2003 Keith Millis Symposium on Ductile Cast Iron

# The Current State of Worldwide Standards for Ductile Iron

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## ABSTRACT

Technical Standards are essential for the expanded use of any engineering material. The Society of Automotive Engineers (SAE) Division 9 Iron and Steel Castings Standards Committee has been reworking existing, (and issuing new), standards for automotive iron and steel castings. This paper will review the status of the SAE standards for Ductile Iron, Austempered Ductile Iron (ADI), Compacted Graphite Iron (CGI) and high Silicon-Molybdenum (Si-Mo) Ductile Iron. The SAE Standards, (and draft standards), will be critically compared to those for ASTM and ISO. Salient differences in the standards will be discussed and implications to design engineers will be addressed. Comparisons to other, competitive materials (and their standards) will be made.

## INTRODUCTION AND BACKGROUND

In the automotive design community, SAE standards are used to direct and inform the design engineer about the capabilities of various materials. The SAE Division 9 Iron and Steel Castings Standards committee is charged with the task of reviewing, updating and issuing appropriate standards for the use of ferrous castings in automotive applications. By comparing these standards to other existing (and proposed) world standards, a more complete picture of the materials can be obtained.

This work was undertaken to critically review those SAE standards and compare them to other standards. The salient elements (and differences) in the standards will be reviewed. New, and unique elements of the various procedures will be highlighted by the authors.

The SAE Division 9 ISCSC has responsibility for all automotive ferrous casting standards. We have not included discussions of gray iron and steel castings standards in this work. Originally, knowing that this work was being prepared for the 2003 Keith D. Millis Symposium, a symposium focused on ductile iron, CG Iron had NOT been included. Upon reconsideration, the authors included CG Iron because the producers of ductile iron are, (in many cases), also the producers of CG Iron. Furthermore, new developments in the “shape control” of graphite in cast irons are generic to the production of both ductile iron and CG iron and therefore relevant to the ductile iron user and producer communities.

## DISSCUSSION(S)

Following, by material type, are the various discussions of the ISO, SAE and ASTM standards and draft standards.

## DUCTILE IRON

Changes are being proposed in the newest SAE J434 revision (JAN03) that are aimed at creating a smooth transition between ductile iron grades. New grades are also being included that have not been available in previous Standard publications to aid in this iron-grade continuum.

Iron grade mechanical properties are being identified primarily in MPa, with the secondary designation in ksi. In addition, the casting hardness range is primarily reported in Brinell Hardness (HBW), although the pascal range is also listed.

**Table 1** shows the comparisons between the SAE JAN03 (current draft), SAE JUN84 revision, and the ASTM A536-84 standard. **Table 2** gives specific properties for each of the iron grades as identified in J434 JAN03 draft:

**Table 1 The Comparison of the recent SAE standards with the comparable ASTM standard.**

| SAE J434 JAN03 (Draft 2003) | SAE J434 JUN86 (Current Issue) | ASTM A536-84 |
|---|---|---|
| D400 | D4018 | 60-40-18 |
| D450 | D4512 | 65-45-12 |
| D500 (1) | - | - |
| D550 (1) | D5506 | 80-55-06 |
| D700 (2) | D7003 | 100-70-03 |
| D800 (3) | - | - |

(1) Grades D500 and D550 are new grades that bridge the gap between D450 and D700 for maintaining an iron grade continuum

(2) The yield strength was reduced to 65 ksi. from 70 ksi.

(3) D800 is a new grade which accommodates the 70 ksi yield previously designated in the D7003 grade. This grade is pearlitic or tempered martensite.

**Table 2 The specific properties outlined in SAE J434 draft standard of January 2003.**

| SAE J434 Grade (Tensile Strength MPa / ksi) | Hardness Range (HBW) | Yield Strength (MPa / ksi) | %E |
|---|---|---|---|
| D400 / 58 | 143-170 (4) | 275 / 40 | 18 |
| D450 / 65 | 156-217 | 310 / 45 | 12 |
| D500 / 73 (1) | 187-229 | 345 / 50 | 6 |
| D550 / 80 (1) | 217-269 | 380 / 55 | 4 |
| D700 / 102 | 241-302 | 450 / 65 (2) | 3 |
| D800 / 116 (3) | 255-311 | 480 / 70 | 2 |

(4) The lower limit of 143 HBW is new to this draft.

Yield strength estimations are also included in this new draft for various section thickness' as shown in **Table 3.**

Relative to iron hardness testing, the 10mm ball is formally designated as tungsten (HBW), where previously steel (HB) was accepted.

An Appendix has been added to aid the designer or engineer by giving additional information such as chemistry composition, microstructure, mechanical properties, Charpy impact data, and typical iron grade applications.

Two changes have been made with chemistry designations as noted in **Table 4**:

**Table 3- The typical variation in yield strength as a function of section thickness.**

| SAE J434 Grade (Tensile Strength MPa / ksi) | Relative Wall Thickness | Yield Strength (MPa) |
|---|---|---|
| D400 / 58 | 20 mm or less<br>21 mm - 40 mm<br>41 mm-60 mm | 275<br>260<br>250 |
| D450 / 65 | 20 mm or less<br>21 mm - 40 mm<br>41 mm-60 mm | 310<br>295<br>285 |
| D500 / 73 | 20 mm or less<br>21 mm - 40 mm<br>41 mm-60 mm | 345<br>330<br>320 |
| D550 / 80 | 20 mm or less<br>21 mm – 40 mm<br>41 mm-60 mm | 380<br>365<br>350 |
| D700 / 102 | 20 mm or less<br>21 mm - 40 mm<br>41 mm-60 mm | 450<br>435<br>425 |
| D800 / 116 | 20 mm or less<br>21 mm - 40 mm<br>41 mm-60 mm | 480<br>465<br>455 |

**Table 4- Changes in chemistry in the new draft standard vs. the June 1986 version.**

| Chemical Element | SAE J434 JAN03 (draft) | SAE J434 JUN86 (Current) |
|---|---|---|
| Phosphorus | 0.050% max | 0.015-0.100% |
| Magnesium | 0.025-0.060% | - |

## AUSTEMPERED DUCTILE IRON (ADI)

The commercial production of ADI began in 1972. For several years, ADI production grew in spite of the absence of coordinated standards for its production. The ASTM 897M-90 standard in 1990 was the first internationally recognized standard for ADI. (That standard has since been revised in 2002). SAE J2477 has been approved and is in publication in 2003. As of this writing, ISO/CD 17804 is in final draft review.

**Table 5** compares the tensile strength-yield strength-elongation designations of the various ISO, SAE and ASTM grades. **Table 6** compares the typical and specified Brinell hardness ranges for those same grades. As one can see, in the middle grades, (grades 1050, 1200 and 1400), there is considerable agreement. However, some discussion is necessary regarding the ISO grade 800 and the SAE and ASTM grade 1600. Furthermore, there are specifics of each of these standards that make them unique and merit review.

**Table 5- A comparison of the ISO, SAE and ASTM standards for ADI. (Convention used in table: Tensile Strength (MPa)-Yield Strength (MPa)-%Elongation).**

| ISO/CD 17804 (Draft 2002)* | SAE J2477 Issued 2003 | ASTM A897/A 897M (2002) |
|---|---|---|
| **800-500-10** | | |
| | | **850-550-10** |
| **900-600-08** | **900-650-09** | |
| **1050-700-06** | **1050-750-07** | **1050-700-07** |
| **1200-850-03** | **1200-850-04** | **1200-850-04** |
| **1400-1100-01** | **1400-1100-02** | **1400-1100-01** |
| | **1600-1300-01** | **1600-1300-00** |

*ISO designation for sections less than 30mm.

**Table 6- A comparison of the Brinell hardness ranges for the various ADI grades.**

| Grade (TS MPa) | ISO/CD 17804 (Draft 2002)* | SAE J2477 Issued 2003** | ASTM A897/A 897M (2002)* |
|---|---|---|---|
| **800** | **250-310** | | |
| **850** | | | **269-321** |
| **900** | **280-340** | **269-341** | |
| **1050** | **320-380** | **302-375** | **302-363** |
| **1200** | **340-420** | **341-444** | **341-444** |
| **1400** | **380-480** | **388-477** | **388-477** |
| **1600** | | **402-512** | **444-512** |

*Typical (not specified) **Specified

## ISO/CD 17804 (draft 2002)

As of this writing, this rather lengthy document is in the latter stages of revision before release. This standard specifies five distinct grades of ADI by tensile strength and elongation, (i.e. grade 900-8). It also specifies Brinell hardness for each grade.

The ISO draft standard, like the ASTM standard, does not specify hardness. It lists the typical properties in the annex.

One differentiating feature of the ISO draft standard is their use of an elongation gage length of 5 x d (versus the SAE and ASTM use of a 4 x d gage length). The authors of the ISO draft address that difference with a table in the standard's annex that compares a 4 x d elongation with that referenced in the standard.

Another feature of the ISO draft standard is its approach to minimum property requirements for various section sizes (or modulii). The SAE and ASTM standards are essentially silent on the issue of section size but the ISO draft standard outlines different minimums for section modulii up to 30mm, from 30-60mm and above 60mm. (The SAE standard only applies to castings with section sizes up to 65mm). The gradation of minimum properties over that range of sections in the ISO draft standard is significant. For example, Grade 800-10 lists the following minimums by section:

| Section(mm) | Tensile(MPa) | Yield(MPa) | Elong% |
|---|---|---|---|
| t<30 | 800 | 500 | 10 |
| 30<t<60 | 750 | 500 | 6 |
| 60<t<100 | 720 | 500 | 5 |

The most salient difference between the ISO draft standard and the SAE and ASTM standards is the inclusion of a Grade 800. Grade 800 ADI has a metal matrix structure of pro-eutectoid ferrite and Ausferrite and is of lower (typical) hardness than the SAE and ASTM low hardness grades. Grade 800 is reported to have better machinability than the conventional, lower-strength grades of ADI. Grade 800 has not been a significant factor in North American ADI development, however it has been central to ADI growth in Europe where the vast majority of components have been machined complete after Austempering.

## SAE J2477 (released 2003)

The SAE J2477 standard was essentially based on the ASTM standard with some technical improvements based on commercial capability. It also includes an extensive appendix that outlines the critical characteristics for the production of ADI, a list of typical properties (not specified) including fatigue coefficients and exponents, and descriptions of the microstructures.

The salient differences between SAE J2477 and the ASTM standard are the upward adjustment of minimums in tensile strength and/or yield strength and/or elongation in grades 900, 1050,1400 and 1600. These upgrades are based on commercial data and better reflect industrial capability.

SAE J2477 specifies hardness as a requirement and the ranges have been adjusted (relative to the ASTM standard) to reflect the statistical capabilities of commercial producers.

SAE J2477 also specifies un-notched Charpy impact and minimum Young's Modulus. There is a great deal of discussion regarding Young's Modulus. The 148 GPa minimum modulus specified in this standard is reported by most producers to be low, however, the SAE committee felt strongly that Young's Modulus be included because it is a critical characteristic used by design engineers in their finite element modeling.

An effort is now underway to include Young's Modulus and fatigue coefficients and exponents for ADI (and various other grades of ductile iron), in SAE J1099, the fatigue design standard.

### ASTM A897/A 897M - 02

This is a 2002 revision of the original documents (A897 and A897M) that were released in 1990. This document combines those in-lb and metric standards in to one document.

In this standard, tensile strength, yield strength, elongation and impact strength are specified and Brinell hardness is "typical" (not specified).

This document outlines 5 grades designated by tensile strength, yield strength and elongation, (i.e. 850-550-10 and 1400-1100-1).

## COMPACTED GRAPHITE IRON (CGI)

The roots of Compacted Graphite Iron go back to the early days of ductile iron as evidenced by the CGI patents filed and received by Millis, Gagnebin and Pilling in 1948 and 1949. With improved mechanical properties relative to gray iron and improved castability, machinability, and thermal conductivity relative to ductile iron, CGI is ideally suited to components with simultaneous mechanical and thermal loading such as cylinder blocks and heads.

Today, with reliable production process control technology now available, specification of CGI in automotive applications is beginning to grow.

To nurture that growth, a new material standard for Automotive Compacted Graphite Iron (CGI) Castings has been established by the SAE. The standard provides for five grades of conventional CGI, with graphite morphology limited to 20% nodularity, and two grades designated 'HN' permitting nodularity up to 50%. The grades are further distinguished by their minimum mechanical properties, including ultimate tensile strength, 0.2% yield strength and elongation. Appendices to the SAE J1887 standard provide additional information on compacted graphite iron and visual reference micrographs for percent nodularity determination.

Demand for greater performance, particularly in diesel engine applications, has prompted engine designers to seek stronger materials to achieve durability and performance targets without increasing the size or weight of their engines. With at least a 75% increase in ultimate tensile strength, 40% increase in elastic modulus and approximately double the fatigue strength of typical gray cast iron, Compacted Graphite Iron is ideally suited to meet the current and future needs of the designers. SAE Standard J1887 – Automotive Compacted Graphite Iron Castings was established to assist the design engineer in the specification of CGI material properties and microstructure for optimal performance.

### SAE J1887 Overview

As shown in **Figure 1,** the graphite particles in Compacted Graphite Iron appear as individual 'worm-like' or vermicular particles when viewed in the two-dimensional plane-of-polish. The particles are elogated and randomly oriented as in gray iron, however they are shorter and thicker with an irregular surface and rounded edges. These graphite attributes are the source of the improved mechanical properties relative to gray iron.

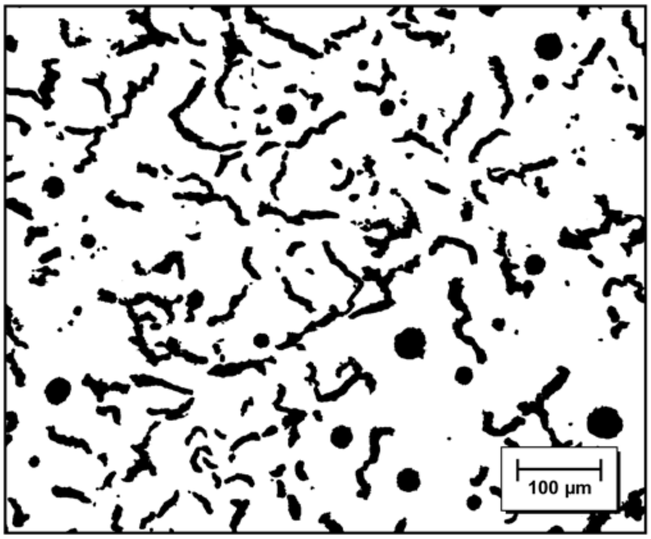

**Figure 1 : CGI microstructure containing 10% nodularity.**

Compacted Graphite Iron invariably includes some nodular (spheroidal) shaped graphite particles. The amount of nodular graphite present is the first measure by which Compacted Graphite Irons are assessed. As the nodularity increases, the strength and stiffness also increase but only at the expense of castability, machinability and thermal conductivity. The percent nodularity specified should therefore consider both the production and performance requirements of the product. As shown in **Table 7**, the SAE standard includes five grades of conventional, 0-20% nodularity CGI. Within this nodularity range an optimal balance between mechanical and physical properties can be expected. The standard also includes two grades in which the nodularity range is extended to 20-50%. The 'High Nodularity' grades (denoted by 'HN' in the Standard) were established for applications with less demanding machinability and/or castability requirements such as exhaust manifolds and bedplate castings.

Flake graphite particles are not permitted in CGI, as the presense of even a small amount of flake graphite results in an immediate 20-30% decrease in the strength and stiffness of the iron. In addition to the graphite structure, SAE J1887 grades are defined by their mechanical properties. Designated by the minimum ultimate tensile strength in Mpa, the conventional CGI grades are C250, C300, C350, C400, C450 and the high nodularity grades are C300HN and C500HN. The minimum requirements for 0.2% yield strength and elongation are also defined for each grade in the standard. As shown in **Figure 2.** the tensile and yield strengths of CGI are directly proportional to the amount of pearlite in the microstructure. Pearlitic structures are readily obtained in CGI by alloying with conventional pearlite stabilizers such as copper and tin.

Appendix A to the standard contains additional information on compacted graphite iron that is not a part of the standard requirements. This material description includes information on production methods, material properties, factors influencing the material properties and machinabiltiy. Appendix B to the standard contains a visual reference of CGI microstructures containing from 0% to 50% nodularity.

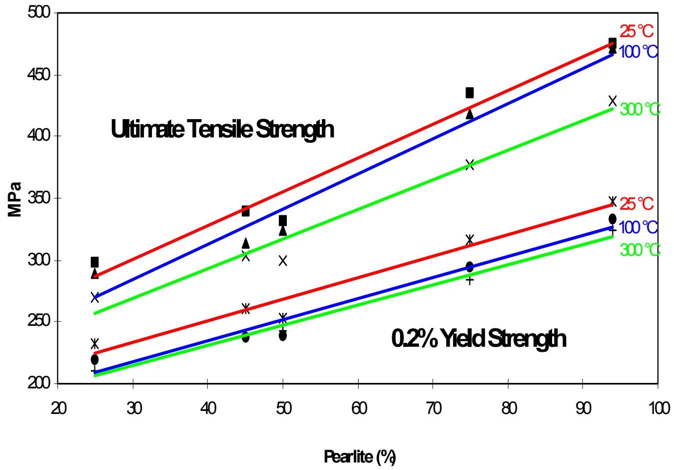

**Figure 2 : Utimate tensile strength and 0.2% yield strength of 0-10% nodularity CGI as a function of pearlite content and temperature.**

## HIGH SILICON MOLYBDENUM (Si-Mo) DUCTILE IRON

This new SAE standard (J2582) covers the hardness, chemical analysis and microstructural requirements for ductile iron castings intended for high temperature service in automotive and allied industries. Commonly known as SiMo ductile iron, typical applications are in piston-engine exhaust manifolds and turbocharger parts.

Castings may be specified in the as-cast or heat treated condition. As in other new and revised SAE standards, this standard includes an appendix which provides typical information on the application of high temperature ductile iron castings, their processing conditions, chemical composition, mechanical properties and microstructure.

**Table 7: Minimum mechanical properties and microstructure for compacted graphite iron**

| Grade | Typical Hardness Range | Minimum Tensile Strength | | Minimum 0.2% Yield Strength | | Minimum % Elongation | Typical Matrix Microstructure | Graphite Morphology % Nodularity |
|---|---|---|---|---|---|---|---|---|
| | | MPa | Ksi | MPa | Ksi | | | |
| C250 | 121-179 HB | 250 | 36.3 | 175 | 25.4 | 3.0 | Ferritic | <20 |
| C300HN | 131-189 HB | 300 | 43.5 | 175 | 25.4 | 3.0 | Ferritic | 20-50 |
| C300 | 143-207 HB | 300 | 43.5 | 210 | 30.5 | 2.5 | Ferritic / Pearlitic | <20 |
| C350 | 163-229 HB | 350 | 50.8 | 245 | 35.5 | 2.0 | Ferritic / Pearlitic | <20 |
| C400 | 197-255 HB | 400 | 58.0 | 280 | 40.6 | 1.5 | Pearlitic / Ferritic | <20 |
| C450 | 207-269 HB | 450 | 65.3 | 315 | 45.7 | 1.0 | Pearlitic | <20 |
| C500HN | 207-269 HB | 500 | 72.5 | 315 | 45.7 | 1.5 | Pearlitic | 20-50 |

There are many other grades of Silicon and/or Molybdenum ductile irons used in commercial applications. Many of these are European and Asian focused. Subsequent revisions of this standard will include these grades as well.

As of this writing, SAE J2582 has been balloted and is being edited for publication.

## Grades of Si-Mo

There are three basic grades of SiMo that account for a majority of the casting volumes. The significant elements are Silicon and Molybdenum. Silicon is higher than typical Ductile iron grades to provide a higher A1 transformation temperature and the Molybdenum improves the high temperature thermal fatigue properties.

**Table 8 – Mandatory Ranges for Silicon and Molybdenum for all three SAE Si-Mo Iron grades.**

| Grade | Hardness HBW | Silicon % | Molybdenum % |
|---|---|---|---|
| 1 | 187-241 | 3.50-4.50 | 0.50 maximum |
| 2 | 187-241 | 3.50-4.50 | 0.51-0.70 |
| 3 | 196-269 | 3.50-4.50 | 0.71-1.00 |

**Table 9– Typical ranges for all other elements for the SAE Si-Mo Iron grades.**

| Element | Typical Ranges % |
|---|---|
| Carbon | 3.30-3.80 |
| Manganese | 0.10-0.50 |
| Phosphorus | 0.050 max |
| Sulfur | 0.035 max |
| Magnesium[1] | 0.025-0.060 |

[1] Dependent on section thickness and substitution by Cerium and other rare earth elements

Since the balloting, the committee has had feedback from producers of castings using Si-Mo for thicker castings (turbocharger housings) indicating that the carbon range for these castings is typically around 3.0% to avoid carbon floatation. The committee will be making this correction on the following revision to the standard.

## Microstructure of Si-Mo

The microstructure of high temperature Si-Mo ductile iron is typical of most Ferritic ductile irons with the exception of a molybdenum carbide rich phase which is present at the eutectic cell boundries. This dark phase can easily mistaken as a Pearlitic structure but higher magnification reveals the nature of this molybdenum rich phase as shown in **Figures 3-6**.

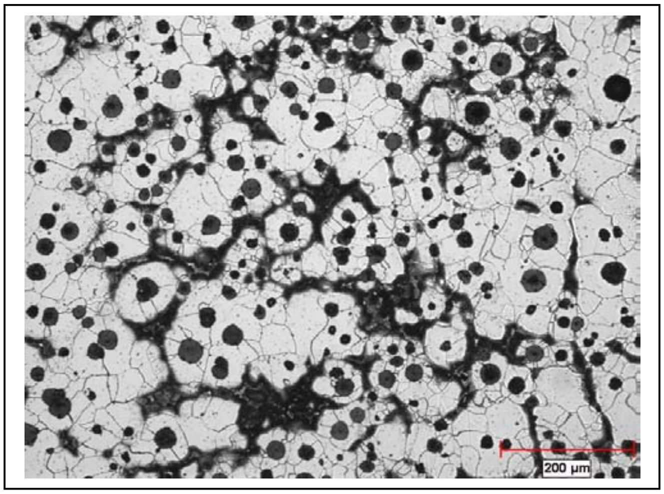

**Figure 3- At relatively low magnification the dark, Molybdenum carbide phase is not easily resolved.**

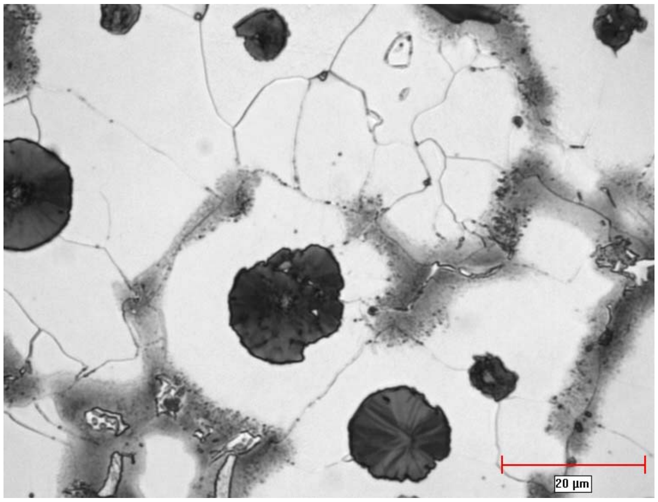

**Figure 4- As the magnification is increased the Molybdenum carbide rich fields begin to be discernable.**

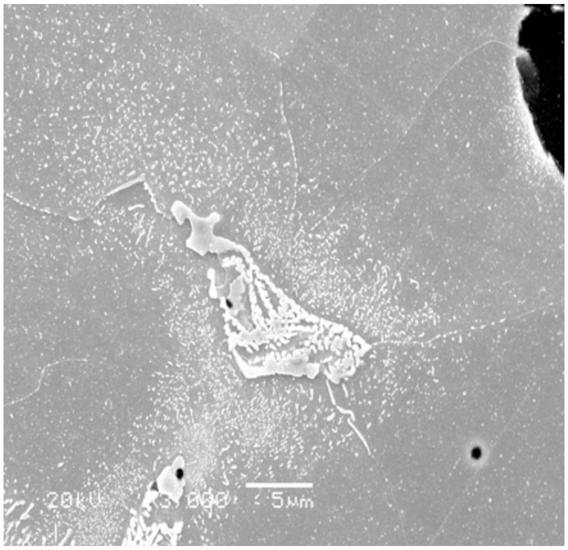

**Figure 5- This SEM photomicrograph taken at much higher magnification shows that the Molybdenum carbide rich region is clearly resolved and its morphology can be characterized.**

As designers of Si-Mo castings strive to produce castings of thinner cross sections, the casting is subject to extreme rates of solidification and as a result, wall sections with high nodule counts and very small nodules, (as seen in Figure 6), are common. The challenge for the casting industry is to develop new standards for microstructure ratings and new criteria for acceptable nodule size in counting nodules. The DIS Research Committee has recently produced a microstructure rating chart that includes this but standards organizations must modify their standards to account for the drive towards thin walled ductile Iron castings.

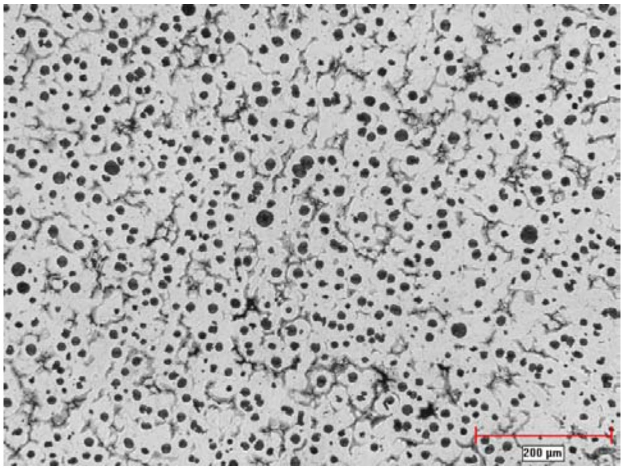

**Figure 6- A typical Si-Mo Iron microstructure from a thin-walled casting exhibits an extremely high nodule count and small nodule size.**

## Mechanical Properties of Si-Mo

With increasing levels of Molybdenum, strength is increased and elongation is decreased. Typical Mechanical properties are shown in **Table 10.**

**Table 10 Shows the typical properties of the three SAE Si-Mo Iron grades.**

| Grade | Tensile Strength | | Yield Strength | | Elongation % | Youngs Modulus | |
|---|---|---|---|---|---|---|---|
| | MPa | ksi | MPa | ksi | | Gpa | Mpsi |
| 1 | 450 | 65 | 275 | 40 | 8 | 152 | 22 |
| 2 | 485 | 70 | 380 | 55 | 6 | 152 | 22 |
| 3 | 515 | 75 | 415 | 60 | 4 | 152 | 22 |

## SUMMARY

The SAE Ferrous Committee continues to review the standards for Ductile Iron, ADI, Compacted Graphite Iron and SI-Mo Ductile Iron in order to keep them updated in terms of the material properties and capabilities. This information is necessary for design engineers to consider these materials for applications.

Efforts by other organizations like ASTM and ISO are simultaneously underway to create and update standards for Ductile Iron, ADI, Compacted Graphite Iron and Si-Mo Ductile Iron.

## REFERENCES

### DUCTILE IRON:

1. SAE J434 JUN86 Automotive Ductile (Nodular) Iron Castings
2. ASTM A536-84 (Reapproved 1999) Standard Specification for Ductile Iron Castings

### ADI:

1. ASTM A 897/A897M-02 Standard Specification for Austempered Ductile Iron

### CGI:

1. I.C.H. Hughes and J. Powell, “Compacted Graphite Irons – High Quality Engineering Materials in the Cast Iron Family, “ SAE Paper 840772, 1984.
2. E. Nechtelberger, H. Puhr, J.B. van Nesselrode and A. Nakayasu, “Cast Iron with Vermicular/Compacted Graphite – State of the Art,” International Foundry Congress, Chicago, Illinois, April 1983.
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4. S. Dawson, I. Hollinger and P. Smiles, “The

Mechanical and Physical properties of Compacted Graphite Iron," Global Powertrain Congress, Detroit, October 1998.
5. S. Dawson, I. Hollinger, M. Robbins, J. Daeth, U. Reuter and H. Schultz, "The Effect of Metallurgical Variables on the Machinability of Compacted graphite Iron," SAE Technical Paper Series 2001-01-0409, March 2001.

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## ADDITIONAL RESOURCES

www.sintercast.com
www.appliedprocess.com
www.ductile.org/didata
www.ironcastings.org