Although Chemical Composition is the primary metallurgical characteristic defined by ASTM A518 and related Standards, Microstructure is also a very important determinant of anode performance. Microstructure is not directly mentioned in Standards A518 or BS1591, whereas heat treatment, which affects microstructure is.

Microstructure: The following comments on microstructure were written by an expert metallurgist, R.S. Charlton, P. Eng. of B. H. Levelton & Associates, Richmond, BC Canada, [L49]

As for most, if not all alloys, the corrosion resistance of high silicon cast iron is affected by a number of metallurgical and microstructural factors, including:

- *Shape or form of graphite*
- *Segregation of alloys*
- *Secondary phases (silicides, carbides)*
- *Grain size*

Corrosion Resistance of High Silicon Cast Iron is attributed to the development of a thin passive barrier film of hydrated oxides of silicon on the metal surface. Any flaws in the barrier, which develop over time, reduce its effectiveness. The passive film will bridge fine spheroidal grains more readily than coarse flakes.

It is well documented that a uniform metallurgical structure has better corrosion resistance than non-uniform structure. Segregation promotes both non-uniform film and second phases in the base material which underlies the film.

The grain structure and graphite form in cast irons affect mechanical properties. Flake graphite is a severe stress riser. Fine spheroidal graphite is not. Fine grains, lack of segregation, and absence of secondary phases, reduce opportunities for localized yielding and stress raising.

A fine-grained high silicon cast iron with spheroidal graphite will have better corrosion resistance and mechanical properties than cast iron of equal chemistry with flake graphite.

(end of quotation from Charlton).

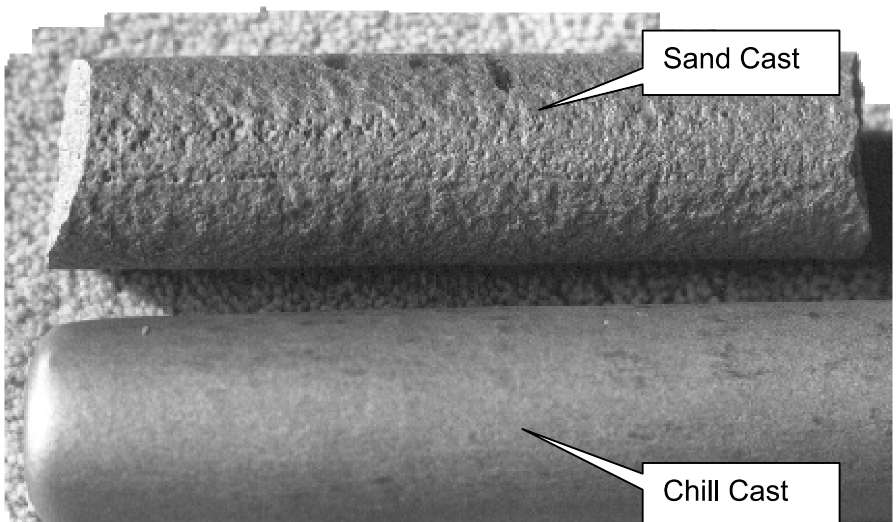
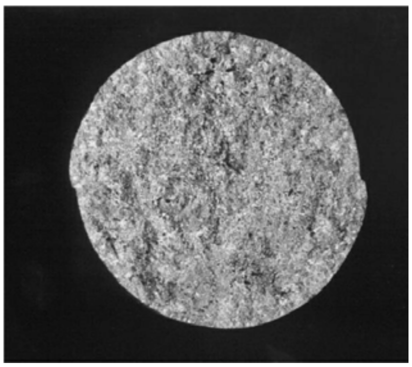


Figure 1: Evidence of the influence of microstructure: Corroded surfaces of sand cast and chill cast high silicon cast iron anodes after accelerated consumption testing.

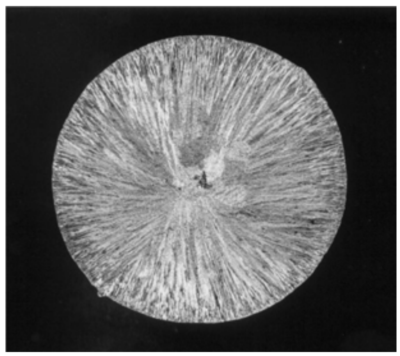
Metallic Structure influences Corrosion Resistance of High Silicon Cast Iron Electrodes:

In Figure 1, the Chill Cast electrode is smooth after accelerated testing, whereas the Sand Cast electrode is severely pitted. Testing in chloride and sulphate electrolytes showed that consumption of sand-cast material exceeded the consumption of chill cast material by 10 to 20%. [L13A]. The electrodes shown in Figure 1 were subjected to the identical test conditions, and had virtually the same chemistry. But their metallurgical structures are significantly different, as represented in Figures 2a and 2b

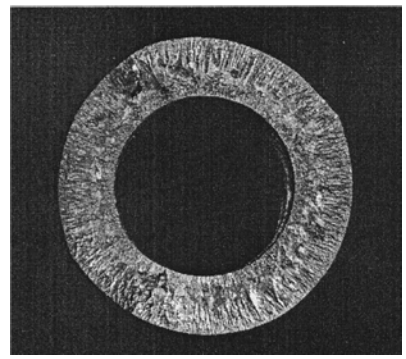
Figure 2: Metal Structure Differences, Sand and Chill Cast Sections



2a Stick Sand Cast



2b Stick Chill Cast



2c Tubular Chill Cast

Note: The three sections shown have not been treated after fracture. Features are visible to the eye.

In Figure 2c it can be seen that Chill Cast Tubes present a columnar grain structure similar to that shown in Figure 2b for a Chill Cast Stick. The macrostructure of a Centrifugally Cast Tube (not shown) often appears (at first glance) to be relatively similar to that of a Chill Cast Tube. But as will be demonstrated, as amplified by microscope, microstructures may present significant differences between Chill and Centrifugal castings. These differences affect performance. There are *very good* microstructures and *not as good* microstructures, and metallurgists have the ability to distinguish one from the other.

Optimizing Metallographic Structure for HSCI Electrodes

Sand cast electrodes are made by pouring molten iron into molds made from sand and resin. Sand is an insulator and the resin burns. Slow cooling of cast irons creates relatively large flake graphite, large grains, and alloy segregation. In contrast, chill cast electrodes are poured in metal molds that extract heat rapidly from the metal. Fast cooling promotes rapid solidification, fine grains and graphite structure, and absence of alloy segregation.

Occasionally requests are received for objective evidence that the metallurgy of static *Chill Cast* High Silicon Cast Iron electrodes is equal to or better than that of centrifugally cast electrodes.

In response, investigations and reports were commissioned from Levelton Engineering Ltd [L10, L11].

Levelton's metallographic evaluation was applied to both solid stick and tubular electrodes differentiated by the primary casting process used for their manufacture: Sand Casting, Centrifugal Casting and Chill Casting. The evaluations were based upon:

- Analysis of micro structural characteristics of specimens from sample electrodes.
- Development and application of a *Rating System* for metallurgical attributes, established by Bob Charlton, P. Eng. as indicative of relative performance, using a scale of one to five, with one being least favourable and five most favourable.

  Appendix A presents Levelton's Evaluation Criteria, and the Tabulated Ratings that relate.

Executive Summary: Metallographic Comparison Findings

Based on detailed examination of the range of specimens available, and quality rating according to the criteria established, Levelton presented average **Metallographic Rating Values which are summarized as follows:**

Table 1:	**Stick (Solid Rod) Anodes**		**Tubular Anodes**	
Manufacture Process	Sand Cast by Manufacturer "X"	**Anotec *Chill Cast***	Centrifugally Cast by Manufacturer "Y"	**Anotec *Chill Cast***
Metallographic Rating Average Values	2.2	**4.0**	3.1	**3.6**

Based upon anecdotal reports, and customer complaint records, these Metallographic Ratings appear to correlate well with experience from the field, as well as from evaluation testing.

Attached: "Appendix A: Metallographic Evaluation: Criteria, and Ratings"

5.0 EVALUATION CRITERIA

From Levelton Reports January 2002 (L50) and July 2002 (L51)

The metallurgical attributes selected for the evaluation criteria of the five FeSi electrode samples were as follows: grain size, grain orientation, homogeneity, carbon form and volumetric flaws (shrinkage/porosity). Opinion will always be a component of any rating system but the following definitions and discussion might be an aid, especially for the non-metallurgist:

Grain size

- Small grain size improves mechanical properties, corrosion resistance and consumption rate in impressed current cathodic protection service.
- Perspective on cast structures is necessary for the context of this assessment; smaller grains tend to a more uniform structure and therefore are usually more desirable in developing the protective hydrated silicon barrier layer film on FeSi electrodes. Note that for some metal alloys, improved corrosion resistance is exhibited by larger grain size.

Grain orientation

- Chilled castings will exhibit a macroscopic columnar grain structure of microscopically visible primary dendrite arms oriented perpendicular to the heat extraction surface.
- A coarse, directional structure could be argued to be one in which preferred corridors existed along which wastage can proceed, but a fine homogeneous structure should develop the desirable uniform hydrated silicon film on the electrode surface.

Homogeneity

- Structures that are more uniform throughout are more desirable.
- Grossly different adjacent structures present themselves as localized differences in potential and can drive corrosion.
- Refer also to the comments above regarding grain size and uniformity.

Carbon form

- A structure with spheroidized carbon results in superior mechanical and corrosion resistant properties in comparison to flake structures.
- Flake-type graphite is characteristic of grey iron and consistent with brittle behaviour.

Volumetric Flaws

- Shrinkage and porosity are characteristic casting flaws and are obvious mechanical deficiencies.
- Volumetric flaws present themselves as isolated or inter-connected excursions into the matrix and likely serve to interrupt the desirable hydrated silicon film complexes that develop on the FeSi electrode surface.
- Volumetric flaws are localized deviations that likely relate to localized corrosion and non-uniform consumption.

7.0 Rating of Microstructural Findings

From Levelton Reports January 2002 (L50) and July 2002 (L51)

The micro structural characteristics of the five FeSi anode samples were assessed using a scale of one to five, one being the least favourable, five the most desirable. A simple average was tabulated for each anode specimen type to permit comparison of the structure for the useful thickness of the anode (see Table 3). We eliminated the intermetallic phase from the rating criteria because the phase form is not easily defined with optical microscopy, and thus not considered rigorous.

Anode Type	**Stick**			**Tube**			**Tube**			**Stick**		
Sample ID	B			E			C			F		
Description	**Chill Cast; Cr**			**Centrifugal; Cr**			**Chill Cast; Cr**			**Sand Cast; Cr**		
Depth (in.)	0.060	0.125	0.250	0.060	0.125	0.250	0.060	0.125	0.250	0.060	0.125	0.250
Grain Size	4.5	3.5	4.0	2.5	2.5	2.0	5.0	4.0	3.0	1.0	2.0	3.0
Criteria												
Grain Orientation	4.0	4.0	4.0	4.0	3.5	3.0	3.0	3.0	3.0	2.0	3.0	3.5
Homogeneity	4.0	3.5	3.0	3.5	3.0	2.0	4.0	4.0	3.0	2.0	2.0	3.0
Carbon Form	5.0	5.0	4.0	3.0	3.0	1.0	5.0	5.0	2.0	1.0	1.0	2.5
Porosity Shrinkage	3.5	4.0	4.0	5.0	4.0	4.0	3.5	4.0	2.5	2.0	2.5	2.5
Rating at Depth, Average	4.2	4.0	3.8	3.6	3.2	2.4	4.1	4.0	2.7	1.6	2.1	2.9
Overall Average	**4.0**			**3.1**			**3.6**			**2.2**		

Refer to Page 3 Photographs of representative microstructures for the specimens reported.

REPRESENTATIVE PHOTOS of MICROSTRUCTURES

Chill Cast Stick
Rating 4.0

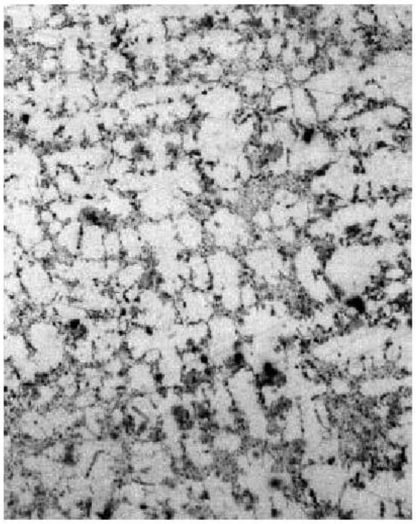


Figure 6
Sample B

- Free graphite present as very fine globules in interdendritic phase.
- Isolated graphite present as larger nodules.

Chill Cast Tube
Rating 3.6

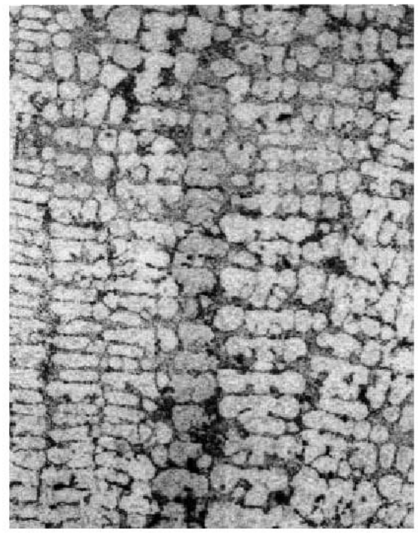


Figure 7
Sample C

- Discrete graphite globules partitioned between dendrite arms.

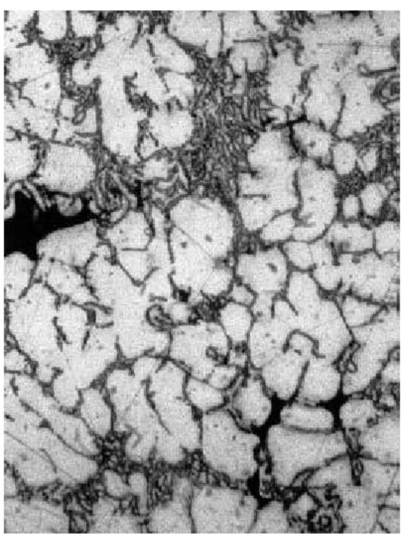


Figure 9
Sample E

- Comparatively coarse random grain structure.
- Interdendritic segregation of second phase.

Figure 10
Sample F

- Structure appears coarse.
- Coarse, flake graphite, randomly oriented.