DIS Holds Seminar in Rolling Meadows, Illinois

View Ductile Iron Related Publications

Located in Strongsville, Ohio, USA
15400 Pearl Road, Suite 234; Strongsville, Ohio 44136
Billing Address: 2802 Fisher Road, Columbus, Ohio 43204
Phone (440) 665-3686; Fax (440) 878-0070
email:jwood@ductile.org
Why Primary Graphite is Bad!

Author: Rudolf Sillén
CEO, NovaCast Foundry Solutions AB

Primary graphite can easily occur in ductile iron if the carbon equivalent is too high in relation to the cooling rate. Primary graphite can be the cause of casting defects such as shrinkages and carbon flotation. Let us compare two cases:

Case A: Assume a hypereutectic alloy with C=3.9 and Si=2.8 giving CEL=4.6% (see illustration).

During solidification primary graphite will precipitate from the liquidus temperature until the eutectic temperature is reached. Dissolved carbon in the liquid is thereby reduced by 0.3% (4.6 - 4.3). The dissolved carbon in the liquid is thus reduced to 3.6% (3.9 - 0.3). If the austenite can dissolve 1.8% carbon then the amount of carbon available to create eutectic graphite is 1.8% (3.6 - 1.8). This eutectic graphite expands and can reduce, or in optimal cases, eliminate shrinkages. Note that the primary graphite is precipitated too early and is therefore not effective for reducing shrinkages that occur at a later stage in the solidification process.

Case B: Assume another alloy with C=3.9 and Si=1.6 giving CEL=4.3%. That alloy will start to solidify as eutectic (no primary austenite, no primary graphite). Therefore the carbon in the liquid remains at 3.9% during the eutectic solidification. The amount of eutectic graphite is therefore 3.9 - 1.8=2.1%.

Thus this alloy has almost 20% more eutectic graphite than the hypereutectic alloy which is a quite substantial improvement!

If the amount of eutectic graphite and its expansion is not sufficient to compensate for the contraction of the austenite and the remaining liquid then micro shrinkages are created. Therefore it is very important to avoid primary graphite.

Where is the eutectic point?

The traditional iron-carbon phase diagram shows that the eutectic point is around 4.3%. However, that is during equilibrium conditions with a slow cooling rate.

Therefore, if the chemical composition of an alloy is higher than 4.3 e.g. 4.5 but the cooling rate is high, the solidification will probably NOT be hypereutectic as expected but eutectic! An alloy that is hypereutectic as calculated with the formula C+Si/4+P/2, will solidify with primary graphite in a casting only if the cooling rate does not exceed a certain level. Especially for ductile iron it is important to use an alloy that does not solidify with primary graphite in order to avoid defects. Therefore the optimal active carbon equivalent (ACEL) value must be chosen depending on the cooling rate of the castings. In order to be able to keep a certain target for ACEL, thermal analysis using grey solidification as in ATAS should be used for maximum accuracy.
The diagram above illustrates the approximate location of the eutectic point as a function of the casting modulus which is related to the cooling rate. The illustration below shows the occurrence of shrinkages both for hypo- and hypereutectic compositions. For ductile iron the eutectic "point" seems to be more like a plateau.

**Expansion of primary graphite**

If the alloy solidifies as hypereutectic then the primary graphite grows directly in the contact with the liquid phase. Its expansion offsets the contraction of the liquid phase. An alloy with ACEL=4.5 will result in an expansion of about 0.8% between the liquidus temperature (about 1200 °C) and the eutectic temperature. The contraction of the liquid phase is about 0.75% which means that the total volume change from liquidus to the eutectic temperature is more or less zero. If the casting uses a feeder then the effect might be that the feeder does not start to pipe as there is no need for feed metal initially. Instead shrinkages might develop close to the feeder neck when feed metal is required later in the solidification process.

Below is a picture of a real case where the feeder did not pipe. The micro to the right of the photo shows many large nodules which proves that the solidification was hypereutectic. When the solidification was eutectic then the feeder piped and the shrinkage disappeared.
If the alloy solidifies slightly hypoeutectic (ACEL 4.2 – 4.25) then some primary austenite will be the first phase. Then there is a contraction in liquid state and the feeders will start piping more easily. Another effect might be that the graphite spheroids, precipitated at the eutectic temperature, are surrounded by austenite at an earlier stage and their growth rate is thereby reduced. The graphite precipitation pattern might be more gradual with more expansion at the end of freezing.

The picture illustrates the density changes for a sample with hypereutectic composition during solidification. Initially the density increases resulting in a contraction in liquid state. When liquidus is reached (TL) then primary graphite is precipitated and expands. At the same time the liquid contracts. The expansion and contraction during this phase (S1) are almost the same which means that the density does not change. When the low eutectic is reached (TElow), eutectic graphite is precipitated which causes an expansion. The first part (S2) until TEhigh is reached is the recalescence. Then the second phase of eutectic freezing commences (S3), often with a slight density increase especially close to the solidus temperature (TS) also called end of freezing. Then the density increases further in solid state (pattern mans shrinkage). The picture below shows a typical hypereutectic curve analyzed by ATAS.
Conclusion:
Avoid precipitation of primary graphite! For maximum eutectic graphite adjust the chemical composition to fit the solidification rate in the casting! Using chemical analysis to calculate the carbon equivalent is not suitable due to the limited accuracy (+/- 0.05 or more). The foundryman might believe that the carbon equivalent is within range when it is not! Use ATAS and the ACEL method in order to achieve the desired target for ACEL with high accuracy (+/- 0.01).
Making a Large Ductile Iron Casting with Foam

Hodge Foundry, Monterrey Mexico

This document is a PowerPoint presentation
To view this document, Click here

Use the escape button to stop the presentation
Monterrey, Mexico

Making a Large DI Casting with Foam

Presented
October 26, 2006
Following completion of our Capital Development Plan, Hodge offers a diverse array of Manufacturing Capabilities:

- **Melt Capabilities:**
  - Three 30-ton channel induction furnaces
  - Wire treatment method for producing Ductile Iron (two triple-path injection machines)

- **Molding Capabilities:**
  - High Bay: Four pits (largest 20 x 40 x 7 ft), with overhead crane capacities (hot metal) ranging from 30 to 100 tons
  - Lower Main Bay: Five pits (largest 20 x 40 x 7 ft), with overhead crane capacities ranging from 30 to 75 tons
  - Middle Bay: Significant floor molding capabilities, with overhead crane capacities to 25 tons

- **Sand Systems:**
  - Five sand mixers (2 mobile, 3 stationary); Total capacity of 7,000 lbs./min.
  - Reclamation system enabling over 90% sand re-use
Target Markets

- Energy & Power Generation
- Mining and Minerals Processing Equipment
- Plastic Injection & Die Casting Equipment
- Other Specialized Industrial Equipment
  - Machine Tools
  - Paper
  - Aerospace
  - Steel
  - Chemical
  - Automotive
Energy & Power Generation – Wind Castings
Mining and Minerals Processing
Plastic Injection & Die Casting
Specialized Industrial Equipment
120° SAG Mill Segments

- 1/3 of a SAG mill head.
- 11,000mm (36’) O.D.
- 3,800mm (12.5’) I.D.
- 22.5° sloped conical plate with flanges.
- Minimum 229mm (9”) thickness as cast.
- 111,000# ship weight.
Why Fullmold Foam?

- Cope is too large and heavy to roll over for finishing.
- Pattern stability and handling for traditional pattern would be poor.
- Only temporary pattern storage is needed.
- Cost vs. wood is much less.
Casting Specifications

- EN-GJS-500-7U with 395 Mpa (57,000 psi) UTS, 4% E in 240mm (9.5”) diameter integral cast coupon.
- HBW 165 minimum in coupon.
- Nodularity form V+, Size 5+ per ISO 945.
- Si <2.35% for impact.
Casting Specifications

- 6 sq. in. (3870 sq. mm) Max. indication of shrinkage in critical zones.
- 12 sq. in. (7740 sq. mm) Max. indication of shrinkage in non-critical.
- No linear indications >75mm (3”).
- No dross in critical areas.
- 2% maximum dross in non-critical areas.
Foundry Engineering

- Stock allowances determined to eliminate dross and carbon flotation.
- Drawing is marked up with stock for pattern construction.
- Gating design for fill in <3 minutes
- Minimize number of ladles (2 @ 40T)
Foundry Engineering

- First simulation is of plain casting to look for hot spots.
- Iterations run until engineering is confident of meeting specification.
Pattern

- Marked up drawing and pattern worksheet are sent to pattern vendor.
- Foam density 1.1 #/cu. Ft (17.6 kg/cu. m).
- Pattern supplied in pieces.
- Wooden sweep of the drag contour is supplied.
- Pattern layout forms used to make the pattern are inspected.
- Metallurgical coupon patterns also supplied in foam.
Molding

- A sweep of the drag surface contour is set up.
Molding

- The drag is swept, checked and coated.
Molding

- The pattern is assembled, cores & chills set in place.

- Fullmold coating on pattern.
Pouring

- Mold is weighted down (min. 270 T).
- Alloys weighed.
- Wire injector is set up.
- Furnace temperatures adjusted.
- 2 - 40T ladles @ 76,000# each.
- 1340-1360° C (2440-2480° F) pour temperature.
Inspection

- 100% surface coverage Magnetic Particle Inspection.
- 100% volumetric coverage Ultrasonic Flaw Detection.
- Ultrasonic velocity 5573-5624 m/s.
Inspection

- Dimensions and geometry measured with articulated arm portable CMM.
Delivery
ABSTRACT

There could be a number of situations where ductile iron parts might be rubbing against hardened steel parts under dry conditions for part of the time or all the time. Using laboratory methods, the wear and friction characteristics of ADI, Q & T, ductile iron, and as-cast ductile irons were evaluated.

A multi-specimen wear testing equipment capable of continuously monitoring applied torque, specimen temperature and ambient temperature was employed in the laboratory testing. The specimen holder was of the type called 3 pads-on-disk. The wear patterns of these different types of ductile irons were compared and presented in the form of graphs. Also the friction coefficients under these different material combinations were evaluated. The friction coefficients continuously changed with the time of testing and a typical graph is presented in this paper. An analysis of the results is also presented.

INTRODUCTION

In most of the mechanical assemblies there are some moving parts and some stationary. As a result of this there is a continuous relative sliding action in these mechanical devises. Frictional forces in these sliding surfaces result in wear. Friction and wear is not an intrinsic property of any material but it is a system property. The best way to study the process, therefore, is by actual observation of an assembly in the field run. However, the time of such testing would be long. Designers may like to see some relative behavior of the materials under laboratory conditions, which are for most of the time accelerated to yield quick results. One has to be real careful in interpreting and applying these results in the practical situations. One such method could be dry sliding of one test material over another test material under controlled pressure and sliding velocity. Keeping all these limitations in mind the objective of the work reported in this paper was to find out the dry sliding wear and dry frictional behavior of various continuously cast ductile iron samples over hardened 52100 steel disks when relatively lower loads are employed. This paper reports a part of the larger on-going wear and friction investigation program at Wells Manufacturing Company.
BACKGROUND
Ductile iron had been replacing several steel parts in the machinery since last 50 years. Besides mechanical properties the wear resistance of ductile iron was also of great interest to many investigators. Based on actual application the test procedures were designed or adopted by investigators. The range of ductile irons investigated include the as cast materials, as cast alloyed ductile irons to various grades of austempered ductile irons (ADI). Janowak et al [1] described the type of metal matrix obtained in ADI by various austempering temperatures. Comparative studies made by Liu et al [2], and Riposan et al [3], involving flake graphite cast iron, CG iron and nodular graphite ductile iron also placed ductile iron high from wear resistance point of view. A number of research workers took special interest in ADI. Zhou et al [4] studied wear resistance of different ADI components and concluded that the wear resistance is closely related to the amount of ausferrite. Gundlach et al [5] concluded from their tests that during the abrasion tests (jaw crushe) the surface of ADI samples got work hardened and thus better wear resistance was realized. Mayr et al [6] and Bing-Qing et al [7] also concluded that the stress induced martensite formation was there in ADI. Schissler [8] studied ADI using abrasion wear testing methods. Schissler concluded that the amount of retained austenite in their tests influenced the wear of the ADI surfaces. Prasanna et al [9,10] using a wet grinding type testing equipment on ADI samples concluded that ADI when austempered at a temperature in the range of 240 C to 280 C yielded best wear resistance results. Cast iron is widely used in conditions of dry-sliding wear in which two metallic surfaces are in rubbing contact. Examples include brake drums, brake discs, and clutch plates [11]. The cast irons were evaluated for wear under laboratory conditions as well as field-testing. Different types of ductile irons were tested but most of the time investigators were looking at the ADI for improved wear characteristics. The tests were conducted using extremely higher friction forces or impact forces. No detailed analysis of the friction coefficients during the testing had been reported. Based on this information it is thought that planning of tests using 3 pads-on-disk adapters, a relatively new test procedure for this purpose, could yield information beneficial to evaluate ductile iron test materials in laboratory conditions. The dry test conditions could be selected with relatively lower forces and study the effect of this combination on wear and friction characteristics. Presented investigation was on ductile irons of different matrices obtained by as cast and heat treatments. The information generated was on wear and friction coefficients under dry conditions.

DUCTILE IRON MATERIAL UNDER INVESTIGATION
Continuous casting of ductile iron bars proved to be outstanding in manufacturing shrinkage free and consistent quality bars. Continuous cast bars are relatively free from many types of inclusions. The soundness of these bars is unsurpassed by any other type of casting process.
Continuous casting of ASTM A536-84 grades 65-45-12 and 80-55-06 ductile irons is very much feasible and a number of customers use these products as some components in their hydraulic, agricultural, automotive and earthmoving machine assemblies. Therefore, these two grades were selected for investigating wear and friction behavior under laboratory conditions. The as-cast bar size of 80-55-06 grade (5506 DI) was 5.500" and of 65-45-12 grade (4512 DI) was 4.000". The as-cast chemistries of the material are given in the Table 1. The sulfur and Mn levels were lower and 5506 grade ductile iron was obtained by using some alloying with elements such as Cu and Sn.

The pad samples that were used in the wear and friction testing were prepared from 8" length bar samples taken from single continuous cast bar of 6' length.

The as-cast un-etched and etched microstructures of the 4512 DI and 5506 DI samples were examined and found to be possessing better than 90 % nodularity. The average pearlite contents in the matrix of 4512 DI and 5506 DI were about 30 % and 67 % respectively.

The bars used for making various pad samples were heat-treated. The 5 % nital etched microstructures of these heat-treated pads (ADI, and Q & T) are given in the Figures 1 to 4. ADI treatments resulted in coarse to fine ausferrite structure as given in the Figures 1 to 3. The tempered martensite structure could be seen in Figure 4. The microstructures were taken from pads used in preparation of test samples.

For the purpose of testing the pads samples of 4512 DI and 5506 DI have varying levels of pearlite. Also by heat-treating to ASTM A897-90 ADI grades 1, 3 and 5 samples got different amounts of bainitic ferrite and carbon saturated stable austenite in the metal matrices. The tempered martensite is another matrix in the samples that we are interested in evaluating in the wear tests. The material mechanical properties such as hardness and tensile, yield and elongations (4512 DI & 5506 DI) are given in Table 2. The test bars were taken from the continuously cast bars.

Samples from these materials were used to heat treat to get different matrix conditions for evaluation. The samples were taken from approximately mid-radius of the cast bar. The samples were then rough turned to required diameter before sending to appropriate heat treatment. The samples were subjected to the heat treatments as given in Table 3. Resulting hardness values were also recorded in the Table 3. These samples were used to make pads of 3/8" diameter and 0.101" thick. Material used for the disks in the testing was 52100 steel, which was austenitized at 1650 F and quenched and tempered to a hardness of about 60 Rc.
Table 1: As cast chemical composition of 65-45-12 and 80-55-06 grades.

<table>
<thead>
<tr>
<th>Element</th>
<th>4512 DI wt %</th>
<th>5506 DI wt %</th>
<th>Element</th>
<th>4512 DI wt %</th>
<th>5506 DI wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>3.57</td>
<td>3.38</td>
<td>Copper</td>
<td>0.022</td>
<td>0.058</td>
</tr>
<tr>
<td>Silicon</td>
<td>2.46</td>
<td>2.47</td>
<td>Vanadium</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.23</td>
<td>0.20</td>
<td>Tin</td>
<td>0.009</td>
<td>0.041</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.013</td>
<td>0.009</td>
<td>Titanium</td>
<td>0.015</td>
<td>0.011</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.029</td>
<td>0.027</td>
<td>Phosphorus</td>
<td>0.029</td>
<td>0.029</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.033</td>
<td>0.027</td>
<td>Sulfur</td>
<td>0.008</td>
<td>0.008</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>Aluminum</td>
<td>0.011</td>
<td>0.011</td>
</tr>
</tbody>
</table>
Table 2: Mechanical properties of as cast 65-45-12 and 80-55-06 grades.

<table>
<thead>
<tr>
<th>Material Grade</th>
<th>BHN Edge</th>
<th>BHN Center</th>
<th>Tensile, psi</th>
<th>Yield, psi</th>
<th>Elongation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>65-45-12</td>
<td>170</td>
<td>178</td>
<td>78,200</td>
<td>48,400</td>
<td>16.0</td>
</tr>
<tr>
<td>80-55-06</td>
<td>238</td>
<td>242</td>
<td>100,800</td>
<td>59,300</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Table 3: Heat treatment conditions and final hardness.

<table>
<thead>
<tr>
<th>HEAT TREATMENT</th>
<th>AUSTENITIZING TEMP (F)/DURATION</th>
<th>QUenching Temp (F)/DURATION</th>
<th>HARDness Rc</th>
</tr>
</thead>
<tbody>
<tr>
<td>4512 DI ADI GRADE 1</td>
<td>1634 / 74 MINUTES</td>
<td>729 / 85 MINUTES</td>
<td>26</td>
</tr>
<tr>
<td>4512 DI ADI GRADE 3</td>
<td>1634 / 74 MINUTES</td>
<td>603 / 159 MINUTES</td>
<td>38</td>
</tr>
<tr>
<td>4512 DI ADI GRADE 5</td>
<td>1634 / 74 MINUTES</td>
<td>481 / 240 MINUTES</td>
<td>45</td>
</tr>
<tr>
<td>5506 DI Q &amp; T</td>
<td>1650 / 120 MINUTES</td>
<td>WATER QUENCHED TEMPERED AT 500 F</td>
<td>55</td>
</tr>
</tbody>
</table>

WEAR TESTING MACHINE AND THE TEST PROCEDURE

For the wear test in the laboratory a multi-specimen test machine was used. The machine has the capability to run from 9 to 7200 rpm with various pulleys. The loads on the samples could be up to 807 lb and the specimen could be maintained if necessary at higher
temperature (up to 300 F) with appropriate fluid surroundings. The sample loading table and spindle could be seen in the Figure 5. The machine is equipped with data acquisition system which could be made to obtain the specimen temperature, temperature of the surrounding chamber, torque, rpm and time values at every 2 seconds duration or any higher durations as desired. A continuous display of these values is also there on the control panel. The panel displaying the test parameters is shown in Figure 6.

![Multi-specimen testing machine](image1)

Figure 5: Multi-specimen testing machine

![The Control Panel](image2)

Figure 6: The Control Panel

For the current laboratory wear testing a 3 pads-on-disk adapter was used. The pads, pad- holder, and a disk are shown in the Figure 7. In a given test 3 pads of 0.375” diameter and 0.101” thick are mounted in a rotating upper adapter at a position 0.75” on a radius.

![Samples and Sample adapter](image3)

Figure 7: Samples and Sample adapter

This is equivalent to using three samples for testing on almost similar conditions (counter surface, temperature and lubrication / no lubrication etc.) The lower disk specimen is a stationary one. The
material for this disk could be same as pads or any other counter faces that need to be evaluated for friction and wear with respect to the pad material.

In the present investigation the pads were made out of 4512 DI as cast, 5506 DI as cast, 4512 as cast ductile iron heat treated to ADI grades 1, grade 3, and grade 5, and 5506 DI as cast which was Q & T heat treated. In these experiments the disks used were only made from Q & T 52100 steel. The pads and the disks were ground to size and the starting surface finish was uniform as given in the typical measurements using a Federal Pocket Surf Indicator. The pads measured a surface roughness of Ra 10 to 15 micro inches and the disks measures a radial surface roughness, Ra of about 32 to 48 micro inches and tangential roughness of about 42 to 54 micro inches.

The test conditions were as followed: No lubricant was used and no external heating was employed. The machine has the capability to measure the temperatures of the disk and the surroundings. Several trial tests were conducted with different loads and rpm to get test parameters that yield measurable values and tests could be conducted in the laboratory without undue noise and vibration. Some trials were made using deionized water, a smear of oil on the surfaces of pads etc. Finally dry test condition under a fixed weight of 5 lb was selected as this test procedure gave adequate measurable wear rates. A predetermined load of 5 lbs was employed through out the testing. The leverage was 2 and as that resulted in a thrust of 10 lb. Also the rpm was kept constant around 100. The data such as the time, torque, and temperatures (disk and surrounding the adapter) were periodically measured (every 20 seconds interval) and put into a data acquisition system. Single test duration was for 12,000 revolutions (approximately 2 hours). At the end of the test, machine stops automatically. At that time the adapter was taken out, the pads and the disk were cleaned of the debris, and the pads and disk were weighed using a high precision balance with least weighing capacity of 1/10^6 of a mg. The debris was also collected from the table at the end of each test. The color of the debris collected was red and it was a powder. Obviously it looked like an iron oxide as reported in the literature in similar situations [2]. All the data pertaining to these tests were saved in a DAS file for analysis. For any 3 pad sample set, this testing was repeated 12 times to cover a total of over 144,000 revolutions.

The wear data were assessed with respect to revolutions of the spindle. Each pad covered a distance of 4.71” per revolution. The data obtained was over 12,000 revolutions (approximately 2 hours duration), so that amounted to a distance of 4,710 feet. The testing machine could be programmed to stop automatically after 12,000 revolutions of the spindle. At the end of each test the samples were taken out and weighed after cleaning. Weight loss was recorded for each of the run. For each combination of materials twelve runs were made. The results of these tests were
then analyzed to find out the wear loss by weight and by volume and also to find out the variation of friction coefficients during the tests.

**EXPERIMENTAL RESULTS**

At the end of 12 run test procedure the pads were examined using optical microscope, stereomicroscope and SEM. One of the pad was cut into half and the section and the remaining semi-circular surface were mounted and polished to examine the microstructure of the wearing surface and its cross section. Figures 8 to 13 show etched microstructures of all these sectioned mounts. The surfaces of pads were examined using Hitachi S3500 N Scanning Electron Microscope. The wear morphology of worn surfaces was examined at 400x or higher magnifications and given in Figures 14 to 19.

The weight loss data of each pad and each disk was recorded for every run and data over twelve runs were presented as volume loss for each material combination. A typical graph for 4512 DI is given in the Figure 20. These are the graphs generated using the weight loss information.

DAS provided information on the torque during the tests. Torque and the direct thrust on the samples (10 lb) that will help calculate the friction coefficients. The frictional coefficient, $f$, was calculated as a ratio of $(F_f/F_n)$, Where $F_f$ is frictional force calculated using the geometry of the test set up and the torque and $F_n$ is the normal force which was kept at 10 lbf in all of these experiments. The frictional coefficient values were averaged over a small periods of time (moving average) to suppress noise in the DAS. A typical plot of the friction coefficients in various runs (against cumulative revolutions) of ADI Grade 5 sample set is given in Figure 21.
Figure 18: ADI G 5, SEM, Surface, 400x

Figure 19: DI Q&T, SEM, Surface, 400x

Figure 20: The volume loss of 4512 pads and 52100 steel disk over 12 runs

Figure 21: The frictional coefficients of ADI Grade 5 vs. 52100 steel over 12 runs
DISCUSSION

During the tests the three pads were constantly rubbing against the surface of the disk at an average surface velocity of 37.3 fpm. The design of the adapter was such that the debris produced during the rubbing action was less likely to be caught in between the pads and the disk. However, one of the mechanisms involved could be abrasive wear even though the pressure between the pads and the disk was only 30 psi and the surface velocity was only about 37 fpm. Abrasive wear occurs when hard protuberance (asperity) on the surface of a material or a hard particle entrapped between surfaces plastically deforms or cuts a surface as a result of motion. Adhesive, fatigue and oxidation mechanisms could also play a role in the wear of surfaces that are pressed together, and have a relative motion [12]. From the debris collected it was clear that there is some amount of oxidation of the surface that is taking place and the abrasive wear constantly exposes virgin metal surface for further oxidation. The loss of weight information was converted into volume loss because of the use of different materials for pads and disks (it was assumed that the pads of ductile iron had a density about 7.1 g / cm3 and disk of steel had a density of about 7.8 g / cm3). The volume loss curves were derived from the weight loss information. These curves give cumulative volume loss information over 12 tests of a given sample combination. A comparison graph of the cumulative volume loss of pads over 12 tests of all samples is given in the Figure 22. As expected wear of 4512 DI was higher than others.

Two runs in the beginning could be removed from analysis to accommodate running-in wear. In the second running-in period wear of ADI G3 was higher than ADI G1. There are still ten two hour runs remaining to analyze. The average wear of these ten runs could be compared to see relative wear of these materials. Comparison purpose the wear of 4512 ductile iron pads was taken as a base. The relative wears of the rest of materials is presented in the Figure 23. Wear ratio of 5506 DI was 89 % of the wear experienced in the case of 4512 DI. ADI grades 1, 3, and 5 had a relative wear of 18, 14 and 9 % respectively. The wear ratio of Q & T ductile iron was on the lower end (8 %). This is in line with the starting hardness values of ADI grades. In this test there is no evidence of work hardening of retained austenite in the ADI grade 1 as reported by other workers [6,8]. This may be due to the absence of excessive stresses causing deformation of the surface layers. Microstructures, at 500 magnification, given in the Figures 8 to 13 do not indicate any surface material deformation including the graphite nodules. The test load was thus insufficient to cause that type of extensive deformation. This was in line with the test objective.

However, a very thin layer of surface in the case of ADI grade 1 might have gone through some transformation as it could be assessed from the surface coefficients of friction. The coefficients of friction in the case of ADI grade 1 were similar to DI Q & T material. The grand average values (average of the average values of all runs) of the friction coefficients were presented in the
Figure 24. ADI grades 3 and 5 had lesser values (0.35 & 0.44 respectively) than ADI grade 1 and Q & T grade. In the case of ADI Grade 1 there might be a thin layer of retained austenite transforming to martensite and it could be sensed by the observation of frictional coefficients only (0.72 & 0.78).

In general the hardness measurements on the pads were a little higher (Rc) than at the starting time as given in Table 4. This may also be due to general work hardening of the surface of pads due to deformation of a very thin layer that could not be seen in ordinary optical microscopy. The average disk temperatures that were monitored during the tests are given in the Table 5. The temperatures did not exceed 44 °C. From this observation it was clear that there was no excessive heating of the pads during the tests. It’s also clear from the values that the mechanical properties are unlikely to be affected by these temperatures.

Table 4: Hardness of pads after wear testing.

<table>
<thead>
<tr>
<th>Material</th>
<th>ADI Grade 1</th>
<th>ADI Grade 3</th>
<th>ADI Grade 5</th>
<th>DI Q &amp; T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness, Rc</td>
<td>31.5</td>
<td>41.5</td>
<td>49.0</td>
<td>55</td>
</tr>
</tbody>
</table>

The surface SEM wear morphologies presented in the Figures 14 to 19 indicate extensive abrasive wear patterns on the 4512 DI and 5506 DI. However, the surface abrasive marks were relatively lesser in ADI grades and Q&T sample. In fact in the latter samples the graphite nodules could be seen clearly without any smearing over it.

Table 5: The average temperature of the disk (last 10 runs).

<table>
<thead>
<tr>
<th>Material</th>
<th>4512 DI</th>
<th>5506 DI</th>
<th>ADI G1</th>
<th>ADI G3</th>
<th>ADI G5</th>
<th>5506 Q&amp;T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. C</td>
<td>39.3</td>
<td>39.8</td>
<td>42.8</td>
<td>34.7</td>
<td>32.2</td>
<td>43.5</td>
</tr>
</tbody>
</table>

To see if there was any martensitic transformation of retained austenite, the ADI Grade 1 pad was selected for further analysis. The pad’s cross-section was checked for micro hardness. Micro hardness measurements were made in three planes, one along the rubbing surface, second at the mid-section and third parallel and close to the other side of the pad.
Figure 22: Wear of Pads by volume of all materials tested using dry sliding test method.

Figure 23: Wear ratios of different pad materials
The readings are given in the Table 7. The results were not significantly different to indicate that the retained austenite close to the rubbing surface was transformed into martensite. A number of investigators in the earlier works indicated that possibility [6,8]. That might be true only when higher amounts of deformation were employed. In these tests the wear of the pads was in accordance with the starting hardness of the pads.

The wear rates were calculated for all the sample materials that were tested based on last ten run averages. These values are given in terms of volume loss, cm3 x 100 per 5280 feet (one mile) of rubbing. Table 6 gives the wear rates. Least wearing materials were ADI grade 5 and Q & T ductile irons.

Table 6: The wear rates of the ductile iron materials tested.

<table>
<thead>
<tr>
<th>Material</th>
<th>4512 DI</th>
<th>5506 DI</th>
<th>ADI G1</th>
<th>ADI G3</th>
<th>ADI G5</th>
<th>Q &amp; T DI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear rate, cm3x100/mile</td>
<td>0.217</td>
<td>0.192</td>
<td>0.040</td>
<td>0.029</td>
<td>0.019</td>
<td>0.018</td>
</tr>
</tbody>
</table>
Table 7: Micro hardness, (HV), ADI Grade 1 Pad, 500 gram test load.

<table>
<thead>
<tr>
<th>Reading no.</th>
<th>Before testing</th>
<th>Near Test Surface</th>
<th>Mid-Section</th>
<th>Near the Other Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>335.1</td>
<td>417.0</td>
<td>457.5</td>
<td>342.2</td>
</tr>
<tr>
<td>2</td>
<td>383.8</td>
<td>432.5</td>
<td>326.3</td>
<td>335.7</td>
</tr>
<tr>
<td>3</td>
<td>391.7</td>
<td>421.5</td>
<td>348.2</td>
<td>440.0</td>
</tr>
<tr>
<td>4</td>
<td>369.4</td>
<td>307.0</td>
<td>384.6</td>
<td>335.7</td>
</tr>
<tr>
<td>5</td>
<td>404.9</td>
<td>390.1</td>
<td>417.9</td>
<td>270.1</td>
</tr>
<tr>
<td>6</td>
<td>322.7</td>
<td>401.5</td>
<td>355.0</td>
<td>315.0</td>
</tr>
<tr>
<td>7</td>
<td>326.9</td>
<td>320.3</td>
<td>425.1</td>
<td>303.7</td>
</tr>
<tr>
<td>8</td>
<td>310.4</td>
<td>419.7</td>
<td>300.4</td>
<td>390.9</td>
</tr>
<tr>
<td>9</td>
<td>390.1</td>
<td>319.7</td>
<td>303.1</td>
<td>442.9</td>
</tr>
<tr>
<td>10</td>
<td>371.6</td>
<td>227.0</td>
<td>409.2</td>
<td>331.9</td>
</tr>
<tr>
<td>Average</td>
<td>360.7</td>
<td>375.2</td>
<td>350.8</td>
<td>372.7</td>
</tr>
<tr>
<td>Stndev</td>
<td>33.80</td>
<td>51.17</td>
<td>56.71</td>
<td>54.36</td>
</tr>
</tbody>
</table>

SUMMARY

Ductile irons as cast and heat treated were evaluated for wear and frictional characteristics using a 3 pads-on-disk test method. The following main conclusion are drawn from the work:

1) 3 pads-on-disk method, a relatively new method, could be used to evaluate friction and wear behavior of materials under dry conditions using lower applied stresses at the interfaces of the rubbing surfaces.

2) When interfacial pressures are relatively lower the wear loss of material is related only to the starting hardness of the samples. No extensive evidence of martensite formation was seen in ADI grade 1 samples.

3) Oxidational wear was present when dry wear tests in atmosphere were conducted besides abrasive and probably adhesive wears.

4) The wear rates of ADI grade 5 and Q & T ductile iron pads under these conditions were only about 9 % of the wear rates of 4512 DI pads.

ACKNOWLEDGEMENTS

I would like to thank Robert O’Rourke, Wells Manufacturing Company’s product design manager for his useful suggestions during the course of the work. Thanks are due to Don Barry, laboratory technician who helped me conduct various experiments reported in this paper. Author thanks Kathy Hayrynen and Applied Process Inc.’s staff for the help in ADI heat-treating of the samples.
Author also thanks Mike Anderson and his colleagues of Falex Corporation for their advise during development of test procedure.

REFERENCES


INTRODUCTION

Over the past 40 years, iron foundries have incorporated a vast array of furnaces for melting. In particular, induction furnaces provide an economical method to melt and hold large quantities of molten metal allowing for great flexibility in production requirements. However, control over slag generation and subsequent buildup of insoluble, emulsified oxides and sulfides continues to be a significant problem. Failure to control these inevitable by-products can lead to loss of electrical efficiency, inability to adequately heat the charge, and eventual refractory and furnace failure.

Slag Formation: The formation of slag in iron melting is inevitable. The composition of slag varies with the type of melting process. The cleanliness of the metallic charge, often consisting of sand-encrusted gates and risers from the casting process or rust- and dirt-encrusted scrap, significantly affects the type of slag formed during the melting operation. Additional oxides, sulfides and non-metallic compounds are formed when liquid metal is treated with materials to remove impurities or to alter the properties of the system (inoculation and nodulizing). Since these oxides, sulfides and non-metals are not soluble in molten iron, they float in the liquid metal as an “emulsion”. This emulsion of slag particles remains stable if the molten iron is continuously agitated, such as in the case of the magnetic stirring inherent in induction melting. Until the particle size of the non-metals increases to the point where buoyancy effects counteract the stirring action, the particle will remain suspended. When flotation effects become great enough, the non-metallic particles rise to the surface of the molten metal and agglomerate as a “slag”. Once the non-metals coalesce into a floating mass on the liquid metal surface, they can be removed or de-slagged. The use of fluxes accelerates these processes.

When slag makes contact with the refractory lining of a furnace wall (or other areas of the holding vessel) that is colder than the melting point of the slag, the slag is cooled below its freezing point and adheres to the refractory furnace wall or inductor channel. The adhering material is called buildup. High-melting point slags are especially prone to promoting buildup. Buildup is an on-going process and is a classical nucleation and crystalline growth phenomena. Shortly after the initial liquid slag phases start to precipitate as a thin solid film or substrate on any furnace refractory surface, subsequent buildup can proceed more easily and rapidly. This liquid glass or slag phase nucleates easily and grows on the just deposited buildup because the surface of the initial buildup (solid slag phase) is crystallographically similar to the liquefied slag or glass phase attempting to precipitate out of solution. Failure to “flux” or remove these emulsified phases from the metal bath during the melting and holding process will allow more buildup to form and will reduce the overall efficiency of the metal handling system. Frequent additions of specific Redux EF40 fluxes can prevent these problems while having no adverse effect on furnace refractories.

A short discussion of the concepts involved in coreless induction furnace melting is necessary so that one can better appreciate the problems of buildup in channel induction furnaces.

Induction Melting – Coreless Induction Furnaces: The coreless induction furnace is a refractory-lined vessel with electrical current carrying coils surrounding a refractory crucible. A metallic charge consisting of scrap, pig iron and ferroalloys are typically melted in such a vessel. When an electrical current is applied to the coil, a magnetic field forms, that in turn creates thermal energy resulting in the melting of the charge. The magnetic currents in the molten metal cause an intense stirring action, thus ensuring a homogenous liquid.

During the melting process, slag is generated from oxidation, dirt, sand and other impurities. Slag can also be generated from the scrap, erosion and wear of the refractory lining, oxidized ferroalloys and other sources. In a coreless induction furnace, slags normally deposit along the upper portion of
the lining or crucible walls and above the heating coils. Figure 1 shows typical slag buildup in a coreless induction-melting furnace.

![Figure 1: Typical slag buildup in a coreless induction furnace (gray shaded areas)](image)

The hottest area of medium and high frequency coreless furnaces is at the mid-point of the power coil. All areas of slag deposit will be at a much lower temperature than those occurring at the center of the coil. Slag can also be deposited in areas midway down the crucible lining, where insufficient metal turbulence from magnetic stirring occurs.

**Channel Furnaces:** Another type of induction melting furnace is the channel furnace. Channel furnaces can be configured as either vertical or drum-type furnaces. Whereas in a coreless furnace, the power coil completely surrounds the crucible, in a channel furnace, the induction field is concentrated around a separate channel loop housed within an inductor that is attached to the upper-body (uppercase). The uppercase contains the major portion of the molten metal bath. In a coreless furnace, solid charge materials are melted using the induction field, whereas in a channel inductor, the induction field is used to superheat colder molten metal within the channel loop. A vertical channel furnace may be considered a large bull-ladle or crucible with an inductor attached to the bottom. Figure 2 illustrates how insoluble components, such as slag, accumulate over time in the inductor loop or throat area. Buildup on the sidewalls of channel furnaces (slag shelf formation) is also a common occurrence.

![Figure 2: Slag buildup in the inductor and throat of a vertical channel furnace (gray shaded area)](image)

A continuing problem experienced by many iron foundries is the deposition of insoluble oxides and sulfides within the throat opening of the channel furnace. Once the throat has clogged, the channel furnace inductor can no longer transfer the necessary heat to the uppercase for continued operation. This results in a significant loss of electrical efficiency; it also leads to a significant reduction in the true service life of the refractory.
Figure 3: Buildup in inductor channel (left) resulting in restricted metal flow and severely constricted throat opening, sectioned (right) illustrating heavy saturation.

Figure 3 illustrates examples of severe buildup in inductor channels and how this buildup can severely restrict the flow of molten metal, eventually leading to inductor failure and possible run-outs.

Pressure Pour Furnaces: Pressure pour furnaces are sealed holding/pouring furnaces blanketed with either an inert gas or air atmosphere and have an inductor attached to the bottom or side. Pressure pour furnaces are designed to hold liquid metal at a constant temperature for extended periods of time. When the furnace is pressurized, a stream of molten metal exits the vessel for mold filling. These furnaces are not designed to melt metal. Circulation of liquid metal through the inductor loop provides the continuous superheating of liquid metal to keep a constant temperature of the remaining liquid metal in the furnace. Pressure pours are widely used in the processing of magnesium-treated ductile irons; they are usually pressurized with an inert atmosphere. As in a vertical channel furnace, slag often builds up in the inductor loop and throat areas (Figure 4). Slag buildup also occurs along the sidewalls, effectively reducing the capacity of the vessel. Additional buildup in the “fill (receiver) siphon” and “pour (exit) siphon” areas restricts metal flow rates into and out of the vessel. The “choking” or “formation of restrictions” in the siphons is often an ongoing battle throughout the day since these siphons must be kept open. Careful refractory selection and proper back-up thermal insulation can lessen the degree of buildup that forms.

Figure 4: Traditional throated-pressure pour vessel showing slag buildup in (gray shaded areas)

When sufficient buildup forms, it will prevent adequate heating of the molten metal from the inductor. The inductor will have to be replaced because it can be extremely difficult to access and remove the buildup. Attempts to modify the furnace design with a throatless inductor (Figure 5) have been partially successful in eliminating buildup, but an aggressive, periodic cleaning procedure is still necessary.

Figure 5: Throatless pressure pour vessel showing slag buildup in (gray shaded areas)

Depressurizing a ductile iron pressure pour vessel and removing the top hatch for cleaning allows outside air to enter the vessel. This increases metal oxidation/resulfurization, and can aggravate buildup problems since oxygen is introduced into the vessel. The buildup must be removed by scraping from the sidewalls, inductor channel and throat. If the buildup is dense and well fused (hard), it is very difficult to remove. If the buildup is porous and soft, then it is possible that routine maintenance (scraping the sidewalls and rodding the inductor throat area with a metal tool or green wooden pole) can control accumulations. One major advantage of using the Redux EF40 flux when confronted with a dense, fused buildup, is that the flux alters the glass-like structure of the buildup that results in a “softening” of the buildup. Removal of the buildup is greatly simplified after fluxing and the time required for buildup removal can be reduced by up to 90%. When the buildup becomes severe, power factor readings of the inductor drop and the efficiency of the pressure pour is dramatically reduced.
SOURCES OF BUILDUP CONSTITUENTS

Buildup represents a complex ceramic deposit of insoluble complex oxides and sulfides that occurs in the throat and in the inductors of the channel furnace. The presence of insoluble oxides within the melt occurs as a result of oxygen availability in the furnace. Insoluble sulfides within the melt can originate from charge materials as well as various contaminants such as machining fluids, dirt and by-products from desulfurization.

Different theories surround the creation of the primary insoluble oxides and have been described by S. Singh\(^1\), R. Stark\(^2\) and others. Currently, the two theories which are the most plausible are (1) the diffusion of oxygen (air) through the porosity within the refractory and subsequent oxidation of the molten metal, and (2) residual insoluble oxides as by-products of the primary metal source or from the ferroalloys being used in the melt. A list of commonly recognized sources of primary oxides or sulfides is shown below:

- Oxidation of molten metal exposed to the atmosphere
- Dirty, rusty scrap or charge materials, oxidized surfaces
- Erosion of upstream refractories in the furnace uppercase or receiver
- Contamination from minor elements used for inoculation or nodulizing
- By-products from metal treatment operations such as desulfurization with calcium carbide
- Residual contaminants from fluxing in the channel furnace uppercase

Circulation of Molten Metal in a Channel Induction Furnace – Mechanical Mechanism of Buildup

Figure 6 illustrates the circulation and metal flow through both single and double loop inductors. Not only can buildup occur in the inductor loop and throat areas, but it also occurs in stagnate or low metal flow areas immediately adjacent the inductor loops.

![Figure 6: Circulation and metal flow (shown by the arrows) in a single loop inductor and double loop inductor.](image)

In either case in Figure 6, the “stirring action” is not as well defined when the furnace is left on “low-hold power” which often occurs when “idling” over a weekend. During these periods, the areas of minimal flow occur in the boat section (the transition section between the channels at the top of the inductor) or in the refractory areas in the throat that are adjacent to the molten metal stream emanating from each channel. These areas represent the “dead” zones where metal does not circulate as effectively as it does within the channel. This mechanical explanation for buildup formation can be further supported by sedimentation of the insoluble oxides in the low flow areas. Although buildup can occur in the inductor loop and throat areas, it also occurs in stagnate or low metal flow areas immediately adjacent the inductor loops. When this buildup occurs, insufficient metal flow between the inductor and uppercase limits heat transfer and interferes with the melting operation.
Stark\(^3\) has often commented that “pulsing” an inductor is necessary for early prevention of buildup. He has suggested that if an inductor is switched onto high power for 1 to 8 minutes for every half-hour interval of operation, the average metal temperature is increased and continual turbulence of the molten metal will reduce the severity of the clog. For example, 3 to 5 minutes of high power for each 30 minutes of operation is common for a 750-kilowatt inductor. It is important to note that periodic superheating or pulsing can lead to a continual increase in molten metal temperature, so it is critical to carefully monitor the temperature. Although this should not be considered as the ultimate solution for clogging or buildup condition, the “pulsing” concept results in an increase in molten metal movement and has definitely shown merit as a means for reducing inductor buildup.

Singh studied the mechanism of alumina buildup formation in pouring tubes and referred to three basic conditions that had to be satisfied: (1) particles have to come in contact with the refractory surface, (2) particles have to adhere to the refractory surface, and (3) particles have to adhere to each other so as to sinter and form a network. He explained the importance of metal velocity; especially in those areas close to a refractory surface where flow velocity is a function of the frictional force between the refractory surface and the molten metal. If the metal flow is kept at a high velocity and not allowed to remain in an idle or slow-moving state, the tendency for buildups to occur is usually reduced.

Stirring action in an inductor is pronounced when the inductor is placed on high power. This “stirring action” refers to the actual metal flow through the inductor channels. Whether in a single loop or a double loop inductor, the molten metal is superheated within the inductor channels and enters the upper body through the throat. While “inductor pulsing” may provide temporary relief from channel clogging, in the long run, it does not remove buildup from the inductor loop or throat area. Often a furnace operator will attempt to insert a steel rod or green wooden pole into the throat area even though accessibility is often severely limited. When significant accumulations of buildup cannot be removed, the furnace is taken out of operation, the throat(s) are scraped clean and a newly lined inductor(s) is (are) installed. Normal inductor life may be as long as 18 months, however, if buildup occurs, the useful life may be reduced to only a few months and in some cases, a few weeks.

THERMODYNAMIC EXPLANATION OF BUILDUP FORMATION

While sedimentation of insoluble oxides in the low flow areas of the channel furnace is the main source of buildup, it is also important to consider the thermodynamic feasibility of complex mineralogical compound formation based on charge constituents and refractory composition.

The order of precipitation of ceramic compounds (buildup formation) in the metal bath is a function of the compounds’ Gibbs free energy of formation, or \(DG_f\). The larger the negative value of \(DG_f\), the more likely a ceramic compound or slag will precipitate from the metal bath. However, what remains unknown is the likelihood that complex slag phases may precipitate simultaneously. Although no research has been done to prove this theory of simultaneous or preferential insoluble precipitation, researchers have observed such phenomena under the microscope. Researchers at the University of Missouri at Rolla used x-ray cathode-luminescence to depict the various ceramic phases present within buildup taken from channel furnaces and proved that the concentrations varied as the location within the buildup changed.

The order of precipitation of ceramic compounds can be hypothesized by thermodynamic calculations but remains extremely difficult to determine due to complex chemistry of the systems involved. Table 1 lists the complex compounds, the mineral names, the melting points as well as the insoluble compounds’ free energy of formation\(^4\).

<table>
<thead>
<tr>
<th>Formula</th>
<th>Mineral</th>
<th>Melting Point (°F)</th>
<th>(DG_f) @ 2700°F (Cal/Mole °F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeO</td>
<td>Wustite</td>
<td>2,514</td>
<td>-77,370</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>Hematite</td>
<td>2,957</td>
<td>-59,630</td>
</tr>
<tr>
<td>Fe$_3$O$_4$</td>
<td>Magnetite</td>
<td>2,912</td>
<td>-67,250</td>
</tr>
<tr>
<td>FeOAl$_2$O$_3$</td>
<td>Hercynite</td>
<td>3,236</td>
<td>-5,404</td>
</tr>
<tr>
<td>MnOAl$_2$O$_3$</td>
<td>Galaxite</td>
<td>3,362</td>
<td>-9,346</td>
</tr>
</tbody>
</table>
As shown in Table 1, calcium sulfide (CaS) has the highest melting point and is the most stable compound (having the lowest $\Delta G_f^0$) of all the minerals listed. Because CaS has a much higher melting temperature than molten iron, it will readily precipitate out of solution and not react with other elements in the liquid iron. Precipitated CaS particles in the melt will act as potential nuclei substrates upon which other mineral compounds will form. If there is a significant presence of CaS in the liquid iron, a dense matrix will form that has a “higher refractoriness or durability” than the surrounding refractory walls of the melting vessel. The dense matrix of CaS will attract other mineral compounds shown in Table 1 to nucleate and deposit on the refractory wall, eventually leading to premature deterioration. Subsequent restricted molten metal flow due to this buildup will cause superheated molten metal to further break down the furnace refractory.

The Gibb’s free energy of formation value signifies the amount of energy needed to “pull apart the compound” into its basic components at a given temperature. The more negative the value, the more difficult it becomes to break down the insoluble compound, thus, the compound will tend to precipitate out of solution. Since the theoretical Gibb’s free energy of CaS is strongly negative, CaS will remain intact and un-reacted with other potential reactants in the metal. The continual presence of CaS will result in the formation of a dense matrix, having “higher refractoriness or durability” than the surrounding refractories. This will lead to the eventual deterioration of the refractories. Restricted molten metal flow due to the buildup, will cause superheated molten metal to break down the refractories.

Another common buildup component present in furnaces melting or holding ductile-base iron is the mineral forsterite, 2MgOSiO₂. This mineral is composed of magnesium oxide and silica (MgO and SiO₂) and can originate from a myriad of sources such as iron slags, refractories, and magnesium ferrosilicon nodulizing additions. If present, forsterite can quickly clog the top section of the inductors, creating a severe run-out potential. During continual operation, any iron oxide (FeO) within the molten metal will create an even stronger, higher-melting point, insoluble compound with the existing forsterite compounds. Utilizing Redux EF40 flux in controlled quantities can reduce the melting point of forsterite and eventually eliminate its formation.

The complexity of the buildup order of precipitation can very be puzzling as both calcium sulfide and forsterite are present; yet both will be difficult to remove by conventional superheating methods. Both compounds have higher melting points than the typical iron pouring temperatures and are very stable thermodynamically. It becomes an issue of buildup removal and attempting to identify the sources causing the buildup. Other insoluble compounds will behave similarly.

The thermodynamic characteristics of insoluble buildup components and furnace refractory components have similar constituents. Reviewing the general principles of the crystallization of ceramics may offer some explanation for buildup sedimentation. At the melting point of a ceramic material (or any material), the Gibb’s free energy of formation ($\Delta G_f$) for a given quantity is the same whether it is crystalline or liquid. As the temperature of the system decreases, the crystalline form has a lower free energy and crystallization can take place. However, this will not readily happen unless nucleation sites are present.

In the absence of nuclei, crystallization does not occur unless the system is cooled to a point below a critical temperature at which crystallization becomes spontaneous. Unfortunately, very little is known about the thermodynamic properties of the complex systems involved so it is not possible to develop a method to predict critical temperatures for crystallization. However, in practice, buildup formations can be partially controlled by re-evaluating the thermal losses in the refractory areas.
affected by the buildup. Any refractory wall with high heat loss in contact with the molten metal should be an area of concern. This “super-cooled” wall will act as a starting point for the buildup.

**FACTORS AFFECTING THE FORMATION OF BUILDUP IN CHANNEL FURNACES**

As the concentration of metallic oxides and sulfides within the molten metal increases, there is a greater propensity to form a ceramic buildup or clog in the inductor channels or throat openings. A change in the scrap quality for the primary melting unit, (coreless, channel furnace, induction furnace, cupola, arc furnace, or a gas-fired furnace) will affect the generation of more oxides. Such a change may be related to a chemistry change or may simply represent a physical size difference (greater surface area) in the charge.

Buildup may form in many areas of the furnace that experience significant heat losses such as in the throat area or inductor channels. Metallic oxide carryover may occur as contaminants oxidize when additions of various alloys are made to the molten metal in the transfer vessel, prior to filling the channel furnace. Un-dissolved alloy additions can contribute to the clogging if the temperature of the molten metal in the transfer vessel is not high enough.

In particular, as demand for ductile iron castings increases, larger quantities of ductile iron are being melted and held in channel furnaces or pressure pour vessels, so the incidence of clogging has become more frequent. When ductile iron is treated with magnesium and rare earth metals, the resultant by-products (MgO, MgS or CeO) are very insoluble. As more treated ductile returns are remelted, the concentration of MgO, MgS, and rare earth metallic oxides increases. MgO and CeO will tend to form complex oxide combinations with Al₂O₃ or SiO₂. These will have high melting temperatures, exceeding the normal operating temperatures of ductile-base and treated ductile iron.

It has been observed that a lower average molten metal temperature will tend to increase buildup, especially over periods of slower production rates. Typically, this will allow for low-temperature buildup compounds such as fayalite (FeO SiO₂) to form. Periodic inductor superheating along with an addition of proprietary fluxes such as Redux EF40L may prevent buildup. Maintaining a higher average melt temperature will also help to accelerate the flux reaction.

Simplified chemical methods to combat buildup in a channel furnace include the controlled introduction of heavily oxidized steel at minimum heel level and a subsequent heat-up to 2900°F have been reported to minimize buildup constituents. This procedure should be conducted over a 30 to 45 minute period. Filling the furnace to capacity after the oxidized steel addition and immediately de-slagging should follow this procedure. One adverse effect of this procedure is possible reaction of the oxides with the refractory.

The continuous addition of a mild flux such as Redux EF40L will minimize and in most cases, eliminate the formation of insoluble buildup along furnace walls. This flux will also tend to emulsify the buildup components and suspend them into the floating slag. Although care must be exercised for the amount of flux used and when it should be introduced, Redux EF40L fluxes are less reactive on almost all furnace refractories. Whatever slag or buildup has occurred when using Redux EF40L fluxes is easy to remove since it appears that the structure of the glass-like slag has been altered. Slag analysis history before and after the flux application is always recommended.

**THE PREVENTION OF INSOLUBLE BUILDUP**

Coreless Induction Furnaces: For coreless induction furnaces, the addition of ½ to 1½ pounds of Redux EF40L (see Figure 7), to every ton of furnace charge is beneficial in preventing buildup.
If Redux EF40L isn’t used on a continuous basis, then slag buildup will usually proceed more rapidly once the first stages of buildup appear on furnace refractories. For coreless and channel furnaces, the procedure described below should be followed to prevent buildup.

1) During the back-charging sequence for either 60 cycle or medium frequency coreless furnace, add ½ to 1½ pounds of Redux EF40L per ton of metallic charge entering the furnace. Redux should not be added to an empty furnace; there should always be a molten metal bath remaining inside the furnace.

2) If a second back-charging is used, an additional ½ to 1½ pounds of Redux EF40L per ton of metallic charge should be added during the charging.

3) Once all of the solid charge has been melted, the slag from the top of the molten metal bath must be removed. It is important to not leave any residual slag inside the furnace after fluxing.

4) A representative slag sample before and after the Redux EF40 flux additions should be taken in order to quantify changes in slag composition.

Channel Holders and Pressure Pour Furnaces: For channel holders or pressure pour furnaces, the addition of ½ to 1½ pounds of Redux EF40L per ton of molten iron to every transfer ladle will assist in keeping those ladles clean. Redux fluxing or cleansing of the metal in the ladle and removal of various slag phases from the metal helps to prevent downstream buildup in holders and pressure pours. Redux EF40L users have reported significantly reduced furnace maintenance as less slag or buildup adheres to furnace walls. Additionally, fluxing will restore full furnace volume and lead to increased production. More importantly, the reduced quantity of buildup is accompanied by a “softer, less glass-like buildup” that is much more easily scraped from the walls, without any subsequent damage to the refractory.

There are two alternate treatment methods being used to combat insoluble buildup in channel furnace/pressure pour uppercases, throat sections and inductor channels. These methods are described below.

Uppercase Slag Ring Buildup: To combat a slag shelf in the upper case, a continuous Redux EF40L flux addition of ½ to 1½ pounds per ton of molten iron should be added through the cover of the uppercase or through the receiver/fill spout. For satisfactory results, it is important that the fill spout refractory be composed of a 65% alumina-mullite or higher grade refractory. Redux EF40L must be added to a clean, molten surface. Redux EF40L will be ineffective if it remains on top of a slag crust. The quantity of the Redux EF40L flux will vary depending on the severity of the slag ring buildup in the uppercase. Flux addition rates as much as 4.0 pounds per ton of molten metal entering the furnace may be necessary along with timely slag removal as more slag will be created with the elimination of the slag ring or buildup.

The length of time required for such uppercase fluxing will be dependent on the severity of the slag shelf, but may last for 3 to 4 days before the slag shelf disappears. It is extremely important to deslag the furnace every day and remove all of the slag. Numerous foundries using Redux EF40L have reported that buildup removal after fluxing is much easier and faster. The time necessary to remove the stubborn buildup can be reduced by 75 to 90%. This is a direct result of altering the buildup structure and creating a softer buildup.

Figure 7: Redux EF40L shown in briquetted form (14 gram tablets).
In situations where there is a severe clogging of the inductor, two alternate methods are used to un-clog the throat section or inductor channels of a vertical channel holding/melting furnace as well as a pressure pouring channel furnace.

**Severe inductor throat buildup:** This procedure often requires 48 hours to implement. On the first day, the cover of the channel furnace or small “man-hole” cover of a pressure pour furnace is removed and slag is removed from the furnace. A clean molten metal surface is necessary for Redux EF40L to have maximum effect. Next, the molten iron level is lowered to a minimum heel, typically 4 to 15 tons depending on furnace size. An addition of 2 to pounds of Redux EF40L per ton is added to the molten heel after it has been heated to 2750°F (1510°C). The furnace cover should then be closed but not sealed and the inductor should be turned on full power for 3 to 4 hours, making sure that the molten iron temperature doesn’t exceed 2900°F (1600°C). It may be necessary to add another 2 to 3 pounds of Redux EF40 Flux per ton of molten iron, after 2 hours of superheating has occurred. The reactivity of the first addition may have been depleted after 2 hours. After the superheating period of the inductor has been completed, the molten iron should be cooled to normal holding temperatures. There will be more slag created which should be removed. However, depending on the foundry, it can be left inside for removal on the following day. A slag coagulant may be needed to assist in the removal of slag.

A second application of flux may be required and a similar procedure followed the next day. However, Redux EF40L additions are often reduced to 1 to 1½ pounds per ton using the same superheating schedule. It is again important to remove all of the slag, and a slag coagulant may be needed to assist in the removal.

In situations where the inductor cannot be revived because of severely clogged throats and/or inductor channels with the previously outlined procedure, then as a last alternative, plunging the flux into the throat with a specially designed plunging apparatus has restored such furnaces. An example of severe clogging which can lead to catastrophic inductor failure is shown in Figure 8.

**Figure 8: Illustration of totally clogged inductor channel taken from a 10-ton channel furnace.**

The economic impact of buildup: Foundry X melts ductile base iron in a 35-ton vertical channel furnace utilizing a twin-loop water-cooled inductor. After installing a new inductor at the end of 2005, Foundry X started to experience severe buildup in the throat/boat section of the inductor in January to mid-February 2006, just weeks after the inductor was replaced.

From past experience, Foundry X knew that the downtime associated with a clogged inductor would be very costly. Typical downtime when the throat/inductor clogs is typically five days. During this period, Foundry X has to completely drain the furnace, reams out the throat opening and does a “hot inductor change”. Foundry X estimated that the total costs in downtime and lost production stemming from the “hot change” is roughly $90,000.

Normally, the conductance ratio, (a measure of inductor electrical efficiency) at the beginning of a new refractory campaign is close to 100%. Typical conductance ratio history will see a gradual decline over a period of the first three to four weeks declining to 75 to 85% and will stabilize out while the power factor remains relatively unchanged. As shown in Figure 9, a continual decline in the conductance ratio to less than 75% occurred during the first three weeks followed by a further decline for the next five weeks. It should be noted that Foundry X has always experienced buildup in the throat/boat section of the inductors when melting ductile-base iron. Methods employed by Foundry X for buildup removal were periodic superheating on a low heel, the addition of silicon carbide followed by a periodic superheat, and “green poling.” However, none of these procedures seemed to improve the ever-worsening buildup problem. During the last few weeks of this 5-week period, periodic
superheating of a low molten metal heel was done to help battle the buildup. The situation continued to worsen as the conductance ratio dropped into the low 50% range.

In mid-February, the furnace readings were indicating that buildup was becoming a major problem of concern and attempts to reduce the heel and superheat the metal were initiated. As shown in Figure 9, these “superheating” campaigns were ineffective and the efficiency of the furnace continued in a downward spiral.

After carefully reviewing published information on the Ductile Iron Web Site shown below

http://www.ductile.org/magazine/2004_1/slag_buildup.htm

and as a last resort, Foundry X decided to embark upon a two-consecutive day fluxing procedure using Redux EF40L starting on March 5 and 6, since they felt they had nothing to lose. The flux would be added in a controlled amount to a minimum molten heel free of slag. For the procedure, the inductor was turned to high power to superheat the molten iron to between 2850 to 2900°F followed by the addition of 0.1% Redux EF40L (2 pounds per ton). The superheating was continued for 3 additional hours. The furnace was then cooled back to normal holding temperatures and the slag was removed. This procedure was repeated the following day whereupon it was observed that both conductance and power ratios significantly improved. Because of the very favorable results from the Redux EF40L campaign, a second fluxing campaign commenced the following weekend using the same 2 pounds per ton addition. Figure 9 shows a significant improvement in conductance ratio. Repeating the fluxing procedure at later days showed further improvement and the conductance ratio climbed back to the 90’s.

Figure 9:  Conductance and Power Ratio data collected from January 3, 2006 to early July 2006

Foundry X continues to utilize Redux EF40L in their operation and is considering a maintenance addition of Redux EF40L with each furnace charge to insure that future inductor clogging is eliminated. The nominal costs associated with an addition of Redux EF40L to each charge is offset by improved furnace efficiency and elimination of costly downtime from inductor clogging.

Ductile iron foundries utilizing channel or pressure pour furnaces or both, need to examine the cost benefits of adding fluxes with their charge as a preventative measure to guard against buildup. Foundries utilizing fluxes in their melting operation have found that the costs associated with adding flux to each charge is insignificant compared to downtime for replacement of a terminally clogged inductors or severe sidewall buildup. Many of these foundries have found that they have been able to greatly extend refractory life with the addition of fluxes to their charges. Lastly, concerns regarding the addition of ferrous fluxes to foundry melting and holding units have largely proved to be inaccurate regarding potential refractory attack.

Conclusions

Buildup is a complex molten metal issue plaguing many foundries today. In ductile iron foundries, buildup is responsible for the majority of downtime at the various pouring stations. Insoluble buildup can be a direct result of tramp oxides/sulfides within the charge. Other buildup components can be
traced back to residuals in alloy additions as well as chemical reactions against the refractories within the furnaces or transfer vessels. Yet other sources may be the result of an oxidizing atmosphere or residual coatings coming in with the charge.

This paper offers some important criteria for developing a plan of attack to combat the buildup where it has developed and how to correct it utilizing a preventative maintenance plan of adding a mild fluxing agent, Redux EF40L, to each charge. Methods that have been successfully employed to reduce buildup in channel furnace upper cases and methods to un-clog severely restricted inductor throats are discussed.

The paper also discusses the thermal conditions of the refractory walls that are prone to the buildup deposition.

References:


3. Stark, Ronald A., Private Communication

4. AFS 8D Channel Furnace Sub-committee and University of Rolla, Missouri 1990.

Acknowledgements: The authors would like to thank Mr. Pete Satre, Allied Mineral Products, Inc. as well as Mr. Greg Lemley and Brian Naro, ASI International, Ltd. for reviewing the original manuscript and their constructive comments.
MEETINGS - BUSINESS - PEOPLE

MEETINGS

The Ductile Iron Society 2007 Annual Meeting will be held on May 30 - June 1, 2007 at the Radisson Hotel and Conference Center in Green Bay, Wisconsin with a visit to Waupaca Foundry.

The Keith Millis Symposium will be held at the Orleans Hotel and Casino in Las Vegas, Nevada, October 20-23, 2008. The meeting will feature a full technical program.

BUSINESS

PEOPLE

Ashland Names Scott Hoertz to Head Casting Solutions Business

Dublin, Ohio - Scott Hoertz has been named vice president and general manager of Ashland's Casting Solutions business group. Hoertz, who was previously director of global marketing for Ashland Composite Polymers, will begin his new role immediately. The announcement was made by Hank Waters, president, Ashland Performance Materials and Ashland Water Technologies, divisions of Ashland Inc. (NYSE: ASH)