculant B. Ferrosilicon zirconium was almost as effective in eliminating porosity but somewhat higher levels of 0.05% zirconium had to be added. This was not unexpected because of the higher atomic weight of zirconium. Inoculant C is a potent proprietary gray and ducile iron inoculant30 containing 30 to 33% oxy-sulfide forming elements that was modified by the addition of 9.0% zirconium (in the form of ferrosilicon zirconium). With zirconium additions of 0.025%, trace to no subsurface porosity was found. Since zirconium forms much more stable nitrides than titanium, more zirconium must be added because of its higher atomic weight. Hence, it is likely that higher levels of zirconium need to be added to Inoculant C for complete porosity elimination. Although Inoculant C did not entirely eliminate porosity, it was the most effective of the three inoculants tested in reducing chill and produced the most uniform microstructure, consisting of 100% Type A graphite flakes.

Metallographic inspection of the castings made with 70% ferrotitanium showed that higher addition rates of titanium (0.05% and greater) were effective in tying up nitrogen as titanium compounds (TiCN or TiN) and preventing re-precipitation as gas holes during solidification. Similar results were observed with the proprietary inoculants. The ferrotitanium additions were not, however, effective in preventing surface reactions associated with lustrous carbon pock marking reactions from the high pour ing temperatures employed during this phase of the investigation. The proprietary inoculants also showed some signs of lustrous carbon related surface porosity.
**Effect of Zirconium and Selenium Inmold Additions** -- Addition of selenium to stainless steel castings poured in green sand molds is very effective in eliminating porosity. Selenium is a surface-active element and can result in degenerate graphite forms. To evaluate the effect of controlled amounts of zirconium and selenium on porosity elimination in gray iron, very small amounts were added (8.0% zirconium as FeSiZr) to a proprietary 9-gram inmold inoculating tablet. A second experiment was also run with a supplemental addition of 3.3% selenium to a 8.0% zirconium modified proprietary inmold inoculating tablet. The casting results obtained from these tests are listed in Table 13.

Castings made with either zirconium by itself or with both selenium and zirconium contained subsurface porosity. The presence of porosity in the above castings is probably the result of addition of insufficient treatment alloy. It is interesting to note that the microstructures of both castings treated with the 9 gram inoculating tablets were somewhat improved, containing 100% Type A graphite, compared to the standard ladle inoculation with 75% foundry grade ferrosilicon containing 0.75% calcium, which contained some Type B and D graphite. Additional experimental work remains to be conducted in this area using larger inserts with greater amounts of zirconium and selenium additions.

**Effect of Iron Oxide Additions** -- The addition of even small amounts of red iron oxide had an overwhelming effect on porosity elimination. The results of additions of varying amounts of 200 mesh red iron oxide (Fe₂O₃ or hematite) to PUN core sand mixes are shown in Table 14.

Additions of as little as 0.25% red (hematite) iron oxide were sufficient to inhibit the formation of all traces of porosity in test castings poured under adverse testing conditions. It must be noted that since commercial foundry grades of red iron oxide occur naturally, not all grades may work like the grades used in the experiments. Further, it has been shown that additions of Fe₃O₄ (magnetite) are not nearly as effective as hematite in controlled casting tests. Casting tests run comparing hematite to magnetite are shown in Table 15.

These results clearly show the effects of iron oxide mineralogy and chemistry. Although two of the iron oxides had similar mesh sizes (320 mesh x down), the 325 mesh red iron oxide (hematite) clearly outperformed the black iron oxide (magnetite) as well as a coarser (100 mesh) European hematite ore of relatively high purity. It can be concluded that iron oxide purity doesn't appear to be a determining factor in the performance of an iron oxide and its subsequent effect on porosity elimination. Although black iron oxide additions are commonly in use today, much of the acceptance of black oxides is more likely related to reduced surface area considerations. Sand additives with reduced surface area allow for reduced resin consumption and improved core making economics. However, careful consideration must be given to the superior effectiveness of red oxide in preventing porosity when choosing an oxide addition.

It should be noted that although some iron oxides may contain various percentages of TiO₂ (titanium dioxide) in their mineralogy, it is doubtful whether sufficient time or quantities of the element titanium could be reduced and be available to react with nitrogen during the casting process. Hence, the presence of titanium dioxide in iron oxide would not impart any beneficial effect on minimizing porosity susceptibility of nitrogen bearing resins. All of these findings illustrate that red iron oxide almost always outperforms black iron oxide in producing sound, porosity free castings as well as minimizing other resin related defects such as lustrous carbon.

To determine the effect of iron oxide granularity, other grades of hematite (Fe₂O₃) were tested using the conditions outlined in Table 15. At 1.5% and 4.00% levels, a much coarser grained hematite addition was also effective in eliminating defects even though it was relatively randomly distributed in the core due to its large particle size. This behavior, coupled with how effective 0.25% red iron oxide was in eliminating porosity, appears to preclude the long accepted role of iron oxide in preventing defects. The role of iron oxide in preventing porosity has long been linked with its ability to react with silica to form a slag; cryolite will liquefy in-situ to form such a barrier. At the low levels investigated and because of the behavior of the coarse grained hematite, it appears probable that iron oxide is somehow affecting the kinetics of gas absorption by the solidifying metal. Regardless, such small additions could certainly not be effective barrier formers at the levels employed.

To further establish if the formation of a slag-type barrier at the mold-metal interface is a viable mechanism responsible for porosity elimination, additions of sodium fluoroaluminate (or cyrolite) were employed as sand additives. Cryolite has a melting point of 1,825°F and does not rely on reacting with silica as does iron oxide to form a slag; cryolite will liquefy in-situ to form such a barrier. Additions of 0.5%, 1.0% and 2.0% were evaluated in exactly the same manner as the previously reported iron oxide additions. The results obtained from these tests are shown in Table 16. In these castings, veining defects were minimized but considerable burn-on was present which appeared to be the result of severe sand fluxing. However, in all cases, severe subsurface porosity was found in the test castings.

**Core Washes** -- A considerable number of experimental core washes were applied to test cores to determine effectiveness as porosity inhibitors. Most of the washes were proprietary formulations but contained varying amounts of red iron oxide. Others were made by incorporating additives to a base gel. Casting tests were run using those conditions previously described that promoted porosity. Results of these tests indicated that proprietary red iron oxide (Fe₂O₃) bearing washes provided very slight or no reduction in porosity defects. Experimental washes composed of aluminum powder and titanium powder provided similar performance. However, a 100% red iron oxide (Fe₂O₃) wash, and another prepared with sodium silicate and iron oxide (Fe₂O₃) completely prevented the formation of porosity. This achievement was accomplished but at the expense of severe surface finish
Porosity Defects in Gray and Ductile Iron Castings

degradation. The sodium silicate red iron oxide wash deteriorated the casting surface only slightly but the 100% red iron oxide wash had a very deleterious effect on the surface. Overall results tended to indicate that adequate amounts of iron oxide were not employed in proprietary washes; however, in experimental washes with red iron oxide, too much was added with a resultant loss in surface smoothness. Apparently, a delicate balance exists between the amount of iron oxide needed for porosity elimination compared to the amount that results in deteriorated surface finish.

Core Post-Baking -- To determine the effect of core baking on porosity elimination, several test cores were subjected to post-baking or curing for three different times. The results of these tests are summarized in Table 17.

Castings made with test cores baked at 450°F but for only one hour contained severe porosity defects. Intermediate times of 2 hours significantly reduced the extent of porosity. Baking for 4 hours at 450°F produced a distinctive core color change to chocolate brown and had a significant effect on porosity elimination. For thorough baking to occur, it has been found that a color change usually accompanies such a treatment and up to 55% of the binder is volatilized. Although such lengthy times may be impractical, higher baking temperatures or short times at high temperatures might be effective in reducing overall binder level in the core surface layers. Baking also demonstrates that some free hydrocarbons are undoubtedly volatilized and nitrogen components from the Part II resin may undergo further reactions to form more stable compounds.

DISCUSSION

Although several variables have been identified that either exaggerate or promote the formation of porosity defects in PUN binders, these variables are in one way or another related to the gaseous decomposition products generated by the resin during casting. Decomposition gases consisting of both hydrogen and nitrogen are readily liberated during casting pouring and during subsequent solidification. High pouring temperatures further enhance both the breakdown rate and amount as well as favor increased gas solubility in the liquid metal. High pouring temperatures also have a significant effect on liquid metal surface tension, which has been shown to have a significant effect on porosity formation. 9,11 Because both hydrogen and nitrogen are readily available and extremely soluble at the casting temperatures employed, their effect on potential porosity defects is often additive.

Numerous chemical analyses taken during this investigation showed that considerable pickup of both hydrogen and nitrogen occurred in the immediate subsurface layers when conditions favoring porosity were employed. At depths of 0.25 in. and more below the cored surface, hydrogen and nitrogen levels tended to be quite low and representative of the base metal. It is probable that just before solidification, momentary super saturation of both hydrogen and nitrogen exist just under the casting surface. This complex nitrogen/hydrogen effect has long been recognized by other investigators. 6,27,35 Further, if a considerable amount of nascent nitrogen is dissolved in a casting from unbalanced binder ratios favoring excessive polysiloxane components, the presence of even a small amount of hydrogen will serve to lower the overall solubility of nitrogen. Stated another way, hydrogen may be exerting a catalytic effect on nitrogen to enhance porosity formation.

The same effect of alloying elements on gas solubility is well known and acts in a similar manner. To further aggravate conditions, if the melt initially has a high gas content resulting from the use of poor charge metallics or carbon additives, 36 then the tolerance for additional solution of nascent mold or core gases is reduced considerably and porosity formation becomes extremely favorable.

Microstructures of sound and porosity containing castings taken in the immediate vicinity of the mold-metal interface were identical. In all cases, no differences in either matrix structure or graphite morphology were found. Both microstructures contained the same ferritic type matrix with Type A graphite. The solidification rate and composition of all base gray iron heats favored this type of structure. Although it is widely recognized that hydrogen and nitrogen are carbide stabilizers and favor formation of pearlite as well as alter graphite structure, 37-41 it appears that insufficient time was available during solidification and subsequent cooling through the transformation temperatures, for such phases to form. Although most gas holes exhibited a bright or shiny interior of a graphitic nature, no such films were observed during optical metallography. Further examination of these areas with a scanning electron microscope showed distinct layers of what appeared to be a crystalline graphitic coating lining the interior of the gas holes. The presence of this crystalline film has been reported by numerous other investigators. 1,8

The morphology of gas holes that formed took many shapes, even in the same casting. Both fissure type gas holes as well as small spherical and pear shaped holes were very often observed in the same casting. Although for the most part, gas holes that formed were located just underneath the surface, and most extended no more than 0.25 in. into the casting, a few castings contained gas fissures almost 0.50 in. long (see Figure 5). Because of the sub-surface nature of the defects, the incorporation of large amounts of alloying elements that form stable nitrogen compounds may not be needed since only these sub-surface layers are affected. Incorporation of proprietary nitrogen stabilizing elements or "scavengers," which include both titanium and zirconium based ferroalloys, may offer additional possibilities for treating binder induced porosity defects. Likewise, inmold inoculating tablets incorporating zirconium for nitrogen control and small amounts of selenium for hydrogen control also offer promise for defect elimination.

Although the porosity studies focused on using ladle additions of nitrogen stabilizing ferroalloys, the use of beneficiated ilminite ore has also been shown to be a very effective method of introducing the element titanium. Mikelenis 42 reported that ilmenite ore was the most cost effective method of introducing 0.04 to 0.07 percent titanium levels to cupola melted irons. The ilmenite was added as 3 in. x 2 in. ilmenite ore to the cupola charge. In this research, it was reported that titanium recovery levels were 30 to

40 percent of the total amount of titanium in the ore. Other developments aimed at improving titanium recoveries are based on using beneficiated ilmenite ore that incorporate a proprietary blend of halide containing fluxes. Such products are available in the form of a briquette or tablet and can be used either as a furnace addition or ladle addition. These products may also provide improved melt quality by coalescing liquid and/or solid slags with the mild fluxing agents incorporated in the tablet or briquette.

It is not well understood how small amounts of red iron oxide (0.25% addition rates) were so effective in eliminating subsurface porosity in the test castings. It has been suggested that the red iron oxide is exerting some type of "catalytic effect" on binder decomposition products that minimize or alter the generation of nitrogen and hydrogen gases. One such theory is that when exposed to the sudden high temperatures of iron casting, red iron oxide (Fe₂O₃) readily releases oxygen. This released oxygen immediately reacts with nitrogen decomposition products from the binder to form stable NOₓ compounds. Since hematite (red iron oxide) has a much higher concentration of oxygen compared to magnetite (black iron oxide), and based on the improved performance of red iron oxide compared to black, this mechanism certainly appears to be very feasible.

**CONCLUSIONS**

1. Unbalanced PUN systems favoring excess Part II or polyisocyanates promote the occurrence of gaseous mold-metal reactions resulting in both surface and subsurface gas defects. High binder levels also tended to slightly increase defect propensity even when balanced ratios were employed. Balanced or slightly unbalanced isocyanate/polyol hydroxyl ratios favoring excess Part I were relatively unsusceptible to such defects although a few cases of slight porosity were found.

2. Inadequate mixing that results in poor distribution of the binder components in the mix was also found to accentuate porosity formation.

3. The temperature of the molten iron as it contacted the core surface was found to have a significant effect on porosity formation when castings were poured under conditions favoring their formation. Severe porosity defects were formed at 2700°F and higher. As the temperature was reduced, these defects became fewer in number and intensity until none formed at 2550°F.

4. Porosity formation was found to be very sensitive to core sand type. Lake sands were relatively insensitive to defect formation while high purity, round grained white silica sands were found to be very sensitive.

5. Cast iron composition had an effect on porosity formation. Ductile iron was least susceptible to defect formation while low carbon equivalent irons were most susceptible.

6. Addition of titanium compounds, either in the form of 70% ferrotitanium or proprietary gray iron inoculants containing titanium were effective in eliminating porosity defects. Zirconium additions were also somewhat effective in eliminating defects at the addition levels employed. Incorporation of ferrosilicon zirconium into a proprietary inoculant was also found to reduce the incidence of defects.

7. The addition of small amounts of red iron (Fe₂O₃) oxide (82% minimum purity) to silica sand mixes was extremely effective in eliminating porosity. Sound castings were obtained with additions as small as 0.25% red iron oxide. Black iron oxides were not anywhere as effective as red iron oxide.

8. No metallurgical changes in either graphite morphology or matrix structure occurred in the gas affected mold-metal interface region. A layer or film, probably graphitic in nature, was found lining the internal surfaces of most gas holes.

9. Porosity defects tended to form in geometric hot spots or re-entrant angles on the test casting. The location seems to indicate that localized heating of the core re-entrant angles creates a condition that results in a momentary super saturation of the surface layers. Gas analysis taken well beneath the affected surface layers showed normal gas contents.

**REFERENCES**


Porosity Defects in Gray and Ductile Iron Castings


Porosity Defects in Gray and Ductile Iron Castings


List of Figures:

- Figure 1: Cylindrical test casting illustrating gating system employed.
- Figure 2: Dimensions of cylindrical test casting.
- Figure 3. Types of porosity defects encountered in test castings
- Figure 4: Effect of pouring temperature on porosity formation.
- Figure 5: Morphology of subsurface gas porosity (1.5 x magnification)

List of Tables

- Table 1: Compositions of Test Castings Poured
- Table 2: Effect of Binder Ratio on Porosity Formation
- Table 3: Effect of Binder Level on Porosity Formation
- Table 4: Effect of Pouring Temperature on Porosity Formation
- Table 5: Effect of Sand on the Formation of Porosity
- Table 6: Effect of Acid Surface Treatments on Porosity Susceptibility
- Table 7: Effect of Sand Type on Porosity Formation
- Table 8: Physical and Chemical Properties of Sands
Porosity Defects in Gray and Ductile Iron Castings

- Table 9: Effect of Mixing Time and Mixing Efficiency on Porosity Formation
- Table 10: Effect of Type and Composition of Castings on Porosity Formation
- Table 11: Effect of Core Aging on Porosity Formation
- Table 12: Effect of Titanium and Zirconium Additions on Porosity Formation
- Table 13: Effect of Selenium and Zirconium Additions on Porosity Formation
- Table 14: Effect of red iron oxide (hematite) on Porosity Formation
- Table 15: Effect of Iron Oxide Type on Porosity Elimination
- Table 16: Results of Casting Tests with Cryolite Additions

Tables

**Table 1: Compositions of Test Castings Poured**

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**Table 2: Effect of Binder Ratio on Porosity Formation**

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<tr>
<td>1.50% (1998 version)</td>
<td>35:65</td>
<td>severe</td>
</tr>
<tr>
<td>1.50%</td>
<td>35:65</td>
<td>severe</td>
</tr>
</tbody>
</table>

*Test conditions:* PUN binder with washed and dried silica sand (W/D) Iron Chemistry - 4.3 C.E. iron, Pouring temperature - 2700°F

**Table 3: Effect of Binder Level on Porosity Formation**

<table>
<thead>
<tr>
<th>Binder Level</th>
<th>Ratio: Pt I : Pt II</th>
<th>Porosity Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0%</td>
<td>60:40</td>
<td>nil to trace</td>
</tr>
<tr>
<td>3.0%</td>
<td>50:50</td>
<td>moderate</td>
</tr>
<tr>
<td>3.0%</td>
<td>40:60</td>
<td>severe</td>
</tr>
<tr>
<td>3.0%</td>
<td>35:65</td>
<td>very severe</td>
</tr>
<tr>
<td>1.8%</td>
<td>60:40</td>
<td>none</td>
</tr>
<tr>
<td>1.8%</td>
<td>50:50</td>
<td>trace</td>
</tr>
<tr>
<td>1.8%</td>
<td>35:65</td>
<td>severe</td>
</tr>
</tbody>
</table>

Porosity Defects in Gray and Ductile Iron Castings

<table>
<thead>
<tr>
<th>Binder Level</th>
<th>Pouring Temperature (°F)</th>
<th>Porosity Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5%</td>
<td>60:40</td>
<td>none</td>
</tr>
<tr>
<td>1.5%</td>
<td>50:50</td>
<td>none to trace</td>
</tr>
<tr>
<td>1.5%</td>
<td>35:65</td>
<td>severe</td>
</tr>
<tr>
<td>1.25%</td>
<td>50:50</td>
<td>none</td>
</tr>
<tr>
<td>1.25%</td>
<td>35:65</td>
<td>moderate</td>
</tr>
</tbody>
</table>

Test conditions: PUN binder on W/D silica sand, 4.3 C.E. iron, Pouring temperature - 2700°F.

Table 4: Effect of Pouring Temperature on Porosity Formation

Table 5: Effect of Sand on the Formation of Porosity

Table 6: Effect of Acid Surface Treatments on Porosity Susceptibility

Table 7: Effect of Sand Type on Porosity Formation
### Table 8: Physical and Chemical Properties of Sands

<table>
<thead>
<tr>
<th>Sand</th>
<th>SiO₂ (%)</th>
<th>Fe₂O₃ (%)</th>
<th>Al₂O₃ (%)</th>
<th>GFN</th>
<th>Perm</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica Sand No. 1</td>
<td>99.88</td>
<td>0.02</td>
<td>0.10</td>
<td>67</td>
<td>95</td>
<td>high</td>
</tr>
<tr>
<td>Silica Sand No. 2</td>
<td>99.88</td>
<td>0.02</td>
<td>0.10</td>
<td>37</td>
<td>225</td>
<td>high</td>
</tr>
<tr>
<td>Silica Sand No. 3</td>
<td>99.88</td>
<td>0.02</td>
<td>0.10</td>
<td>131</td>
<td>20</td>
<td>high</td>
</tr>
<tr>
<td>Silica Sand No. 4</td>
<td>99.6</td>
<td>0.018</td>
<td>0.27</td>
<td>54</td>
<td>180</td>
<td>moderate</td>
</tr>
<tr>
<td>Sand No. 5</td>
<td>99.2</td>
<td>0.13</td>
<td>0.40</td>
<td>55</td>
<td>190</td>
<td>none</td>
</tr>
<tr>
<td>Lake Sand</td>
<td>94.8</td>
<td>0.44</td>
<td>2.12</td>
<td>56</td>
<td>150</td>
<td>none</td>
</tr>
</tbody>
</table>

### Table 9: Effect of Mixing Time and Mixing Efficiency on Porosity Formation

<table>
<thead>
<tr>
<th>Mixing Time per component</th>
<th>Total</th>
<th>Binder Level</th>
<th>Pt 1: Pt II</th>
<th>Porosity Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 seconds</td>
<td>10 seconds</td>
<td>1.5%</td>
<td>50:50</td>
<td>very severe</td>
</tr>
<tr>
<td>10 seconds</td>
<td>20 seconds</td>
<td>1.5%</td>
<td>50:50</td>
<td>moderate</td>
</tr>
<tr>
<td>20 seconds</td>
<td>40 seconds</td>
<td>1.5%</td>
<td>50:50</td>
<td>nil to moderate</td>
</tr>
<tr>
<td>30 seconds</td>
<td>60 seconds</td>
<td>1.5%</td>
<td>50:50</td>
<td>nil to traces</td>
</tr>
<tr>
<td>40 seconds</td>
<td>80 seconds</td>
<td>1.5%</td>
<td>50:50</td>
<td>nil to traces</td>
</tr>
<tr>
<td>60 seconds</td>
<td>120 seconds</td>
<td>1.5%</td>
<td>50:50</td>
<td>none</td>
</tr>
<tr>
<td>120 seconds</td>
<td>240 seconds</td>
<td>1.5%</td>
<td>50:50</td>
<td>none</td>
</tr>
</tbody>
</table>

**Test Conditions:** PUN binders on W/D silica sands, 4.3 C.E iron, Pouring Temperature - 2700°F

### Table 10: Effect of Type and Composition of Castings on Porosity Formation

#### Low Carbon Equivalent Iron (3.40 C.E. - Class 50)

<table>
<thead>
<tr>
<th>Binder Level</th>
<th>Binder Ratio</th>
<th>Temperature</th>
<th>Porosity Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50%</td>
<td>60:40</td>
<td>2,700°F</td>
<td>Subsurface microporosity and small fissures</td>
</tr>
<tr>
<td>1.50%</td>
<td>60:40</td>
<td>2,500°F</td>
<td>nil amounts of porosity</td>
</tr>
<tr>
<td>1.50%</td>
<td>50:50</td>
<td>2,700°F</td>
<td>small fissures and subsurface holes</td>
</tr>
<tr>
<td>1.50%</td>
<td>50:50</td>
<td>2,500°F</td>
<td>nil amounts of porosity</td>
</tr>
<tr>
<td>1.50%</td>
<td>40:60</td>
<td>2,700°F</td>
<td>severe fissures, subsurface porosity</td>
</tr>
<tr>
<td>1.50%</td>
<td>40:60</td>
<td>2,500°F</td>
<td>trace fissures</td>
</tr>
</tbody>
</table>

#### Ductile Iron (60 - 40 - 20)

<table>
<thead>
<tr>
<th>Binder Level</th>
<th>Binder Ratio</th>
<th>Temperature</th>
<th>Porosity Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50%</td>
<td>60:40</td>
<td>2,700°F</td>
<td>none</td>
</tr>
<tr>
<td>1.50%</td>
<td>60:40</td>
<td>2,500°F</td>
<td>none</td>
</tr>
<tr>
<td>1.50%</td>
<td>50:50</td>
<td>2,700°F</td>
<td>none</td>
</tr>
<tr>
<td>1.50%</td>
<td>50:50</td>
<td>2,500°F</td>
<td>none</td>
</tr>
<tr>
<td>1.50%</td>
<td>40:60</td>
<td>2,700°F</td>
<td>nil to trace</td>
</tr>
<tr>
<td>1.50%</td>
<td>40:60</td>
<td>2,500°F</td>
<td>none</td>
</tr>
</tbody>
</table>

#### High Carbon Equivalent Iron (4.30 C.E. Class 20)

<table>
<thead>
<tr>
<th>Binder Level</th>
<th>Binder Ratio</th>
<th>Temperature</th>
<th>Porosity Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50%</td>
<td>60:40</td>
<td>2,700°F</td>
<td>none</td>
</tr>
</tbody>
</table>
## Table 11: Effect of Core Aging on Porosity Formation

<table>
<thead>
<tr>
<th>Core Age</th>
<th>Binder Level</th>
<th>Pt. I : Pt. II</th>
<th>Porosity Extent</th>
<th>Pouring Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 hr.</td>
<td>1.50%</td>
<td>35:65</td>
<td>Severe</td>
<td>2,700°F</td>
</tr>
<tr>
<td>24 hr.</td>
<td>1.50%</td>
<td>35:65</td>
<td>Severe</td>
<td>2,700°F</td>
</tr>
<tr>
<td>1 hr.</td>
<td>1.50%</td>
<td>35:65</td>
<td>Traces</td>
<td>2,600°F</td>
</tr>
<tr>
<td>24 hr.</td>
<td>1.50%</td>
<td>35:65</td>
<td>Traces</td>
<td>2,600°F</td>
</tr>
<tr>
<td>1 hr.</td>
<td>1.50%</td>
<td>35:65</td>
<td>None</td>
<td>2,500°F</td>
</tr>
<tr>
<td>24 hr.</td>
<td>1.50%</td>
<td>35:65</td>
<td>None</td>
<td>2,500°F</td>
</tr>
</tbody>
</table>

Test Conditions: PUN binders on W/D silica sands, High C.E. 4.3 iron, Low C.E. 3.4 iron, Ductile Iron (60 - 40 - 20) Pouring Temperature - varied between 2700°F and 2500°F.

## Table 12: Effect of Titanium and Zirconium Additions on Porosity Formation

<table>
<thead>
<tr>
<th>% Addition</th>
<th>Binder Level</th>
<th>Pt. I : Pt. II</th>
<th>Porosity Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00%</td>
<td>1.50%</td>
<td>35:65</td>
<td>Very Severe</td>
</tr>
<tr>
<td>0.025% Ti as 70% FeTi</td>
<td>1.50%</td>
<td>35:65</td>
<td>Trace to Moderate</td>
</tr>
<tr>
<td>0.050% Ti as 70% FeTi</td>
<td>1.50%</td>
<td>35:65</td>
<td>None</td>
</tr>
<tr>
<td>0.025% Ti as Inoc. A</td>
<td>1.50%</td>
<td>35:65</td>
<td>Trace</td>
</tr>
<tr>
<td>0.030% Ti as Inoc. A</td>
<td>1.50%</td>
<td>35:65</td>
<td>None</td>
</tr>
<tr>
<td>0.025% Ti as Inco. B</td>
<td>1.50%</td>
<td>35:65</td>
<td>None</td>
</tr>
<tr>
<td>0.050% Zr as FeSiZr</td>
<td>1.50%</td>
<td>35:65</td>
<td>None</td>
</tr>
<tr>
<td>0.025% Zr as Inoc. C</td>
<td>1.50%</td>
<td>35:65</td>
<td>Trace to none</td>
</tr>
</tbody>
</table>

Test Conditions: PUN binders on W/D silica sands, 4.3 C. E. iron, Pouring Temperature - 2700°F

Inoculant A - 52% Si, 11% Ti, 1.25% Ca, 1.0% Al, Bal - Fe
Inoculant B - 75% Si, 11% Ti, 5.5% Ba, 3.5% Mn, 1.25% Ca, 1.0% Al, Bal - Fe
FeSiZr - 35% Si, 33% Zr, 2.5% Ca, 1.0% Al, Bal - Fe
Inoculant C - 47.0% Si, 33% oxy-sulfide forming elements, plus 9.0% Zr, Bal - Fe

## Table 13: Effect of Selenium and Zirconium Additions on Porosity Formation

<table>
<thead>
<tr>
<th>% Addition</th>
<th>Binder Level</th>
<th>Pt. I : Pt. II</th>
<th>Porosity Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00% (std 75% FeSi)</td>
<td>1.50%</td>
<td>35:65</td>
<td>Very Severe</td>
</tr>
</tbody>
</table>

Test Conditions: PUN binders on W/D silica sands, 4.3 C. E. iron, Pouring Temperature - 2700°F

Standard Inoculant - Foundry grade 75% FeSi with 0.75% Calcium, 0.33% addition
Inoculant D - 9 gram inoculant tablet containing 27.7% Si, 28.41 oxy-sulfide forming elements plus 8.0% Zr, Bal - Fe
Inoculant E - 9 gram inoculant tablet containing 25.6% Si, 26.88% oxy-sulfide forming elements plus 8.0% Zr, 3.3% Se, Bal - Fe
Zirconium and Selenium percentage levels based on the 35 lb. step cone pouring weight

**Table 14: Effect of red iron oxide (hematite) on Porosity Formation**

<table>
<thead>
<tr>
<th>Binder Level</th>
<th>Binder Ratio</th>
<th>% Iron Oxide</th>
<th>Porosity Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50%</td>
<td>35:65</td>
<td>0.00%</td>
<td>Severe</td>
</tr>
<tr>
<td>1.50%</td>
<td>35:65</td>
<td>0.25%</td>
<td>None</td>
</tr>
<tr>
<td>1.50%</td>
<td>35:65</td>
<td>0.50%</td>
<td>None</td>
</tr>
<tr>
<td>1.50%</td>
<td>35:65</td>
<td>1.50%</td>
<td>None</td>
</tr>
<tr>
<td>1.50%</td>
<td>35:65</td>
<td>2.0%</td>
<td>None</td>
</tr>
<tr>
<td>1.50%</td>
<td>35:65</td>
<td>3.0%</td>
<td>None</td>
</tr>
</tbody>
</table>

**Test Conditions:** PUN binders on W/D silica sands, 4.3 C.E. iron
Pouring Temperature - 2700 °F

**Table 15: Effect of Iron Oxide Type on Porosity Elimination**

<table>
<thead>
<tr>
<th>Binder Level</th>
<th>% Iron Oxide</th>
<th>Mesh Size</th>
<th>Oxide Type</th>
<th>Porosity Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50%</td>
<td>0.0%</td>
<td>----</td>
<td>None</td>
<td>Severe</td>
</tr>
<tr>
<td>1.50%</td>
<td>0.25%</td>
<td>325</td>
<td>Fe₂O₃ (red)</td>
<td>None</td>
</tr>
<tr>
<td>1.50%</td>
<td>0.25%</td>
<td>325</td>
<td>Fe₃O₄ (black)</td>
<td>Severe</td>
</tr>
<tr>
<td>1.50%</td>
<td>0.25%</td>
<td>100</td>
<td>Hematite ore</td>
<td>Severe</td>
</tr>
</tbody>
</table>

**Test Conditions:** PUN binders on W/D silica sands, 4.3 C.E. iron
35 : 65 Ratio of Part I to Pat II, Pouring Temperature - 2700 °F
Fe₂O₃ assay: 87% Fe₂O₃, 8.0% SiO₂, 2% Al₂O₃, Balance not reported
Fe₃O₄ assay: 62% Fe₃O₄, 1.5% SiO₂, 4% Al₂O₃, Balance not reported
Hematite ore: 92.5% Fe₂O₃, 4.75% SiO₂, 1% Al₂O₃, Balance not reported

**Table 16: Results of Casting Tests with Cryolite Additions**

<table>
<thead>
<tr>
<th>Binder Level</th>
<th>Binder Ratio</th>
<th>% Cryolite</th>
<th>Porosity Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50%</td>
<td>35:65</td>
<td>0.0%</td>
<td>Severe</td>
</tr>
<tr>
<td>1.50%</td>
<td>35:65</td>
<td>0.50%</td>
<td>Severe</td>
</tr>
<tr>
<td>1.50%</td>
<td>35:65</td>
<td>1.00%</td>
<td>Severe</td>
</tr>
<tr>
<td>1.50%</td>
<td>35:65</td>
<td>2.00%</td>
<td>Severe</td>
</tr>
</tbody>
</table>

**Test Conditions:** PUN binders on W/D silica sands, 4.3 C.E. iron
Pouring Temperature - 2700 °F for all tests

**Table 17: Results of Casting Tests with Test Cores baked for 1, 2, and 4 hours**

<table>
<thead>
<tr>
<th>Binder Level</th>
<th>Binder Ratio</th>
<th>Temperature</th>
<th>Time</th>
<th>Porosity Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50%</td>
<td>35:65</td>
<td>450°F</td>
<td>1 hour</td>
<td>Severe</td>
</tr>
<tr>
<td>1.50%</td>
<td>35:65</td>
<td>450°F</td>
<td>2 hours</td>
<td>Nil to Trace</td>
</tr>
<tr>
<td>1.50%</td>
<td>35:65</td>
<td>450°F</td>
<td>4 hours</td>
<td>None</td>
</tr>
</tbody>
</table>

**Test Conditions:** PUN binders on W/D silica sands, 4.3 C.E. iron
Pouring Temperature - 2700 °F for all tests
Porosity Defects in Gray and Ductile Iron Castings from Mold Metal Interface Reactions

**Figure 1:** Cylindrical test casting illustrating gating system employed
Back to Article

![Cylindrical test casting](image1.png)

**Figure 2:** Dimensions of cylindrical test casting
Back to Article

![Dimensions of cylindrical test casting](image2.png)

**Figure 3:** Types of porosity defects encountered in test castings. (1x)
Back to Article

![Types of porosity defects](image3.png)
Porosity Defects in Gray and Ductile Iron Castings - Figures

Figure 3 a. Surface porosity (pockmarking)

Figure 3b. Trace subsurface porosity

Figure 3c. Moderately severe porosity

Figure 3d. V. severe dispersed porosity

Figure 4: Effect of pouring temperature and binder ratio on porosity formation

Back to Article

Figure 5: Morphology of subsurface gas porosity (1.5x magnification)

Back to Article
Purchasing Quality Ductile Iron

An abstract of the presentation at the DIS Fall Meeting - October 14, 2000
by Larry McFarland, Aarowcast (Formerly with Caterpillar)

Lyle Jenkins (DIS Technical Director) asked me, in November of 1999, to give this presentation. I have always had the deepest respect for Lyle and his dedication to the foundry industry. I was deeply honored when he asked me to speak. Lyle believed that I could help him deliver a message on a subject with which he is deeply concerned - quality in the United States foundry industry. I started immediately to put together the presentation which I was scheduled to give at the DIS meeting in Wichita, Kansas in June of 2000. God saw fit to alter my life with events in November of 1999 and April of 2000 which changed my decision to be present in June. Those events caused a very positive change in my life. I had thoroughly my career up to then. However, I made the decision to change careers to be able to work for a foundry which I felt has tremendous future potential, that foundry being Aarowcast. In giving this talk I am not going to use a lot of statistics or technical terms. I am going to approach it from the people and management involvement and the effects that I feel it has had on overall industry casting quality.

The information presented is based on my 34 years of experience working with worldwide casting suppliers. I have had the opportunity to evaluate over 500 casting suppliers in 21 countries. This was accomplished during my career at Caterpillar in the following areas: 1966-1976 in the Mapleton Foundry; 1976-1997 in Central Purchasing; 1997-2000 at Engine Division Technical Purchasing. I am now the Technical Support Manager at Aarowcast, Inc.

Caterpillar, as you know, has been one of the largest users of castings for many years. Caterpillar's own foundry organization in the mid 1970's, consisted of two large gray iron casting facilities employing 4,200 and supplying 80% of its gray iron casting needs. The balance of the gray iron and 100% of its ductile iron, malleable iron and steel castings were purchased from the United States foundry industry. There were years in which the total casting dollar volume used by Cat approached one billion dollars. In the mid 1970's Caterpillar's casting needs were so great that the company centralized all rough casting purchasing to maintain capacity, take advantage of dollar volumes purchased and attempt to stabilize the tremendous number of people and dollar assets required to control this tremendous package. The casting supplier family at that time contained over 100 members. It was not uncommon for casting reject rates to be in the 5-6% range and casting salvage was a way of life. Other U.S. companies were sharing the same experiences.

The late 1970's and early 1980's experienced a decrease in the demand for castings. Expediting teams disappeared along with foundry casting order backlogs. The emphasis on castings changed from "Quantity" and "Delivery" to "Quality" and "Cost". It was during the early 1980's that many U.S. companies took a long hard look at quality and cost improvements. This was after the 1970's when casting demand was so high that sub-par quality was acceptable. Companies were even willing to conduct sample casting evaluations for the suppliers to expedite the delivery. We basically "lulled our casting suppliers to sleep" in the quality area. By 1980 U.S. foundries had become below par in quality and technology in comparison to the foreign competition.

Increased emphasis by U.S. companies, on improving quality and reducing costs, forced the foundries to improve. As companies began transferring responsibility for quality back to the casting source, a strong bond began to form between casting users and suppliers. The program to accomplish this was called "casting supplier certification."

During the late 1980's and early 1990's, U.S. foundries improved tremendously and surpassed foreign competition in quality and cost. To do this "customer-supplier communication" was established. Using this communication, casting buyers began transferring the responsibility for quality over to the casting suppliers. Casting buying companies began to train casting suppliers in the areas of material specifications, engineering drawings, dimensional layouts, metallurgical testing and casting soundness testing. The casting supplier was asked to detail to the customer, exactly how he produced the ordered castings along with the methods used to control product quality. Quality plans with significant control point charts were required and agreement to these quality plans was arrived at during foundry certification audits. Casting buying groups used this information to build supplier profiles containing useful information for future purchasing.

In 1992 the Caterpillar General Office interviewed top management of its top 10 dollar volume casting suppliers. The question asked of them was "Why are casting rejections at an all time low of less than 1.0% in dollars?" The answer was always "Because of the much improved communications established by your supplier certification program."

U.S. casting supplier quality and cost improvement was so recognized that Caterpillar decided to outsource 1100 part numbers and close one of its two foundries at Mapleton, keeping only 57 part numbers (blocks, heads, liners) in the foundry which remained open. Other casting buying companies paralleled Cat with similar action. The burden on the foundries of surviving multiple audits by multiple companies was lessened considerably by the development of the QS 9000 program, a welcome and very efficient program.

In the mid to late 1990's the casting user/casting supplier "bond" began to break down. Overall quality levels began to deteriorate as "communications" began to break down. The division of the company into business units reduced internal communications and technology transfer capabilities. This was furthered by the breaking up of a large manufacturing plant into "focus facilities" which thinned the ranks of available technical personnel. Incentive bonus plans brought on price buying and the lowering of acceptable quality levels. Foreign sourcing complicated the issue with language and customs problems, complicated by...
the establishment of casting pipelines to assure delivery. Because QS 9000 became a reality, technical staffs were reduced and a
dependency on third party auditing was accepted. As the number of auditing groups increased, the casting expertise level
decreased and “paid for” audits began to give foundries better ratings than they deserved.

As time proceeds, companies are starting to reconnect their internal communications. The level of casting expertise within
buying companies continues to decline. Foreign sourcing has begun to decline as casting buyers learn that they have to depend
on their domestic casting suppliers for technical expertise. Casting producers would be well advised to begin reestablishing strong
communication bonds with customers. A good place to start would be to include major customer personnel in the auditing
procedures now conducted by “third party” organizations.
Casting Process Simulation in Iron Foundries

Tony Midea
Chairman 1F – Process Modeling and Design Committee
Foseco, Inc

What is computer simulation?

Computer simulation is the use of computer programs to model actual industrial processes. There are several types of computer simulations. The simplest type is “empirical”. An empirical program is based entirely on experimental results and experience. Generally, these programs utilize tabularized results obtained from industrial tests and trials.

Semi-empirical programs are also based upon experimental results, but tend to use some physical relationships and algebraic equations to expand the predictive ability of the program beyond the constraints of the experimental test data. The physics usually involves correlations and simple, first order relationships. In some cases, the programs employ simple finite differencing methods that allow the problem to be broken up into many small problems, and thus increase the accuracy of the simulation.

First principles programs are derived entirely from the laws of physics, and do not use tables of experimental data, rules or guidelines. These programs are commonly referred to as “physics-based” programs. Complex physical relationships and equations are employed to describe the underlying physics of the process. In this situation, material property data becomes the lifeblood of the programs, and the accuracy of simulation becomes dependent on the accuracy of the material thermal data. Finite difference or finite element methods are required for this type of analysis because the complexity of the equations to be solved require that the problem be broken into many small problems.

This paper discusses the details of first principles programs, and shows several examples of how using this type of program results in the optimization of the casting process in iron foundries.

First principles programs can model the myriad process steps involved in the making of iron castings. Mold filling, solidification, metal treatment, heat treatment, metallurgy, etc. can all be analyzed using current tools. For the purpose of this paper, we will discuss only the mold filling and solidification aspects of computer simulation.

For filling analyses, the flow equations are referred to as the Navier-Stokes equations. These equations, in their “full-blown” form, comprise of a 6x6 matrix of flow vector components that must be resolved simultaneously with the continuity, energy and volume of fluid equations to get a solution at any one point in time within the system. This allows for “6-degree-of-freedom” movement, which simply means that the flow is calculated in all possible directions. For each point (volume), at each time step, this matrix of equations must be solved to make progress towards a complete solution. In many cases, terms can be removed from the equations (e.g. compressibility for molten iron) such that the problem is made simpler.

To model turbulence, a first principles program uses the k-e equations, which evolved from the aerospace industry. While not perfect, these equations do an admirable job of predicting the flow behavior of turbulence.

Solidification analyses generally use several phenomenological equations. These equations are based on observation, and are not derived. However, they have stood the test of time and accurately represent heat flow for most known problems.

Fourier’s Equation is used to predict heat conduction, while Newton’s Law of Cooling is used for convection. The Stefan-Boltzmann Law is used to predict radiative heat flow in most analyses.

Because the programs are time and temperature based, the calculations are performed just like the physics being modeled. The program breaks the problem into many small pieces. Then, the analysis begins by calculating the fluid flow and heat transfer for each of these small pieces at small time steps starting with the initiation of the process. When the dynamics of the system are quickly changing, the programs take very small time steps to compute the changes taking place in the system. As the system begins to reach equilibrium (e.g. mold cavity nearly full or solidification of system nearly complete), the programs are able to take larger time steps without sacrificing accuracy.

What does computer simulation do for me?

Computer simulations should be conducted to optimize the process that is being modeled. The goal is to improve efficiency, increase productivity and increase profitability. The optimization process is a means to conduct a cost-effective “what-if” analysis on the computer. Configurations that show promise can then be trailed in a production environment to prove that the computer optimized design works, as advertised, on the shop floor.

If properly conducted, this synergistic relationship between computer simulation and production tests can provide a low cost alternative to common trial and error procedures conducted in production environments for generations.

In order to determine the “power” or complexity required to accurately model the industrial process in question, one must understand the complexity of the industrial process in question.

If the process to be modeled is a simple, repeatable process in which the process variables change only slightly from case to case, then it may be possible to model the configuration using a simple empirical program. The process could be monitored, process variables recorded, and a simple program could be written to model the process. An example of this type of program could be the prediction of feeding distance in cast steel. In this case, a program could be written using the SFSA feeding distance tables as a reference, and feeding distance for a particular case could be predicted quickly and easily. Several programs exist for
Casting Process Simulation in Iron Foundries

Because programs of this nature are based entirely on experimental data for specific cases, care should be taken so that the user does not attempt to apply the program to cases for which the data is irrelevant. For the example above, one should not apply a steel feeding distance program to predict the feeding distance in cast iron.

If the process to be modeled is well understood, and relatively simple, then a semi-empirical program may suffice. In this case, the program still fundamentally relies on experimental data, but may also include some functionality to model small changes in the process variables, and may include some simple physics such that the data could be applied slightly beyond the basis of the experimental data. An example in this case might be a foundry that produces only a few simple steel or iron casting shapes. Again, the danger in this type of program is that application of the program beyond its experimental dataset could lead to incorrect predictions.

A first principles program is the best alternative for all processes. Because the program attempts to model the underlying physics of the process, it can be used to model complex as well as simple processes. It does not rely on tables of experimental results or guidelines. As a result, it can be used to model situations in which process variables vary greatly, and can be used to try new ideas and/or processes.

A physics based program can perform detailed analyses, including flow and solidification predictions for all metal types. To be accurate, however, a physics based program must be equipped with accurate thermophysical data for all of the materials to be modeled in the process.

Ideally, a foundry should be equipped to apply the right tool to the right problem. For example, a foundry should be equipped to use a simple tool to help rig the casting such that the risers are properly sized, and feeding distance rules are obeyed. A quick, solidification analysis could then be conducted to verify that the casting is adequately rigged. At this point, the full physics problem could be modeled to analyze the filling characteristics of the gating system, and the effect on the resultant solidification of the casting.

An Example

A typical use of computer simulation would be to help optimize the gating and risering of a new casting job for a particular foundry. This process can be highlighted using the 400lb ductile iron casting shown in Figure 1 with the initial gating recommendation.

The fill time for this casting is 26 seconds. Figure 2 shows the filling profile at 3.3 seconds. At 3.3 seconds, the runner bar has not yet filled. The colors represent flow velocity. Yellow represents 180 cm/s flow rate, while blue represents 20 cm/s flow rate.

The flow is non-uniform (variation of color in runner bar), and the gates do not fill simultaneously. Figure 3 shows the situation at 4.4 seconds.

At 4.4 seconds, the situation has grown even worse. The gates at each end of the axle are already filling the casting cavity, while the middle ingates have just begun to fill. Worse, the ingates are not full, and the velocity is not uniform within the ingates. This is due to momentum effects caused by an untapered runner bar.

This situation persists throughout the filling process, and would likely result in some reoxidation defects in the casting. Figure 4 shows the porosity predictions for this casting.

White areas represent sound metal, while colored areas indicate areas of potential porosity. The scale is set tightly at 98-99.9% feeding so that we can review every minute facet of shrinkage prediction. Based on prior experience, yellow indicates areas where shrinkage is unlikely when the process variables are within specifications, but could be problem areas should one or more process variables deviate from these specifications; (e.g. pouring temperature, mold hardness, nodularity, etc.). Red indicates areas of predicted porosity.

Even with the poor filling characteristics, the program only predicts one area of potential porosity. At first, it seemed that this problem might be caused by the location of the ingates. A second iteration with was made with a tapered runner bar, and relocated ingates.

The filling was dramatically improved, as shown in Figure 5.

All of the ingates fill at the same time, and the velocity is lower, and more uniform in the runner bar and ingates, as compared to the original gating. While the filling characteristics were dramatically improved, the porosity prediction for this configuration remained unchanged, and was identical to Figure 4.

A final iteration was run using the modified gating shown in Figure 6.

To solve the porosity problem, a 3x6.5” exothermic/insulating insert riser sleeve was connected to the problem area. The gating system was slightly modified to accommodate the riser sleeve and riser basin.

The flow simulation was nearly identical to that shown in Figure 5. The flow was uniform and the ingates all filled simultaneously. In addition, the porosity prediction was eliminated, as shown in Figure 7.

The filling characteristics were dramatically improved by tapering the runner bar and relocating the ingates. The predicted porosity was eliminated by the exothermic/insulating riser.

Other Important Issues

The previous example illustrates just one example of the analyses made possible by using computer simulation. There are many good case studies recently published that greatly expand on the potential of computer simulation.
For those considering computer simulation for their foundry, there are several recommendations from the AFS 1F-Process Modeling and Design Committee. First, success will depend on the expertise of the user. It is recommended that the user have an engineering degree, or an equivalent amount of actual foundry experience. Also, expect one year of on-the-job training for the user to get thoroughly familiar with the program, its use, and the calibration of the tool to your specific foundry. Most users will excel in this area, and be up to speed within 6 months, but plan on one full year to see explicit results in the area of process optimization.

Dimensionally accurate 3D geometry models are required for all simulations. Ensure that the user has access to 3D models of the castings, or the technology to electronically model the patterns.

Finally, accurate thermal data for all of the materials in the casting process is the lifeblood for physics based programs. Without this information, it will be impossible to obtain repeatable, accurate predictions.

Most programs have a baseline set of thermo physical data for metals and mold materials that was obtained from references. In general, the metal data is quite good.

The mold material data requires updating, and this is being done presently by the 1F committee via AFS funding.

Thermo physical data for riser sleeves, hot toppings, etc. can be obtained from your feeding systems vendor.

Accurate interfacial heat transfer coefficient data is also critical to the analysis. Some data is available via AFS, and several research projects are underway to fill in the blanks in this area.

**A Final Note**

The filling and solidification of iron castings is difficult to accurately simulate due to the complexity of the process. For iron simulations, metal chemistry, mold hardness, the inoculation method and quality of inoculant, the nodularity and the nature of the graphitic expansion must all be properly accounted for. More importantly, these variables change daily in the foundry, so the prudent computer simulation user must calibrate the program to match the variations in the foundry.

Generally, this means that several simulations must be conducted for each configuration to determine how the foundry process variables will affect the quality of the casting. Conversely, the user could set up the worst case condition for every configuration, and make this the standard simulation setup. Nonetheless, attempting to predict the solidification behavior of ductile iron is very complex, and the user cannot expect to get the precise answer for every iteration of every casting configuration. Experience has taught us to be very conservative in the simulation setup for iron castings.

In addition, the user should take the time to test the metal and mold material for thermo physical properties, and measure the respective heat transfer coefficients for his respective foundry. Once this data is obtained, the accuracy of the simulations will increase dramatically, and the results will be very dependable.
Figure 1 - Ductile Iron Axle Casting with Original Gating

Figure 2 - Filling Profile at 3.3 Seconds

Figure 3 - Filling Profile at 4.4 Seconds
Figure 4 - Porosity Predictions
Back to Article

Figure 5 - Filling Profile at 5.5 Seconds
Back to Article

Figure 6 - Modified Gating and Risering
Back to Article
Figure 7 - Porosity Predictions

Back to Article
Comparison of Clarifier Drives

By James A. McNish, President
Walker Process Equipment
Division of McNish Corporation
March 2000

ABSTRACT
This paper examines the comparative Precision, Metallurgy and Material Rating of gearing offered by Walker Process Equipment and other manufacturers in the water and wastewater industry. Also discusses, with examples, the corrosion resistance of steel, ASTM A536 Gr. 80-60-03 and ASTM A536 Gr.120-90-02.

As a result of a long and sustained program of drive redesigns, Walker Process Equipment/McNish Corporation produces a split ductile iron ANSI/AGMA Class Q6 precision gear with replaceable races that is superior to any drive we know of competing in our market today.

Let’s look at this comparative chart of selected attributes for gears:

<table>
<thead>
<tr>
<th>GEARs</th>
<th>Ductile Iron</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Other Manufacturers</td>
<td>WPE Today</td>
</tr>
<tr>
<td>Precision</td>
<td>Not Claimed</td>
<td>Producer of Class Q6 Precision Gears</td>
</tr>
<tr>
<td>Metallurgy</td>
<td>ASTM A536 Gr 80-60-03 (or less)</td>
<td>ASTM A536 Gr 120-90-02</td>
</tr>
<tr>
<td>Material Rating</td>
<td>QIT Gr 2¹</td>
<td>QIT Gr 1¹</td>
</tr>
</tbody>
</table>

Note: Ductile Iron Castings have 2 to 5 times better corrosion resistance than carbon steel.²


²Reference: Iron Castings Handbook, Fig. 7, Page 498; Table III, Page 500. Table IV Page 501, published by the Iron Castings Society, Inc.

PRECISION
As a result of the drive redesign program, Walker Process Equipment/McNish Corporation has changed metallurgy, geometry, dimensioning, and tolerances of its gears which allowed it to obtain a ANSI/AGMA Class Q6 rating. This is a statement of precision.

To maintain our quality rating, Walker Process Equipment adopted a new quality control procedure to meet the requirements of an ANSI/AGMA Class Q6 rating.

The program includes the following elements:

Quality Rating Program

- From the Foundry
  - Chemistry and heat treatment certification
  - Tensile test specimen certification
  - Hardness range certification

- From Walker Process Equipment
  - Incoming Inspection Verifies:
    - Hardness
    - Casting dimensions
Comparison of Clarifier Drives

- Finished Gear Inspection Measures
  - Radial tooth run out
  - Tooth size over pins
  - Tooth spacing

This data is then fed into a program for analysis and a printout is produced displaying the AGMA quality of the gear.

We know of no other gear supplier of internal spur gears with replaceable races that meets these quality standards.

**CORROSION RESISTANCE CASE HISTORIES**

**STEEL GEARS**

Walker Process Equipment supplied 12 clarifiers utilizing 80” steel gears that went into operation in 1985. After 13 years we undertook a rehab contract for all 12 gears which were returned to WPE and all were found to be unusable, as you will see in the segment shown in Figure 1.

![Figure 1 – Carbon Steel Gears with 13 Years of Service](image)

**DUCTILE IRON GEARS**

Walker Process Equipment also in the same order supplied four Thickeners utilizing 80” gears made of ASTM A536 Gr. 80-60-03 ductile iron. After the same thirteen years of service two units were returned to WPE for rehab and it was determined that both of the ductile gears were reusable.

The superior corrosion resistance of ductile iron gears is seen in a segment of a used 80 inch gear made of 80-60-03 ductile iron that had 20 years of service at Appleton Paper Co., in Combined Locks, Wisconsin. This gear had been replaced six years ago by the Paper Company even though the corrosion was so slight Walker Process Equipment felt it could be salvaged. As a result, it had twenty years of service in a paper mill and sat out in our yard for the next six years- twenty-six years in total.

Please note the significant lack of corrosion in Figure 2.
Comparison of Clarifier Drives

In the first case history the steel gear showed severe corrosion, which occurred in all 12 steel gears such that none were re-usable, while the 2 ductile iron gears were re-usable. All of these gears had operated in the same environment in the same plant with the same maintenance procedures for the same length of time.

In the second case history the ductile iron gear had 20 years of heavy-duty service, was re-usable, and was stored outside for an additional 6 years.

There is a large disparity in the comparative rates of corrosion as shown in Figure 3. The 80-60-03 ductile iron material clearly provides superior performance.

Since that time, we have upgraded our ductile iron material selection to ASTM A 536 Gr. 120-90-02 as quenched and tempered. This upgrade allowed us to improve our rating from a QIT Grade 2 to QIT Grade 1. For the last few years we have been shipping ductile iron gears with better physicals and an improved corrosion resistance over that of the samples shown.

In summary, Walker Process Equipment/McNish Corporation’s AGMA Class Q6 Precision Gear made of 120-90-02 Ductile Iron with replaceable races is superior to any other gear we know in that it combines both superior precision and superior corrosion resistance.

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Ashland Introduces ExactCalc

Foundry Products Division of Ashland Specialty Chemical Introduces ExactCalc™ Foundry Methoding Software

Dublin, Ohio (USA) - ExactCalc™ software, an advanced, user-friendly tool that helps foundries design gating and risering systems, thereby producing greater consistency and maximum yield, has been created and introduced by the Foundry Products Division of Ashland Specialty Chemical.

Offering benefits over other programs, ExactCalc software includes a "learn" function that enables methods engineers to incorporate their individual foundry best practices, experiences and quality systems when designing complete gating and risering systems. This feature enables the software to build and maintain an invaluable database of knowledge and procedures that is customized to each foundry.

Ashland's Foundry Products Division, a technological leader in the metal casting industry, worked with Novacast AB of Sweden to develop the software, now available worldwide through Ashland and its affiliates. Further information can be obtained by contacting a local Ashland representative.

Ron Aufderheide, global marketing manager for Ashland's EXACTCAST® riser sleeve, said: "ExactCalc software is a comprehensive tool that helps foundry operators optimize the design of their gating and risering systems by incorporating their previous successes and applying those parameters to other jobs where they have traditionally been less successful. This can lead to greater consistency, improved yields, and a better understanding of the variables that exist within the foundry. The ExactCalc software offers a systematic and scientific approach to methoding in accordance with ISO 9000 standards and provides a custom solution for improving productivity, quality and profitability standards at foundries around the world."

ExactCalc software operates under the standards of WINDOWS* software and is compatible with WINDOWS 95 or later operating systems. It includes sub-programs for: Weight, Modulus, Feeding Distance, Feeding Rate, Filter Calculation, Horizontal- and Velocity-Based Running Systems, and an online help file. Selection of the correct EXACTCAST riser sleeve and filter is simplified and automatic using the ExactCalc software databases. All methoding data can be stored as a computer file and/or printed to produce a permanent record for future reference.

In addition to its benefits for the methods engineer, Ashland's ExactCalc software also can be used as a valuable educational tool for training foundry engineers in the basic principles of gating and risering. Its interactive, user-friendly design allows the user to determine the effects of parameter changes such as alloy type, pouring temperature, pouring time, adding chills or cooling fins.

"We're convinced that foundries using ExactCalc software will be able to reduce casting problems and defects, improve their efficiencies and productivity, and accumulate an invaluable electronic library of their knowledge," Aufderheide said.
NEWS BRIEFS

MEETINGS

The next Research Committee Meeting will be held on January 10, 11, 2001 at the Ramada O'Hare in Rosemont, IL. For room reservations, call (847) 827-5131 and mention the Ductile Iron Society.

The Annual meeting of the Ductile Iron Society will be held on June 13, 14, 15, 2001 at the Waterloo Motor Inn in Waterloo, Ontario, Canada with a visit to WesCast, Wingham, Ontario.

PEOPLE IN THE NEWS

Eric Salmon has joined Superior Graphite Co. as an area sales manager, based in Oberruti, Switzerland. He is responsible for sales and technical support of Superior's metallurgical products, including Desulco® and Ark® Electrodes.

Salmon's coverage area encompasses Austria, the Benelux countries, France, Portugal, Spain and Switzerland.

Superior's reputation as a world-class manufacturer of graphite-based products is among the features that attracted him to the company.

"Superior wants to sell products on their technical merit rather than focusing on price," he adds. "Also, the company is aggressive in research and development of cutting-edge technology."

Salmon previously worked for Timcal Ltd. in Sins, Switzerland, as project leader for the introduction of new lubrication technology in hot-strip mills.

He has a doctorate in geology and geophysik from the Institut de physique du Globe, Strasbourg, France.

Desulco is the purest form of carbon additive available and is one of Superior Graphites main products. Ark Electrodes operate under extreme heat in electric arc furnaces to melt steel scrap for the iron and steel industries.

Based in Chicago, Superior Graphite is a high-temperature technology manufacturing company that uses unique technologies to add value to carbons and graphites.

Superior Graphite has promoted Andreas Jentsch to vice president of sales and marketing for the European division. In his new position, he is responsible for the company's metallurgical and industrial product line in Africa, Europe and the Middle East.

Based in Frankenberg, Germany, Jentsch will help increase Superior's international market share for all products and ensure the company continues to improve its already-strong customer focus.

Jentsch joined Superior in 1994 as a regional sales engineer in the European division. He became a sales manager in 1998, a position he held until being named vice president of sales and marketing in April.

In addition to his years of experience at Superior, Jentsch brings to his new position four years of outside experience. He worked at Walzengiesserei Karl Buch in Siegen, Germany, as a production engineer in the roll foundry and as a technical sales engineer for Africa, the European Union and North America.

Based in Chicago, Superior Graphite is a global producer of high-purity graphites and carbons used by numerous industries around the world.

BUSINESS BRIEFS

Dublin, Ohio (USA) Ashland Specialty Chemical Company, a division of Ashland Inc. has commenced operations at its first manufacturing plant in China, a facility in the company's Foundry Products Division. The wholly owned 50,000-square-foot facility is located in the Changzhou New District, a high-tech industrial development zone, between Nanjing and Shanghai, China. It will formally operate as Ashland (Changzhou) Chemical Co., Ltd.

Production is now under way following a dedication and grand opening ceremony held at the plant on October 21 with government officials, company representatives, customers and others.

The facility's initial work force is approximately 25 employees. The office, blending, and resin manufacturing complex produces ISOCURE®, ISOSET® and PEP SET® foundry binders and related foundry products used by automotive, transportation, machine tool and other industries to make items such as industrial and automotive engines, train components, and earth-moving equipment. The plant offers the Foundry Products Division's comprehensive product line and technical support services to customers in the People's Republic of China and throughout the Asia-Pacific Rim.

"This exciting new venture is a reflection of Ashland's commitment to global support of the foundry industry. It expands on our successful history in this region of the world and also signifies the continued business growth we expect in the years ahead. Not
only is it an important step for our Foundry Products Division, but it also paves a path for possible future developments by other segments of Ashland Specialty Chemical Company," said Michael D. Killian, vice president and general manager, Ashland Specialty Chemical's Foundry Products Division.

Philip D. Lepianka, director of global marketing for the division, also commented about the opportunities of serving an increasingly important economic region, and China's industry, which has the world's largest number of foundries and ranks second in casting production.

"China has the potential of becoming one of the world's largest auto markets. Many of our customers, particularly in the auto industry, are investing in China and looking to Ashland to supply them with world-class, quality products and technical services. That industry, in combination with other heavy industries, could drive China to be a significant engine of growth in the region," Lepianka said.

Ashland's foundry business in China, and the manufacturing plant, will be managed by Jiang Fu, who reports to Lepianka. Fu, a native of Beijing, has been associated with the foundry industry since 1984 and joined the company in 1992, serving as the Foundry Products Division's chief representative in China since 1994.

"Once again we would like to thank the officials at the Changzhou New District who have been very supportive and helpful as Ashland developed this wholly owned foreign investment," said John P. Cushman, manufacturing director for the division. "Our relationship with Changzhou dates to 1985 when we first entered the marketplace through a technology license for our foundry chemicals. Their cooperation and the trust and respect we built through the years with these representatives and our business associates made this progress possible."

Grede Foundries, Inc., of Milwaukee, Wisconsin, is proud to announce that its Greenwood, S.C., foundry has achieved a significant safety milestone. With over 400 people employed at this facility, they have successfully completed an entire fiscal year from November, 1999, through October, 2000, without experiencing any industrial injuries deemed serious enough to be recorded by the US Occupational Safety and Health Administration (OSHA). This is the first time in the 80-year history of the Company any of its foundries has accomplished the incredible feat of operating an entire year with an OSHA recordable incident rate of zero. (The OSHA recordable incident rate is calculated as the number of injuries serious enough to require more than simple first aid per 200,000 hours worked.)

This accomplishment is the direct result of the Company's Safety Policy, which states: "It is a fundamental principle of Grede Foundries that no job is so important and no service is so urgent that we cannot take time to perform our work safely. No operation shall be carried on in any plant until safety is assured."

This achievement is particularly noteworthy when compared to other OSHA recordable incident rate statistics reported to the US National Safety Council, as follows:

<table>
<thead>
<tr>
<th>Foundry Industry Average</th>
<th>20.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Industry Average</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Overall, Grede Foundries' OSHA incident rate for FY2000 was 2.0, with all of its foundries well below the all industry average. Grede Foundries operates 12 foundries in the US and the UK and is recognized leading producer of high quality castings in gray iron, ductile iron, and steel.

INTERMET Corporation today reported third-quarter sales of $240 million, an increase of $15 million compared with the same period last year. The increase is due primarily to continuing strong domestic and European light-vehicle sales and to the light-metals acquisitions made at the end of 1999.

Third-quarter earnings were 32 cents per diluted share on net income of $8.0 million compared with 29 cents per diluted share on net income of $7.4 million in the third quarter of 1999. Third-quarter earnings reflect a one-time gain of 11 cents from insurance related to the replacement of fixed assets from damaged plants, while the continuing weakness of the Euro has caused some bottom-line deterioration for the company. Operational earnings for the third quarter were 21 cents per diluted share.

INTERMET posted record sales for the first nine months of 2000 with year-to-date sales of $829 million, up $113 million from strong 1999 nine-month sales of $716 million. Year-to-date net income was $29.4 ($1.16 per diluted share), down $6.8 million from $36.2 million ($1.41 per diluted share) in 1999. 2000 revenues year-to-date reflected strong domestic and European automotive sales and positive contributions from INTERMET's light-metals acquisitions.

The INTERMET board of directors voted to approve a quarterly dividend of 4 cents per share, payable December 29, 2000, to shareholders of record as of December 1, 2000.

"Our earnings from operations declined compared with the third quarter of 1999 due to several continuing production issues," said John Dodridge, Chairman and Chief Executive Officer. "Our Columbus, Georgia, foundry continues to struggle with the ramp-up of new equipment. And, as previously reported, our Alexander City, Alabama, operation has been in the process of launching several complex parts. The plant has resolved most of its production issues; however, as a Tier 1 supplier, it continues to be impacted by difficulties with two machining suppliers.

"We expect that both the Columbus and Alexander City foundries will make substantial progress in the fourth quarter,"
Doddridge continued. "However, there appears to be a risk of slowing vehicle production in the fourth quarter, which could affect us."

"We are pleased that our New River Foundry has successfully restarted one of its two lines and is running smoothly," said Mike Ryan, INTERMET's Executive Vice President of Operations. "The second line is expected to start in early December. This added capacity is providing immediate relief from the over-capacity demand we have been experiencing at tour other ferrous-metals plants."

Superior Graphite Co.'s Russellville, Ark., plant is one of 25 exceptional manufacturing facilities to be named finalists in a competition that recognizes America's top manufacturers.

The recognition, announced in July, came from IndustryWeek magazine's annual "America's Best Plants" award program. The magazine was particularly impressed with the Arkansas plant's production, citing a 54.3 percent increase in annual sales per employee since 1995.

"We're very proud of this achievement, as it confirms that we're a leading world-class company," says Chad Edelan, the plant's quality and technical manager. "The selection proves that we make quality products efficiently; that we take care of our employees; and that we operate a safe facility."

Superior was selected as being in the top tier of U.S. manufacturers, according to IndustryWeek spokesman David Drickhamer. "These results require that everyone - not just the managers - take ownership of the process and truly understand various improvement strategies," Drickhamer says.

A record number of applicants vied for the coveted top 10 winner's list, which will be published in the magazine's October issue. IndustryWeek lauds plants that have made significant, measurable and sustainable progress over five years in areas including quality; customer and supplier relations; use of technology; cost reductions; on-time delivery rates; inventory management; safety; productivity; and product development.

In addition to enhanced productivity, Superior's Arkansas plant has improved its safety rates. Lost-time accidents have dropped 77 percent since 1995, while reportable incidents fell 83 percent in the same period.

The facility also has improved its delivery and lead times for customer orders, averaging 99.64 percent on-time delivery in 1999. "Our employees are the real key to the success of our organization," says Scott Anderson, assistant vice president of production. "Through training, empowerment and trust, we have been able to make great improvements in all areas of the plant. We consider employee development a top priority throughout Superior Graphite Co."

The plant employs 130 people and manufactures graphite electrodes used in steel and foundry electric arc furnaces. In addition to serving the North American market, Superior supplies electrodes to customers in Asia, Europe, the Middle East and South America.

Based in Chicago, Superior Graphite is a global producer of high-purity graphites and carbons used by numerous industries around the world.
ASI International is a relatively new name in the metals industry with an established reputation for quality and service. The origin of the company started in 1983 when the business was originally a marketing unit of a large multinational chemical company which produced binders for the foundry industry. The management and staff of ASI has largely remained unchanged during the ensuing 16 years, changing only in ownership and company name.

ASI has longstanding affiliations with major producers of metals and alloys as well as major trading companies. ASI manufactures specialty high performance inoculants, low silicon nodularizers and desulfuring briquettes, in-mold inoculant tablets, filter insert inoculants, ferroaluminum, iron aluminum hardeners, and a complete line of cupola and electric furnace fluxes.

Affiliations
ASI Represents several world class producers of melting consumables. Some of these companies include:

- **INCO** - The International Nickel Company, the world's largest nickel producer. Products include electrolytic nickel squares, nickel pellets, nickel shot and nickel magnesium alloys.

- **The Carbide/Graphite Group** - Suppliers of arc furnace electrodes, heating elements, calcium carbide, carbon raisers.

- **Great Lakes Carbon** - The largest U.S. producer of calcined petroleum coke.

Quality
ASI is ISO-Compliant as well as Y2K Compliant. ASI works exclusively with producers of alloys and other melting consumables who have attained ISO 9000 certification. Thus, you can be assured of receiving quality products. ASI's quality inspection team inspects all incoming and outbound shipments for product uniformity.

Value
Because ASI has on staff two degree holding metallurgists, including one with a metallurgical Ph.D., we can provide expert advice on selection and/or substitution of alloys to reduce your melting costs.

ASI has recently developed several new products. These include slag defect eliminating electric furnace fluxes, Sphere-0-dox S (patent pending) gray and ductile iron inoculants, Inocu-Bloc (patent pending) Inmold inoculating inserts, ceramic form filter inoculant inserts, new Nodu-Bloc low silicon nodularizers, ferroaluminum briquettes, iron aluminum additives for the primary aluminum industry.

Service
**Technical Assistance** - ASI can provide unparalleled metallurgical technical assistance. Our trained staff has a wealth of experience ranging from cupola melting to elimination of casting defects. Technical credentials include 34 technical papers published, two best paper awards from the American Foundrymen's Society, two Silver Anniversary papers, one Scientific Merit Award, and instruction at over a dozen AFS CMI courses.

Products
**Pure Metals and Alloys** - Nickel, Copper, Tin, Molybdenum, Bismuth, Iron shot, Selenium, Silicon metal, Tungsten, Silicon
Titanium, Aluminum Deoxidation Products


**Proprietary Products** - Redux EF 40 Electric Furnace flux Brix CF 40, SS 946 and CF 32 cupola fluxes INOC-U-BLOC (patent pending) inmold inoculating inserts and ceramic foam filter inoculant inserts, NODU-BLOC nodularizers, Sphere-o-dox S (patent pending) inoculants Ferroaluminum, Iron-Aluminum Hardners, Fluorspar

**Carbon Products** - CPC 100 and 300 by Great Lakes Carbon, Electrode Turnings by The Carbide Graphite Group, Arc Furnace Electrodes.
Odermath was founded in 1850 in Dusseldorf, Germany as a manufacturer of refractories. Through the years Odermath progressed and grew, expanding its product line in refractories, alloys, and casting powders. In the 1980's with the advent of cored wire technology, Odermath began producing cored wires and cored wire injection machines, ladles and RotoStop planetary gearing systems. Odermath US (INC) was founded in 1985, when Odermath Gmbh, of Dusselforf, Germany realized that the markets for iron and steel in the Western Hemisphere provided a great business potential. Today Odermath is one of the largest suppliers of cored wire technology to foundries throughout the world. Odermath is currently serving the iron and steel industry on every continent where iron and steel are produced. Odermath USA (INC) currently serves North America, South America and Australia. Recently a new computerized cored wire mill was commissioned at our Naperville, Illinois facility. This new mill gives Odermath USA (INC) the capability to produce any blend of alloys to a very high degree of accuracy. An experienced team of foundry metallurgists who are constantly striving to improve current products and develop new products drives our research department located in Dusseldorf, Germany.

Cored wire use in foundries, include wires for magnesium treatment, inoculation of gray and ductile irons using automatic pouring systems and alloying wires. Some of the benefits of magnesium treatment using cored wire are lower labor costs, greater control of magnesium residual, one step treatment for desulfurization and magnesium treatment, and less air pollution in the foundry. Inoculation cored wires used in automatic pouring systems, give the foundry the ability to control the inoculation process, precision measurement of inoculant added and total automation of the process.

Our cored wire injection machines are designed and built in the USA, using Allen Bradley electronic systems, and are available with relay or PLC control systems. Our machines have proven to be very rugged and reliable. Magnesium cored wire injection machines (LB-200) are capable of feeding wires at speeds of 20 to 600 feet per minute. Inoculation machines (LB-50) are custom built to fit each foundries needs, and usually run at speeds from 10 inches to 200 inches per minute.

Our ladles are produced at our German headquarters. We produce each ladle to a customers specification, or to the Odermath recommended specification. Every ladle is custom built with exact precision, using the highest quality materials.

RotoStop gearboxes are a planetary gear system, with a patented braking system providing the user with a safe efficient gearing system. This gearing provides positive control and smooth operation for one person, up to 17 ton capacity. An air drive motor can also be added to these gearboxes for automatic operation.

At Odermath our mission is to provide our customers with the highest quality products, and technical support. We provide onsite technical support, continuously responding to our customers needs and further development of new products and process improvement technology. Cooperation of our worldwide sales force, all of whom are metallurgists, gives us a greater pool of knowledge and experience to draw on so that we can better serve our customers’ needs. At Odermath we are committed to serving our customers.
Inoculation Machines (LB 50)

Back to Article
Magnesium cored wire injection machines (LB 200)
Back to Article
Back to Article
Back to Article