Carbidic Ductile Iron

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Why would anybody in their right mind want to add carbides to ductile iron?
Ductile Iron is a great engineering material:

- Great Strength
- Good Elongation
- Excellent Castability
- Excellent Machinability
- Heat Treatable
- Highly Adaptable
Unfortunately its wear properties ultimately needed some improvement!
Where to begin?

How do you make normal ductile iron into a highly abrasion resistant material?
Let's take a look at traditional abrasion resistant cast irons:

White Iron

Ni-Hard Iron
ASTM A532 15% Cr-Mo White Iron

Etched, 1000X

Precipitation Carbides

Chemical Specifications
C: 2.00 - 3.30%
Mn: 2.0 Max
Si: 1.5% Max
Ni: 2.5% Max
Cr: 14 - 18%
Mo: 3.0% Max
Cu: 1.2% Max
S: 0.06% Max

Complex Chromium Carbides

Martensitic Matrix after heat treatment.

Hardness Spec: 59 R_c Min.
ASTM A532 15% Cr-Mo White Iron

**Good Properties:**
1) Extremely Wear Resistant

**Bad Properties:**
1) Brittle
2) Difficult to cast in thin sections and complex shapes.
3) Shrink Prone.
4) Expensive alloys with limited availability and volatile pricing.
**ASTM A532 1D Ni-Hard Iron**

Chemical Specifications:
- **C**: 2.7 - 3.20%
- **Si**: 1.60 - 1.70%
- **Mn**: 0.50 - 0.70%
- **Cr**: 7.0 - 11.0%
- **Mo**: 0.00 - 1.50%
- **Ni**: 4.50 - 4.90%

Hardness Specification: 500 BHN Min.
ASTM A532 1D Ni-Hard Iron

Good Properties:
1) Wear Resistant
2) Impact Resistant

Bad Properties:
1) Brittle
2) Difficult to cast in thin sections and complex shapes.
3) Shrink Prone
4) Expensive Alloys with limited availability and volatile pricing.
What do wear resistant irons have that traditional ductile iron doesn’t?
Carbides!
What is Carbidic Ductile Iron?

1) Carbidic Ductile Iron has no ASTM designation.

2) A normal carbide specification is 10 - 30 % of the matrix.

3) Nodularity is a minimum of 70%. This specification is loose due to the lack of nucleation needed to stabilize carbides, and carbide formation causing poor nodule formation.

4) The grades that Hiler Industries produces are austempered to increase matrix hardness and the toughness of the metal. Final Hardness is 444-555 BHN. This produces a metal with similar physical properties to Ni-Hard alloys.
So how do we get carbides into the iron when we have spent our whole career getting them out?

Happy Metallurgist

Unhappy Metallurgist
Thought process behind making Carbidic Ductile Iron:

1) This iron is basically a compromise between making a Ductile Iron Alloy and a “White Iron” or Ni-hard Alloy.

2) My thought was that you have to make normal Ductile Iron, but modify your process to stabilize the desired % carbides without completely sacrificing nodule formation and nodule count.

3) The starting point, in the beginning, was a normal ductile base iron. The charge materials and chemistry were not changed.

4) Magnesium treatment method does not change, because good nodularity is required to give the metal impact toughness.
Thought process behind making Carbidic Ductile Iron:

5) Carbide stabilizing alloys are added.

6) Inoculation is reduced to maximize carbide stabilization and while providing some potential for nodule formation.
Carbide Stabilizing Alloys in Carbidic Ductile Iron

Elements:

Chromium
Molybdenum
Manganese
Copper (Minor Effect)

Use the most cost effective carbide stabilizers.

Do not overcomplicate the interpretation of the results by using too many alloys. It is best to simplify alloy additions.

The level of carbide stabilizing alloy will be proportional to the % Carbides formed.

The level of carbide stabilizer may have to be increased for thicker sectioned castings.
Inoculation of Carbidic Ductile Iron

The addition of carbide stabilizers will cause thin sections to become almost completely carbidic.

Inoculation is reduced to maximize carbide stabilization.

A small inoculation must be added to maintain graphite nucleation potential in the thin sections.

The elimination of inoculation causes carbidic ductile iron to be extremely brittle in sections under 1/4 inch thickness due to a combination of poor nodule count and high % carbide formation.

Inoculation promotes graphite sphere roundness in carbidic ductile iron.

Low levels of inoculation promotes growth of nodules in the thin sections to prevent stress cracking that can occur during austempering heat treatment if the nodule count is insufficient.
Graphite Structure of Carbidic Ductile Iron

Unetched, 100X Magnification

Nodularity: 90%
NC: 100 Nod/mm²
% Graphite: 6%

Fully spherical graphite formation is difficult to achieve in carbidic ductile iron. This is not due to the effects of magnesium treatment.
Etching the sample reveals that particles of carbide intersect the graphite spheres. This gives the appearance that the graphite spheres are deteriorated in an unetched view.
Graphite Structure of Carbidic Ductile Iron

% Nodularity less than 90% is common due to carbide formation impairing the graphite nucleation. The carbide formation cuts into the graphite nodules as they are nucleating causing graphite that appears to be deteriorating.

% Nodularity is a secondary criteria. The customer specifications often stress wear properties and carbide formation over % Nodularity as being a passing criteria.
Carbide is stabilized through the addition of carbide stabilizers combined with a low % inoculation.

Note: Complex intercellular carbide formation.
As-Cast Matrix Microstructure of Carbidic Ductile Iron

Etched, 500X

The use of carbide stabilizers causes the stabilization of fine pearlite lamella in the matrix.

It is common in Carbidic Ductile Iron for carbide formations to intersect graphite nodules, and to see intercellular carbide surrounding graphite nodules.
The use of carbide stabilizers causes the stabilization of fine pearlite lamella in the matrix.

Matrix: Fine sized pearlite with minimal stabilized ferrite.

Graphite Nodule intersected Complex Intercellular Carbides during nucleation and growth.
Thick vs. Thin Sections in Carbidic Ductile Iron

Carbide Formation and Nodule Formation vary according to section thickness.

The thicker section in the photo is the critical wear resistant section of the part.
Thick vs. Thin Sections in Carbidic Ductile Iron: Graphite Nucleation

There is higher Nodule Count in the thin section.

Both contained 6% Graphite

Thick: Unetched, 100X

Thin: Unetched, 100X

90% Nodularity
100 Nodules/mm²

93% Nodularity
175 Nodules/mm²
Thick vs. Thin Sections in Carbidic Ductile Iron: Carbide Formation

Thinner sections have higher % Carbide formation.

Both contained 6% Graphite

Thick: Etched, 200X  
25% Carbide Formation

Thin: Etched, 200X  
40% Carbide Formation
Thin Sections in Carbidic Ductile Iron

Section thickness affects the formation of iron carbide. There is always an area in these castings where the % Carbides in the matrix has to be maintained to give the material wear resistant properties.

Many parts that we cast have thin sections, <1/4 inch thick, that are not critical areas for wear resistance. Thin sections will have greater than the maximum allowed % carbides.

Graphite nucleation is promoted in thin sections by adding a small post inoculant addition.

Increasing inoculation (% Silicon) will decrease the amount of carbides throughout the casting.

Inoculate enough to promote some graphite nucleation in the thin sections, but not enough to decrease the carbides in the critical sections to the point where the wear resistant properties are compromised.
Cracking in Carbidic Ductile Iron Due to Lack of Inoculation

The cracks in these castings were the result of early experimentation using no post inoculation combined with a carbide stabilizing alloy to form carbides during solidification.
Cracking in Carbidic Ductile Iron Due to Lack of Inoculation

Thin Section Cracking

Less Than 1/4 inch Thick Section

Oxidized Fracture Surface

Paint

Transition between thick and thin section.

The crack occurred during austempering heat treatment.
Cracking in Carbidic Ductile Iron Due to Lack of Inoculation

Unetched, 100X

Graphite: 80% Nodularity, 70 Nodules/mm²

Etched, 100X

Matrix: 40% Carbides, Austempered

Poor Nodule Shape and Count combined with High % Carbides.

Nodule Count and Shape is better in casting thin sections that receive a small post inoculation.
Cracking in Carbidic Ductile Iron Due to Lack of Inoculation

Stress Riser Cracking

The crack occurred during austempering heat treatment.

Edge transition between two thick sections at a cast corner.

The cracks in these castings were the result of early experimentation using no post inoculation combined with a carbide stabilizing alloy to form carbides during solidification.
Cracking in Carbidic Ductile Iron Due to Lack of Inoculation

Note the directional carbide growth in the uninoculated casting.

Directional growth of the carbide in uninoculated carbidic ductile iron makes the material more prone to brittle fracture.

Small inoculant additions help to produce more random directional carbide growth. This makes the material tougher and reduces stress cracking.
Wear Properties

Example of a casting microstructure displaying poor wear properties.

Etched, 200X

10% Carbides in a fully austempered matrix.

Poor carbide formation decreases the wear resistance of the casting.

Low carbide stabilizer additions and high % Silicon cause poor carbide formation.

Nodule shape is much better with lower % carbide formation.
Wear Properties

Example of a casting microstructure displaying poor wear properties.

Graphite Structure

**Unetched, 100X**

- 95% Nodularity
- NC: 100 Nodules/mm²

Nodule shape improves with lower % carbide formation.

Decreased Resistance to wear.
Matrix Microstructure of Carbidic Austempered Ductile Iron

Austempering is the most common means of creating a hardened, wear resistant matrix microstructure allowing Carbidic Ductile Iron to compete with Ni Hard Irons.

Carbidic Austempered Ductile Iron exceeds Ni-Hard in applications where both impact resistance and wear resistance are desired properties.
Microstructure of Carbidic Austempered Ductile Iron (CADI)

Etched, 1000X

The final material is a Carbidic Ductile Iron with Modified ASTM A897, Grade 230-185-01 Austemper Heat Treatment.

BHN Range: 444-555

Graphite Nodule

Carbide

Acicular Ferrite in a matrix of Austenite.
Points to consider concerning austempering:

The iron will grow during austempering. Stress cracking can occur in uninoculated, over-carbidic iron during austempering heat treatment in both thin sections and at sharp corners where changes in plane geometry cause a stress riser to occur.

Carbides may dissolve into solid solution during the austenitizing step of the austempering heat treatment. Take this into account when developing your process to produce Carbidic Ductile Iron. Minimal carbide will cause premature wear of the parts in field service.
Conclusions:

Normal ductile iron can be easily modified to produce wear resistant Austempered Carbidic Ductile Iron that can compete with physical properties of the Ni-Hard class of alloys.

The wear resistant properties are achieved by producing as-cast carbides within the matrix microstructure by carbide stabilizing alloy additions combined with reduced inoculation. The matrix is further modified through an austemper heat treatment. This hardens the matrix and makes a tougher, more impact resistant.

Carbidic Iron is lower cost to produce than Ni-Hard and is not subject to the volatility of alloy prices.
Thank You for your attention!

Any Questions?