DETERMINE THE RELATIONSHIP BETWEEN SOLIDIFICATION TIME AND MECHANICAL PROPERTIES OF HEAVY SECTION DUCTILE IRON CASTINGS

Designed and Conducted By Participating Foundry Members of the Ductile Iron Society Heavy Section Committee

Reported by

ARTHUR F. SPENGLER

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Ductile Iron Society
Research Project Number 23

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The Ductile Iron Society wishes to take this opportunity to thank the individual committee members for their contribution to this project. We want to extend our utmost thanks to St. Marys Foundry, Cast Fab Technologies, Kingsport Foundry, and Teledyne Casting Service for their very substantial material contribution in the form of test block castings, and test work in their laboratories without which this project could not have been completed. In addition, we wish to extend our thanks to Jim Perts, Don Day, and Jerry Scott for their technical assistance.

The Research Committee recognized very early in the development of ductile iron that one of the most important research needs was a better understanding of why reduced properties occur in ductile iron castings with section thickness exceeding 4 inches. This reduction in properties, normally attributed to a slow rate of solidification is much greater in the case of ductile iron than any other ferrous metal. As expected, coarser structures result from slower solidification rates, but degradation of spheroidal graphite along with very substantial reductions in properties was not. It must be understood that in the 1950s and 1960s the material that passed for ductile iron had limitations, but it was far superior to the alloy gray irons used in heavy section castings in those times. Today, engineers are no longer interested in upgrading gray iron. Castings are now designed for conditions requiring the maximum properties that ductile iron can provide.

This program was entered into for two reasons. These reasons are as follows:

1. Provide information and technical assistance to member foundries producing HEAVY SECTION DUCTILE IRON CASTINGS.

2. Develop heavy section ductile iron technology which can be used to produce nuclear waste containers ("Casks") in the United States.

The purpose of this investigation was to determine the causes of the degradation in mechanical properties, and how to correct them. This has been accomplished in Project No. 23.
1.

SUMMARY

Basically; it has been established within the present level of ductile iron technology that there is one complete solution to the problem of reduced properties in heavy section ductile iron castings, and one partial solution to this problem.

The complete solution involves the use of gray cast iron chills within the following perimeters:

1. The use of gray iron chills on both sides of the wall of the casting equal to 33.3% of the casting thickness.

2. The use of gray iron chills equal to 40% to 50% of the casting thickness located in highly stressed areas of the casting. The location of the chills is based on casting design stress requirements.

The partial solution is based on the premise that increasing nodule count will increase mechanical properties. An increase in nodule count can be achieved within limitations by the use of 75% ferrosilicon inoculants containing stoichiometric quantities of rare earths and bismuth, and by the use of extremely small additions of antimony which combines with rare earths from treating alloys. This approach is helpful in extending the required solidification time limits because its use increases the nodule count from 50% to 75% of a nominal 40. This has an effect which is similar to reducing the solidification time.

Using these solutions to improve mechanical properties, it has been found possible to produce heavy section ductile iron castings with properties in the same ranges as similar size steel castings.

INTRODUCTION

This final report reviews the research activities covering a span of over thirty years culminating in Project No. 23. The project provides a feasible and practical solution to the problem of mechanical property degradation (tensile strength, yield strength, percent elongation, and impact) which has always occurred in heavy section ductile iron castings. At present, many of the ductile iron producer who have representatives on the DIS Heavy Section Committee are using the procedures described here in the production of heavy section of ductile iron castings with optimum mechanical properties.

Since the time when ductile iron was initially developed in the mid 1940's and early 1950's the mechanical properties of large heavy section castings have always been inferior to castings weighing up to 100 pounds with sections less than four inches. While this has been recognized since the beginning, it was also thought that even these lower properties in most cases were superior to alloyed gray irons.
This was not always true because there were considerable number of serious large heavy section casting failures in the U.S., Canada, Europe, and South America. Some of these casting failures were catastrophic; shutting down large mining operations and manufacturing plants for months, causing train wrecks, and resulting in the shutdown of public utility systems for extended periods of time.

The primary cause of these failures was the presence of non-spheroidal graphite in the forms of vermicular and exploded graphite (chunky graphite) as shown in Figure No. 1 page 3, and carbide segregation to the grain boundaries of the matrix which in turn causes extremely serious deterioration of mechanical properties. By the late 1950's and 1960's no one had a solution to this problem. There were a few recommended steps which could be taken to marginally upgrade the tensile properties of the iron:

1. Increase the nickel content of the iron to between 1.5% to 2.0%
2. Reduce carbon equivalent value of the final iron to below 4.0.
3. Increase the level of inoculation.
4. Use increased additions of rare earths.

Unfortunately, none of these recommendations completely solved the problem of severe mechanical property degradation.

As early as 1968 members of the DIS engaged in producing heavy section ductile iron castings recognized this, and initiated Research Project No. 8 "FACTORS AFFECTING OPTIMUM PROPERTIES IN HEAVY SECTION DUCTILE IRON". The project was assigned to Case Western Reserve University in Cleveland, Ohio. After struggling with this problem for over nine years, no acceptable solution to the problem of reduced levels of mechanical properties was found. The only answer provided was that the low levels of mechanical properties were due to the solidification phenomena.

There were many meetings, and a large number of progress reports written. These reports were primarily concerned with a series of experiments made by the Case Institute.
High Quality Ductile Iron Shown At 100X Cast Using Controlled Solidification. (Gray iron chills)

Chunk Graphite And Exploded Nodules Shown At 100X. This Figure Shows The Primary Conditions which cause Reduced Properties In Heavy Section Ductile Iron Castings.
The results obtained from each series of tests were always erratic, but there were always enough correlations to encourage further test work. There were also very wide areas of disagreement within the Heavy Section Committee on how the test data was to be interpreted. The final report provided by R. C. Helmink and J. I. Wallace of Case Western Reserve University was not acceptable to the DIS Research Committee. Finally, Sam Carter who was not a member of the Heavy Section Committee was asked by Keith Millis to write the Forward, and to modify the final report. The following is a final report summary of Research Project No. 8 illustrating ideas and conditions which existed prior to 1977 relative to the production of large heavy section ductile iron castings:

**SUMMARY**

**DUCTILE IRON SOCIETY RESEARCH PROJECT NO. 8**

**FACTORS AFFECTING OPTIMUM PROPERTIES IN HEAVY SECTION DUCTILE IRON**

Originally Project No. 8 started out as a program to compare the mechanical properties of 8 inch cubes cast by 18 member foundries represented on the DIS Heavy Section Committee. The cubes were numbered, and treated as blind samples so that the actual source would not be known. Tensile tests were made on samples taken from the center section of these 8 inch cubes. The test results covered a very wide range. Tensile strengths varied from 50,000 psi. to 90,000 psi. Yield strengths varied from 40,000 to 65,000 psi. The percent elongation ranged from 1.0% to as high as 12.0%. For the most part, the majority of mechanical properties reported fell in the lowest 30% of the ranges.

The major cause of poor properties and ductility in the 8 inch cubes appeared to be the deterioration of the graphite configuration from spherical to vermicular, exploded, and chunky graphite. This has always been the cause associated with the decline of mechanical properties and ductility of heavy section ductile iron castings. It became evident from these test results the problem of poor properties was real, and further that all producers of large heavy section ductile castings had a very serious on-going problem for which there was no solution at that time. It was admitted that there was no apparent answer to problem of low properties; they varied from casting to casting even in ductile iron poured from the same heat or treatment. There was absolutely no correlation of data which could be used to explain the variation encountered in graphite shape and property retention. As a result, the need for a systematic evaluation of process variables was recognized by all the members of the Committee. Because of these circumstances, the DIS Research Committee engaged Case Western Reserve University to pursue a systematic research program under the direction of Professor John F. Wallace to determine the causes of the deteriorating mechanical properties in ductile iron. It was agreed by the DIS Research Committee that the areas to be investigated in the course of the project were these:
5.

1. Major variables in loss and retention of mechanical properties.

2. Practices conducive to the best retention of properties.

3. Determine levels of ductility and tensile quality that can be reasonably expected under the best controlled conditions.

4. Compare ductile iron with other metals in loss of properties in heavy sections.

5. Develop a more useful expanded graphite classification system.

6. Determine the relationship between laboratory results and commercially produced cubes.

After a literature review, a plan for the investigation of major variables was agreed upon with the DIS Research Committee. It was agreed that the maximum thickness to be investigated was a 9.5 inch cube.

The ductile iron used for testing in the Case project was cast from fourteen induction melted ductile iron 1500 lb. heats produced from closely controlled furnace charge materials. The base iron was treated in the furnace by plunging magnesium ferrosilicon placed in a clay-graphite plunging bell, and inoculated in the pouring ladles. These heats were divided into three taps with variations for each tap cast. Ductile iron from each tap was poured into three different test specimens:

1. keel blocks solidifying in 5 minutes.
2. 4.5" cubes solidifying in 20 minutes.
3. 9.5" cubes solidifying in 108 minutes.

It should be noted that these values are reasonably close to values calculated using Chvorinov's rule and a K factor of 1.3 for cubes.

These were the major variable studied in Project No. 8:

1. The optimum amount of 75% ferrosilicon required for inoculation.
2. The use of special inoculants with trace elements
3. Holding time after inoculation. (fade)
4. The influence of Restoration with booster inoculation after extended holding.
5. In-the-Mold inoculation methods.
7. The influence of variations in magnesium levels.
8. Effect of base iron sulfur levels.
9. Effect of deleterious residual elements with and without rare earths present.
10. The effect of manganese at low and high silicon levels.
11. The influence of the pearlite stabilizing elements manganese, chromium, copper, and tin on properties and micro-structure.
A comparison of the influence of section size on mechanical properties of steel, nonferrous metals, and ductile iron was also made. The details of are available in (Section IX). The ductile iron test data from Project No. 8 study was compared with the mechanical properties of other metal cast in heavy sections. One of the methods used to improve mechanical properties of these metals is by controlled cooling and solidification (Use of Chills). This approach seems for some reason to have been entirely overlooked or disregarded as a means of upgrading the mechanical properties of heavy section ductile iron. The following is a condensed summary of Project No. 8:

**CONDENSED SUMMARY OF THE WORK AND CONCLUSIONS OF PROJECT NO. 8**

Based on the variables investigated the following conclusions can be made:

1. Varying the amount of inoculant used showed that 0.39%, 0.60%, and 0.90% silicon as standard grade 75% ferrosilicon, when cast immediately, all retained good properties in the 9.5" cube. The elongation was 17% from the 0.39% and 0.60% silicon additions, best elongation of 24% from 0.90% Si addition levels. (Keel blocks from the same heat ranged from 23% to 25% elongation, and showed no effect from all inoculant amounts.)

2. Addition of proprietary inoculants containing Ba, Sr, and Zr show no distinct advantage over standard grade 75% ferrosilicon containing appropriate levels of calcium and aluminum.

3. Additions of a proprietary inoculant containing titanium dramatically reduced the tensile strength, yield strength, and percent elongation. This in turn was brought about by the presence of over 50% vermicular and chunky graphite in the 9.5" cube caused by a relatively small addition of unreduced titanium (0.06%).

4. Inoculation loss caused by holding for thirty minutes could be restored by an addition of 0.14% silicon in the form of ferrosilicon fines added to the runner in a mold. It was also found that commercial ferrosilicon pellets provided similar results.

5. Inmold treatment was found to produce moderately good results in the 9.5" cubes. The elongation produced from this treatment was 17.0%. This was probably due to the high purity of the base iron, a low treating temperature, and a low pouring temperature.

6. It was thought by some, that the presence in a high sulfur base iron (0.077%) would nucleate ductile iron through the presence of sulfide nuclei, and thereby improve mechanical properties. This did not happen in the experimental heats cast.

7. It was stated silicon levels as high as 3.10% and increased levels of manganese up to 0.90% showed no loss of ductility in heavy sections, and negligible increases in pearlite and hardness.
8. It was found that increasing manganese content promotes the formation of pearlite. This pearlite stabilizing effect is further enhanced by the presence residual amounts of elements such as Cu, Cr, Ni, and Sn.

9. The presence of free cerium and other rare earth elements was found to have detrimental influence on the mechanical properties of ductile iron. This was due to the fact that it caused the formation of vermicular graphite, chunky graphite (degenerate forms of graphite), and in some cases carbides. These same elements when combined with deleterious elements did no harm.

10. Magnesium in the range of 0.04% to 0.07% showed no significant effect on graphite configuration and micro structure. It was found that while magnesium levels of from 0.027% to 0.03% may sometimes be adequate for thin sections, they are not satisfactory for heavy sections.

12. It was always found that these individual elements when present in amounts of 0.50% Cu, 0.08% Sn, 0.90% Mn and 0.50% Cr caused an increase in the amount of pearlite present, hardness, tensile strength, but decreased the elongation and overall ductility of ductile iron.

13. When only wear and abrasion resistance is needed, the as-cast pearlitic grade has been found to be serviceable for many applications.

14. In general, the 8 inch cube had a wide variation in properties, chemical composition, percent nodularity, nodule shape, and the level of microshrinkage present. It was believed at the time the original report was written that the variations in mechanical properties were caused by treating practice, inoculation, and to a certain extent by metal composition.

It was the consensus of opinion in 1977 when the final report was written that casting size limitations as in the case of steel, copper alloys, and aluminum were primarily responsible for the property degradation. However: in the case of ductile iron the size effect was substantially greater. It was stated that practices described in the final report would make it possible to maintain reasonably high levels of engineering properties in large ductile iron castings.

Unfortunately, there was no real and effective solution to the problem of deteriorating mechanical properties as section size of ductile iron castings increase. As a result, the failure of large ductile iron casting continued, and it became necessary to severely downgrade the ASTM Specification for heavy section ductile iron castings. This caused design engineers to replace large ductile iron castings with steel castings. Basically this is the reason why Project No. 23 was initiated.
The first part of Project No. 23 was an extensive Literature Survey. This Literature Survey revealed that a surprising amount of research has been done since 1977 on the subject of overcoming the reduced mechanical property problem in heavy section ductile iron castings. The individual references are included in the addendum of this final report. Copies of the individual paper are available on request.

In summary, the most significant part of these research activities indicated that controlled cooling and solidification rates are an absolute necessity, if optimum micro-structures as shown in Figure No. 2 page 3 and mechanical properties are to be obtained in heavy section multi-ton ductile iron castings. This is reported to be possible in castings up to a thickness of 18 inches and possibly more. There are a substantial number of recent papers reviewing methods for obtaining these results, but exact details on how these results were obtained under production conditions were only alluded to. How these results could be reproduced was not explained in complete detail.

The references listed in the Literature Survey were very helpful in determining the scope of this Project. These references make it possible for both foundrymen and design engineers to understand the necessity for having clear concise mechanical property specifications for individual castings. Many of the important reasons for this are explained in the body of the Report.
EXPERIMENTAL PROCEDURE

After carefully reviewing Project No. 8, making the Literature Survey, and a number lengthy discussions with the members of the Heavy Section Committee; it became apparent that a change in melting practice, treating materials, or inoculants would not eliminate the spheroidal graphite degradation which reduces the mechanical properties of heavy section ductile iron castings. (Castings with sections exceeding 6 inches) There are, however; a series of factors which seem to minimize the formation of degenerate forms of spheroidal graphite:

1. A nodule count greater than 60.

2. Using a carbon equivalent range of 4.2 - 4.3 with silicon levels not exceeding 2.60% (Usual range 2.20% to 2.45%).

3. Magnesium levels of 0.04% - 0.05% in the casting.

4. Inoculation with 75% calcium bearing ferrosilicon.

5. Control of the trace elements Ti, As, Sn, Sb, Pb, Bi, Al by additions of stoichiometric quantities of rare earth series elements. This can be done by the utilization of the shape factor equation or Rare Earth Equivalent Equation:

\[ SG = 4.4\%Ti + 2.0\%As + 2.3\%Sn + 5.0\%Sb + 290.0\%Pb + 370.0\%Bi + 1.6\%Al \]

\[ SG < 1 \text{ Graphite shape is Spheroidal} \]
\[ SG > 1 \text{ Degenerate graphite can occur} \]

It should be pointed out that the presence an equivalent quantity of rare earths will neutralize the majority of residual elements, and in doing so form additional nuclei which increase the nodule count. The balance between combined and free rare earth elements is extremely critical because an excess of free rare earths or uncombined rare earths in excess of approximately 0.008% will cause nodule degeneration by acting as a reducing agent changing sulfides to free sulfur.

6. Controlled solidification rates using chills is necessary, if degenerate free graphite ductile iron is to be produced in sections exceeding 3". This is based on the experimental findings of member foundries, and from sources in the Literature Survey.

7. Information developed experimentally and indicated in the Literature Survey the time interval between the liquidus and solidus must not exceed 90 to 110 minutes or the formation of degenerate graphite will occur along with a low nodule count.

8. Graphite degeneration also occurs because the stable sulfides and rare earth residual element compounds tend to be reduced by
long time exposure to carbon in liquid ductile iron a condition which only occurs in heavy section ductile iron castings.

Based on the experience of the majority of Committee members and corresponding foundries in the Far East and Europe, the Committee decided that all conditions being equal; controlled solidification was the most practical solution to the degenerate graphite problem in large heavy section ductile iron castings at the present time.

The purpose of this Project is to verify the validity of controlled solidification (the use of chills) as a means by which the mechanical properties in heavy section ductile castings can be made to meet standard ductile iron specifications. This can be accomplished by eliminating or minimizing the presence of degenerate graphite. The other very important consideration is to provide guidelines that all foundries can use in the production large heavy section ductile iron castings.

There were a number of discussions with research groups from a number of universities interested in this Research Project. Except for one, these groups were primarily interested in providing information based on computer generated solidification simulations. Members of the Committee found that there were computer programs of this kind available from several commercial sources. There was one research group that proposed a project based on holding 250 gram samples of molten ductile iron in a controlled atmosphere furnace for varying extended periods of solidification. This was to be done along with the development of computer simulation formulas. It was the consensus of opinion of the Committee that none of these approaches was practical as far as operating foundries are concerned. The Committee then decided that this investigation could be more effectively carried out by member foundries.

Before any testing program could be initiated it was necessary to determine the cooling rate range which would minimize or eliminate the formation degenerate graphite nodules. Based on the Literature Survey and the experience of Committee members, It was determined that ductile iron containing 95.0% spheroidal graphite can be produced by the use of gray cast iron chills located adjacent to both faces of sections ranging from 6 inches to 24 inches in thickness. The reason gray iron was chosen as the chill material is because it was found to be the most effective readily available material. This is because the coefficient of thermal conductivity for gray iron is 25.0% greater than that of ductile iron and 96.25% greater than dry sand as shown in Table No 1. Therefore: it is evident that sand molds promote a relatively slow solidification rate. In fact, the solidification rate is sufficiently slow (greater than 120 minutes) to allow the disintegration of spheroidal graphite into Chunky Graphite in a 9 inch cube. Based on the literature and the experience of Committee members, it has been found that disintegration of graphite can be avoided if the time interval between the liquidus and solidus temperatures is less than 90 to 120 minutes.
The second requirement was to establish a chill to casting thickness ratio equilibrium which brings about the formation of a uniform matrix structure containing less than 10% pearlite adjacent to the mold cavity liquid metal interface. The requirement is based on preliminary experimental work done by a Member Foundry which had shown that when chill thickness exceeds 33.0% of a casting thickness, significant areas of non-uniform pearlite formed adjacent to mold metal interface.

A third item of special interest was to determine if the addition of 0.02% antimony (Sb) would substantially increase nodule count from a nominal level of 30. The last or fourth item was the ability of a 75% ferrosilicon inoculant containing stoichiometric quantities of bismuth and cerium to increase nodule count. All of these preliminary tests were carried out at Committee Member foundry. The test results are presented in Table No. 2 on the following page.

The data in Table No. 2 was generated from tensile bar samples taken from the mid section of 12" X 12" X 24" TEST BLOCKS cast in NO BAKE molds poured with ductile iron made using standard treating and inoculation practices. This involved treatment with 5% magnesium ferrosilicon, and inoculation 75% ferrosilicon. It was found that significant increase in nodule count occurred when antimony (Sb) was added with the inoculant. The nodule count was increased to 75. When a 75% ferrosilicon inoculant containing bismuth and cerium was used for inoculation a similar increase in nodule count was observed along with a 3% increase in elongation. However; when chills were used, the nodule count increased to a range of 249 to 251. This is a very substantial increase in nodule count above 35 to 40 or even 75. For this reason, it was decided that the practice to be followed should
involve the use of chills only. At this point it was necessary to determine the chill to ductile iron ratio which would produce an iron with a ferritic matrix and 90% plus spheroidal graphite. After a review of the information available, a procedure based on preliminary test data from Table No. 2 was developed.

**TABLE 2**

12" X 24" X 24" TEST BLOCKS CAST: OCTOBER 9, 1991

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>STD. PRACT. W/0.02% Sb</th>
<th>STD. PRACT. W/Bi INOC.</th>
<th>STD. PRACT. W/6&quot; CHILLS ON SIDES</th>
<th>STD. PRACT. W/12&quot; CHILL ON SIDES</th>
</tr>
</thead>
<tbody>
<tr>
<td>% C</td>
<td>3.570</td>
<td>3.570</td>
<td>3.580</td>
<td>3.570</td>
</tr>
<tr>
<td>% Si</td>
<td>2.460</td>
<td>2.250</td>
<td>2.250</td>
<td>2.260</td>
</tr>
<tr>
<td>CE</td>
<td>4.390</td>
<td>4.320</td>
<td>4.320</td>
<td>4.320</td>
</tr>
<tr>
<td>% Mn</td>
<td>0.270</td>
<td>0.290</td>
<td>0.280</td>
<td>0.290</td>
</tr>
<tr>
<td>% S</td>
<td>0.008</td>
<td>0.010</td>
<td>0.009</td>
<td>0.010</td>
</tr>
<tr>
<td>% P</td>
<td>0.014</td>
<td>0.018</td>
<td>0.016</td>
<td>0.017</td>
</tr>
<tr>
<td>% Cu</td>
<td>0.030</td>
<td>0.030</td>
<td>0.031</td>
<td>0.030</td>
</tr>
<tr>
<td>% Cr</td>
<td>0.040</td>
<td>0.040</td>
<td>0.038</td>
<td>0.041</td>
</tr>
<tr>
<td>% Ni</td>
<td>0.070</td>
<td>0.068</td>
<td>0.072</td>
<td>0.069</td>
</tr>
<tr>
<td>% Mo</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>% Mg</td>
<td>0.070</td>
<td>0.069</td>
<td>0.068</td>
<td>0.069</td>
</tr>
<tr>
<td>TENSILE PSI</td>
<td>56,668</td>
<td>53,437</td>
<td>57,754</td>
<td>63,404</td>
</tr>
<tr>
<td>YIELD PSI</td>
<td>36,637</td>
<td>34,102</td>
<td>37,975</td>
<td>40,253</td>
</tr>
<tr>
<td>% ELONG.</td>
<td>19</td>
<td>22</td>
<td>21</td>
<td>18</td>
</tr>
<tr>
<td>NODULE SUMMARY</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVE SHAPE FACT.</td>
<td>1575</td>
<td>1731</td>
<td>1401</td>
<td>1443</td>
</tr>
<tr>
<td>% SPHERICAL</td>
<td>90.51</td>
<td>88.26</td>
<td>95.41</td>
<td>97.49</td>
</tr>
<tr>
<td>NOD. COUNT/mm²</td>
<td>75</td>
<td>69</td>
<td>251</td>
<td>349</td>
</tr>
<tr>
<td>AVE. NOD. DIA. um</td>
<td>45</td>
<td>32</td>
<td>25</td>
<td>27</td>
</tr>
<tr>
<td>% TYPE I GR.</td>
<td>79.67</td>
<td>69.94</td>
<td>88.12</td>
<td>85.55</td>
</tr>
<tr>
<td>% TYPE II GR.</td>
<td>10.84</td>
<td>18.32</td>
<td>7.29</td>
<td>11.94</td>
</tr>
<tr>
<td>% GRAPHITE</td>
<td>16</td>
<td>14</td>
<td>16</td>
<td>15</td>
</tr>
<tr>
<td>% MICRO POROS.</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>% PEARLITE</td>
<td>7</td>
<td>4</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>% FERRITE</td>
<td>74</td>
<td>78</td>
<td>80</td>
<td>65</td>
</tr>
</tbody>
</table>
The test data obtained from TABLE 2 indicates that both the Sb addition and the 75% ferrosilicon inoculant containing balanced quantities of bismuth and cerium increase nodule count from nominal 40 to 74-78 which is considered to be an acceptable level for ductile iron, however; the use of chills did increase the nodule count in the same 12" sections to a 250 range which usually provides optimum mechanical property levels in ductile iron.

In addition, it was found that the 6" thick chills covering both 24"X 24" surfaces of the 12" thick test block provided excellent internal mechanical properties, but that there was a pearlitic layer adjacent to the chilled surfaces indicating that the chill-to-casting ratio had not achieved structural equilibrium. A similar, but more pronounced condition existed when 12" thick chills were use on the 24"X 24" sides of test block No.4. Also the pearlite content of the matrix was increased to the 18% to 20% range.

Based on these tests and the practical experience of committee members, it was decided that gray iron chills having a thickness of approximately 33.3% of the casting thickness placed on both sides of a heavy section casting would provide a uniform matrix microstructure for the majority of section sizes ranging from 9" to 20" that normally have solidification times greater than 90 minutes in sand molds. Also, it was found that no pearlitic rim was formed using this practice. The procedure was found to be empirically correct, and subsequently used throughout the balance of the project. Note: that the relationship or ratio between the heat conductivity factor for gray iron to ductile iron is 0.75, and the ductile iron chill to ductile iron ratio approaches 0.66. The practice involving the use of gray iron chill has been applied to a number of castings produced by member foundries with outstanding success.

The next step in this project was to determine the mechanical properties in chilled and unchilled mid-sections samples taken from 15"X 22.5"X 22.5" test block with a thermocouple located in the center sections of the test block. These tests were carried out by three DIS member foundries. The test data is presented in the following tables and charts. It appears to prove validity of the 33.3% chill to section ratio. It is recommended, however; that each foundry run a few heavy section test block of the section thickness ranges involved because adjustments may have to be made on the basis of local operating conditions and base iron composition.

Based on a review of solidification data from this project and information from foundries in Japan, it is believed that in sections from 4" to 8" free of "agglomerate or chunky graphite" can probably be produced with a chill to casting thickness ratio of 28.0% to 30.0% Castings with sections of 20" to 30" will probably need a chill to casting thickness ratio of 38.0% to 40.0%. These are the two areas of investigation which were not completed due to curtailment of funds.
<table>
<thead>
<tr>
<th>CODE</th>
<th>FDRY #1</th>
<th>FDRY #2</th>
<th>FDY #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHEMICAL COMPOSITION</td>
<td>STD. PRACT. W/ 0.02% Sb</td>
<td>STD. PRACT.</td>
<td>STD. PRACT.</td>
</tr>
<tr>
<td>% C</td>
<td>3.51</td>
<td>3.550</td>
<td>3.49</td>
</tr>
<tr>
<td>% Si</td>
<td>2.14</td>
<td>2.370</td>
<td>2.50</td>
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<tr>
<td>CE</td>
<td>4.22</td>
<td>4.340</td>
<td>4.32</td>
</tr>
<tr>
<td>% Mn</td>
<td>0.29</td>
<td>0.180</td>
<td>0.16</td>
</tr>
<tr>
<td>% S</td>
<td>0.006</td>
<td>0.013</td>
<td>0.006</td>
</tr>
<tr>
<td>% P</td>
<td>0.020</td>
<td>0.023</td>
<td>0.021</td>
</tr>
<tr>
<td>% Cu</td>
<td>0.030</td>
<td>0.060</td>
<td></td>
</tr>
<tr>
<td>% Ni</td>
<td>0.080</td>
<td>0.380</td>
<td></td>
</tr>
<tr>
<td>% Mo</td>
<td>ND</td>
<td>0.010</td>
<td></td>
</tr>
<tr>
<td>% Cr</td>
<td>0.050</td>
<td>0.027</td>
<td></td>
</tr>
<tr>
<td>% Mg</td>
<td>0.057</td>
<td>0.058</td>
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<td>% Re</td>
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<td></td>
<td>0.013</td>
</tr>
<tr>
<td>% Al</td>
<td></td>
<td>0.019</td>
<td></td>
</tr>
<tr>
<td>% Bi</td>
<td></td>
<td>0.00002</td>
<td></td>
</tr>
<tr>
<td>% Pb</td>
<td></td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>% Sb</td>
<td></td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>% Ti</td>
<td></td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>% Va</td>
<td></td>
<td>0.010</td>
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PROPERTY SUMMARY*

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<th>FDY #3</th>
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<td>TENSILE PSI.</td>
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<td>54423</td>
<td>56300</td>
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<td>YIELD PSI.</td>
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<td>40940</td>
<td>39200</td>
</tr>
<tr>
<td>% ELONG.</td>
<td>7.0</td>
<td>7.3</td>
<td>15.7</td>
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<td>BHN</td>
<td>156</td>
<td>143</td>
<td>147</td>
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NODULE SUMMARY

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<th>FDRY #2</th>
<th>FDY #3</th>
</tr>
</thead>
<tbody>
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<td>% SPHERE.</td>
<td>65</td>
<td>68</td>
<td>95</td>
</tr>
<tr>
<td>NOD. TYPE</td>
<td>43% I, 57% I, II</td>
<td>CHUNK</td>
<td>PRED I, II</td>
</tr>
<tr>
<td>COUNT</td>
<td>12</td>
<td>35</td>
<td>50</td>
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MATRIX

<table>
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<th>FDY #3</th>
<th>FDY #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>% PEARLITE</td>
<td>37%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>% FERRITE</td>
<td>48</td>
<td>92%</td>
<td>95%</td>
</tr>
<tr>
<td>OTHER</td>
<td>2.5% POR, SEG 2.5%</td>
<td>SEG. 3%</td>
<td>SEG. 2%</td>
</tr>
</tbody>
</table>
TABLE 4

Test Data From 15" X 22.5" X 22.5" Block Cast With 5" Chills On Sides

<table>
<thead>
<tr>
<th>CODE</th>
<th>FDRY.# 1</th>
<th>FDRY.# 2</th>
<th>FDRY.# 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHEMICAL COMPOSITION</td>
<td>STD. PRACT.</td>
<td>STD. PRACT.</td>
<td>STD. PRACT.</td>
</tr>
<tr>
<td>% C</td>
<td>3.510</td>
<td>3.550</td>
<td>3.49</td>
</tr>
<tr>
<td>% Si</td>
<td>2.140</td>
<td>2.370</td>
<td>2.50</td>
</tr>
<tr>
<td>CE</td>
<td>4.223</td>
<td>4.340</td>
<td>4.32</td>
</tr>
<tr>
<td>% Mn</td>
<td>0.290</td>
<td>0.180</td>
<td>0.16</td>
</tr>
<tr>
<td>% S</td>
<td>0.006</td>
<td>0.013</td>
<td>0.006</td>
</tr>
<tr>
<td>% P</td>
<td>0.020</td>
<td>0.023</td>
<td>0.020</td>
</tr>
<tr>
<td>% Cu</td>
<td>0.030</td>
<td>0.060</td>
<td></td>
</tr>
<tr>
<td>% Ni</td>
<td>0.080</td>
<td>0.380</td>
<td></td>
</tr>
<tr>
<td>% Mo</td>
<td>ND</td>
<td>0.010</td>
<td></td>
</tr>
<tr>
<td>% Cr</td>
<td>0.050</td>
<td>0.027</td>
<td></td>
</tr>
<tr>
<td>% Mg</td>
<td>0.057</td>
<td>0.058</td>
<td>0.040</td>
</tr>
<tr>
<td>% RE</td>
<td>0.012</td>
<td>0.0128</td>
<td></td>
</tr>
<tr>
<td>% Al</td>
<td></td>
<td>0.019</td>
<td></td>
</tr>
<tr>
<td>% Bi</td>
<td></td>
<td>0.00004</td>
<td></td>
</tr>
<tr>
<td>% Pb</td>
<td></td>
<td>&gt;0.0040</td>
<td></td>
</tr>
<tr>
<td>% Sb</td>
<td></td>
<td>0.0034</td>
<td></td>
</tr>
<tr>
<td>% Ti</td>
<td></td>
<td>0.0050</td>
<td></td>
</tr>
<tr>
<td>% Va</td>
<td></td>
<td>&gt;0.0100</td>
<td></td>
</tr>
</tbody>
</table>

PROPERTY SUMMARY*

| TENSILE PSI | 56640 | 60782 | 58600 |
| YIELD PSI  | 37610 | 41115 | 39300 |
| % ELONGATION | 21 | 22 | 25 |
| BHN       | 149   | 152   | 149   |

NODULE SUMMARY

| % SPHERE | 95 | 95 | 95 |
| NOD. TYPE | I 81%, II 14%, III 5% | 1 | 1 |
| COUNT    | 99 | 170 | 168 |

MATRIX

| % PEARLITE | 19 | 0 | 0 |
| % FERRITE  | 63 | 100 | 100 |
| % OTHER    | 2 POR. | 0 | 0 |
*This data is from samples located in the central section of test blocks in order to avoid the rapid cooling effect at corners.

Solidification data was provided by the foundries producing test blocks. All curves were similar. The following figure show examples of typical solidification curves with and without controlled cooling.

Figure 3.

Typical Solidification Data from Chilled and Unchilled 15 Inch Thick Test Blocks Showing the Difference in Solidification Time
In addition to tensile and hardness data, dynamic tear tests were made on both chilled and unchilled specimens taken from the 15" thick test blocks. These test results are shown in Figures No. 4 and No. 5.
Figure No. 5
Dynamic Tear Test Data From The Chilled 15" Thick Test Block
A series of Dynamic Tear Tests were made on samples from the chilled and unchilled 15"X 22"X 22" and mold cooled test blocks with very low residual element levels, and a silicon content of 2.37%. Dynamic Tear Test upper shelf results for chilled blocks were in the 100 ft.-lb. range with transition temperatures below 0°F. Test results from the unchilled block as can be seen from the data tended to be lower and more erratic.

**TABLE 5**

Test Data From 9"X 18"X 18 Block Cast Unchilled And With 3" Chills

<table>
<thead>
<tr>
<th>CHEMICAL* COMPOSITION</th>
<th>STD. PRACT. UNCHILLED</th>
<th>STD. PRACTICE 3&quot; CHILLS ON SIDES</th>
</tr>
</thead>
<tbody>
<tr>
<td>% C</td>
<td>3.42</td>
<td></td>
</tr>
<tr>
<td>% Si</td>
<td>2.71</td>
<td></td>
</tr>
<tr>
<td>CE</td>
<td>4.32</td>
<td>Cast From Same Heat As Unchilled Block</td>
</tr>
<tr>
<td>% Mn</td>
<td>0.210</td>
<td></td>
</tr>
<tr>
<td>% S</td>
<td>0.010</td>
<td></td>
</tr>
<tr>
<td>% P</td>
<td>0.010</td>
<td></td>
</tr>
<tr>
<td>% Cu</td>
<td>0.037</td>
<td></td>
</tr>
<tr>
<td>% Ni</td>
<td>0.750</td>
<td></td>
</tr>
<tr>
<td>% Mo</td>
<td>0.049</td>
<td></td>
</tr>
<tr>
<td>% Cr</td>
<td>0.060</td>
<td></td>
</tr>
<tr>
<td>% Mg</td>
<td>0.038</td>
<td></td>
</tr>
<tr>
<td>TENSILE PSI</td>
<td>64,650</td>
<td>67,250</td>
</tr>
<tr>
<td>YIELD PSI</td>
<td>47,500</td>
<td>48,880</td>
</tr>
<tr>
<td>ELONG.</td>
<td>13.4</td>
<td>20.3</td>
</tr>
<tr>
<td>BHN</td>
<td>164</td>
<td>168</td>
</tr>
</tbody>
</table>

**NODULE SUMMARY**

| % SPHERE. | COUNT | 57 | 48 | 88 | 140 |
| PERCENT TYPE I | 40 | 87 |
| PERCENT TYPE II & CHUNK | 60 | 13 |
| PERCENT GRAPHITE | 14 | 14 |
| PERCENT POROS. | 4 | 2 |
| PERCENT PEARLITE | 12 | 4 |
| PERCENT FERRITE | 88 | 95 |
The tensile test and hardness data shown in TABLE 5 from the 9"X 18"X 18" blocks were similar to the 15" thick blocks showing the wide effective range of the 0.33 chill thickness ratio.

Note that the silicon level is 2.71% and the combination Ni and other pearlite stabilizing is 0.896%. This condition will always tend to have an embrittling effect on ductile iron.

Dynamic Tear results from a chilled 9"X 18"X 18" block which were incomplete due to an insufficient number of samples indicated that the upper shelf level was in the range of 65 ft.- lbs.. The transition temperature was 100°F. The test results are what can be expected based on the silicon and alloy content. Dynamic tear properties can be improved by a sub-critical heat treatment at 1150°F to 1300°F for 5 hours at temperature; furnace cool to 900°F. However; tensile and yield strengths will be reduced, but the elongation will be increased. The influence of increasing silicon content on ductile iron impact properties is shown in Figure No. 6

\[ \text{Figure No. 6} \]
Influence Of Increasing Silicon Content on Impact Properties of D.I.
Note: that the solidification pattern of the 9" block is similar to the 15" block except that the initial drop in temperature is more rapid. Nevertheless, a significantly higher level of properties is obtained from the chilled test block.

![Solidification Data - Typical 9" Test Blocks - 3" Gray Iron Chills](image)

Figure No. 7
Solidification Data from Chilled and Unchilled 9 Inch Thick Test Blocks From Foundry No. 4
SEM SCANS ON SAMPLES TAKEN FROM CHILLED AND UNCHILLED TEST BLOCKS

To understand factors responsible for the degeneration of mechanical properties which takes place in unchilled heavy sections, as in 15" Test Blocks, a series of electron microscope scans were made. Simultaneously, the composition of non-metalics found in the unchilled blocks was determined. This crystalline material were found to be present in and on the surface and of the degenerate graphite present in the slow cooled unchilled 15" test blocks. It was in the form of orthorhombic crystals and what appears to be small particles of slag. The SEM scan analysis indicates that these crystals are magnesium ortho-silicate. Their presence was only noted in degenerate graphite. They did not occur in or near graphite spheroids in the chilled test blocks examined. It appears that some form oxidation is occurring or that the treating reaction is reversing over extended solidification time. For these reasons, a short solidification time (90 to 120 min.) is necessary to avoid the formation of degenerate graphite. See Fig. 8

An SEM scan of carbides present in pearly islands in samples from an unchilled 15" thick sample from Foundry No. 3 were shown to contain both Ti, V, Nb, and Mo. This type of multiple metal carbides is a common cause of brittle failures in ductile iron castings. The source is usually residual elements which are present in the steel scrap used in the base iron charge. These elements precipitate forming carbides when ductile iron solidifies over extended periods of time.

Figure No. 8
Magnesium Ortho-Silicate Crystals 15 kv X 1,000
CONCLUSIONS AND RECOMMENDATIONS

Tests and data collected during the course of this Project explains many of the existing causes for the reduced levels of mechanical properties which occur as ductile iron casting section size increases. In addition, information from our Literature Survey which was confirmed to be reliable was also used in reaching these conclusions and recommendations. We now understand that there are a series of events which take place during the solidification of large ductile iron castings with heavy sections which, if not modified will cause mechanical property deterioration in sections requiring a natural solidification time exceeding 90 minutes. These are influenced significantly by the following factors which are listed below in the descending order on the basis of their importance. Each of these factors will be discussed accordingly.

1. BASE IRON - COMPOSITION AND MELTING PRACTICE

In general, the base iron must be melted using high purity charge materials. This means that the presence of surface active element or elements such as S, O, N, As, B, Bi, Pb, Sb, Al, and Ti must be at the lowest possible levels. If present, these elements must be in the form of stable compounds which cannot be reduced by exposure to extremely high temperatures, and reducing agents such as carbon and silicon over extended periods of time. When these residual elements are present in excess, the solidification window of approximately 90 - 120 minutes becomes much smaller.

It should be understood that while it is desirable to have none or very low levels of these surface active elements present in ductile iron base irons; small quantities of these element will always be present in ductile iron. The quantity depends upon the composition of the melting and treating materials used in the process. This in turn often depends on subversive elements present in the returns, pig iron, scrap, treating materials, and inoculants used by individual foundries. As result melting and treating procedures must be individualized for each heavy section casting producer, and fine tuned accordingly.

These subversive elements can be stabilized by the additions of molecular equivalents of rare earth elements. However; even these reactions which form these very stable compounds can become reversible, if they are exposed to molten ductile iron in the presence of powerful reducing agents such as carbon and silicon for extended periods of time. For example; the six hours required for the 12 inch block or the 10 hours required for the solidification of the 15 inch test block.

A typical example of a base iron for heavy section ductile iron castings grade 60-40-18 is shown in Table No. 6. It should be understood, however; that each individual foundry will make their own modifications.
TABLE NO. 6
TYPICAL HEAVY SECTION BASE IRON COMPOSITION

<table>
<thead>
<tr>
<th>ELEMENTS</th>
<th>PERCENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>3.40 - 3.60</td>
</tr>
<tr>
<td>Silicon</td>
<td>1.10 - 1.30</td>
</tr>
<tr>
<td>Sulfur</td>
<td>&lt; 0.025</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>&lt; 0.025</td>
</tr>
<tr>
<td>Manganese</td>
<td>&lt; 0.350</td>
</tr>
<tr>
<td>Calcium</td>
<td>&lt; 0.003</td>
</tr>
<tr>
<td>Aluminum</td>
<td>&lt; 0.005</td>
</tr>
<tr>
<td>Rare Earths</td>
<td>&lt; 0.006</td>
</tr>
<tr>
<td>Oxygen</td>
<td>&lt; 0.003</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>&lt; 0.006</td>
</tr>
<tr>
<td>Arsenic</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Antimony</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Boron</td>
<td>&lt; 0.002</td>
</tr>
<tr>
<td>Bismuth</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Lead</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Copper</td>
<td>&lt; 0.060</td>
</tr>
<tr>
<td>Nickel</td>
<td>&lt; 0.060</td>
</tr>
<tr>
<td>Chromium</td>
<td>&lt; 0.010</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>&lt; 0.010</td>
</tr>
</tbody>
</table>

Other grades requiring higher tensile and yield strengths and lower elongation will need increased levels of copper, nickel, and molybdenum.

The majority of large ductile iron casting producers use electric furnaces for base iron melting. This practice makes it possible for these foundries to effectively utilize high purity melting material. Electric furnace melted base irons generally contain less entrapped slag than those from other melting procedures.

2. RECOMMENDATIONS FOR FINAL CHEMICAL COMPOSITION

Due to the slow rate at which ductile irons used in large heavy section ductile iron castings solidify, there are certain chemical composition requirements which need to be given serious consideration in order to provide optimum mechanical properties. These requirements are different from what is needed for relatively small equipment component castings which solidify almost momentarily in sand molds. These requirements are reviewed in the following paragraphs.

The CARBON EQUIVALENT VALUE in large heavy section ductile iron multi-ton castings with sections exceeding 6" must not exceed 4.3. A nominal range can be 4.1 to 4.3. This will minimize the possibility of carbon flotation which has resulted in many casting failures caused by below specification mechanical properties.
These failures are always accompanied with black or dark gray fracture in the cope of heavy section castings.

The CARBON CONTENT recommended for consideration is 3.30% to 3.50%. This will vary with the silicon and alloying metal levels.

SILICON LEVELS in a range of 2.20% to 2.50% are needed to insure that ductility (elongation) and impact (dynamic tear) are within a nominal range. A higher silicon content will result in significant reduction of dynamic tear as shown in a 9" thick test block.

The recommended RARE EARTH CONTENT should be less than < 0.010%, and RARE EARTH EQUIVALENT should be < 1. as shown under item No. 5 page No. 9

The other elements contained in the final ductile iron should remain at the same levels as indicated in TABLE NO. 6 page 23.

3. INCREASING NODULE COUNT IN DUCTILE IRON

In the course of the preliminary investigation, an effort was made to determine if it was possible to increase the nodule count in 12" test blocks from a nominal level of 40. Two separate additives were tested.

a. The first test consisted of adding 0.02% antimony (Sb) with the 75% ferrosilicon inoculation. The nodule count was increased to 70 as shown in TABLE 3 page 14

b. The second test consisted of using a 75% ferrosilicon inoculant containing stoichoimetric amounts of bismuth (Bi) and rare earths. Inoculation with this ferroalloy increased the nodule count to 70 and 78. The addition amount was 0.40% silicon.

While preliminary tests indicated that these two additives were effective for increasing nodule count, the use of chills was found to be three times more effective. It appears that in both cases the antimony and bismuth combine with rare earths creating additional nuclei which increased the nodule count substantially. This approach to increasing nodule count should be investigated further in a future project.

4. CONTROLLED SOLIDIFICATION AND COOLING - THE USE OF CHILLS

It must be understood that the mechanical properties of cast metals tend to decline in value as the section thickness increases, some to a greater extent than others, particularly agglomerates such as ductile iron, gray iron, and high silicon
aluminum alloys. Based on the Literature Survey and private communications, a number of different ways to overcome the nodule deterioration problem have been found. Unfortunately, the majority of these recommendations are not effective except under special circumstances. It has been found, however, that controlled solidification and cooling involving use of gray iron chills is by far the most simple and effective approach. In addition, cast iron chills have fewer safety risks connected with their use than the water cooled chills used in Central Europe.

In general, the research of the Heavy Section Committee has established that it is possible to produce heavy section ductile iron castings with optimum mechanical properties over a wide range of section sizes from 6 inches to over 15 inches using gray iron chills. In order to successfully provide uniform controlled solidification in the range of 90 minutes, the correct ratio between casting section size and mass and gray iron chill section size and mass must be established. This was accomplished experimentally by recognizing that the thermal conductivity coefficient for gray iron is from 25% to 33% greater than ductile iron depending on the free carbon or graphite present in the iron. In addition, this coefficient will vary becoming smaller as metal temperatures increase; thus requiring heavier and thicker chills. The committee chose to use 30% or 0.3 for the ratio in castings with thickness ranging from 9" to 18". In castings with sections below 9" the chill to thickness ratio is reduced to a range of about 0.28 to 0.25.

Using a 0.33 ratio in this simple equation makes it possible to control solidification in many different casting shapes providing they have a reasonable degree of uniformity on both sides of the casting, and the chills are cast to follow the surface contour of the casting.

\[ C = KS \]

\[ K = 0.33 \]

\[ C = \text{Chill thickness on both sides of casting section.} \]

\[ S = \text{Casting section thickness} \]

There are of course situations where contoured chill must be cast. Also, in some cases cast iron chill can be used in combination with alternate materials such as silicon carbide brick, carbon sand, and/or zircon sand to provide a rapid solidification rate. It must be understood that these alternate materials have thermal conductivity coefficients from 50% to 90% less than gray iron, and are much less effective. Unfortunately, zircon sand and chromite are not generally used in heavy section castings due to their low thermal coefficients.

Certain foundries particularly in the Far East use a practice which involves the use of controlled solidification with chills only in
areas which are subject to high stress concentrations. These foundries are usually part of a company producing heavy equipment which has a very good understanding of the stresses required in the operation of the equipment they produce. The stress calculation and solidification rate requirements can be obtained using special computer programs.

There are a number of foundries in Central European Countries which do not have the same type of insurance requirements as in the U.S. and Japan that use water cooled chills in molds, and cooling coils in internal cores. The procedure used in water cooled chills and coils is to pass nitrogen or carbon dioxide gas through the chills or cooling coils until a substantial shell of solidified metal is formed. Then water is used in the final stages of solidification and cooling. This practice requires continuous monitoring of metal temperature in the mold, as well as the temperatures and flow rate of the cooling gases and water in order to avoid the possibility of very dangerous internal explosion in the mold.

The purpose of this Project was to determine the most effective way to maximize the mechanical properties of heavy section ductile iron castings. Based on the present knowledge of the ductile iron process, Controlled Cooling (passing through the liquidus and solidus temperatures in 90 minutes or less) is the most effective method; assuming that the level of magnesium is within the normal range, and the ductile iron has been inoculated. This is based on the theoretical premise of graphite crystallization growth kinetics or the rate of solidification. The study of graphite growth kinetics shows that the shape of the graphite in cast iron is determined by the solidification rate (growth kinetics). It has been shown that in liquid magnesium treated irons with a high surface tension when the force of supercooling is relatively small, as is the case when a heavy section ductile iron castings, require many hours to pass from liquidus to solidus, degenerate graphite will forms. Spherical graphite occurs under an opposite set of circumstances. For example, when spheroidal graphite is formed by the force of super cooling (force of iron crystallization) must be sufficiently high to keep the graphite from occurring between grain boundaries in flake, vermicular, and chunky forms. There is a transition point between the level cooling force (crystallization force) required to create flake and or spheroidal graphite.

This transition point is variable depending upon the iron composition. The force rate window can be as small 15 minutes when percentages of rare earth and magnesium present in the treated iron are relatively equal, and substantial quantities of residuals are present. However; when charge materials with very low residual levels are used in combination with treating alloys containing very low levels of rare earths or none, the force rate window can be as large as 120 minutes. Therefore: each foundry producing ductile castings must determine the window of force rate which will fit their present operating requirements. This window can be small for casting which solidify in 4 to 12 minutes, and large as possible for multi-ton castings.
Based on our test data, it has been shown that extended solidification time results in these changes:

1. A reduction in nodule count.

2. An increase in the size of the graphite spheroids.

3. A pronounced decrease in the spherical shape of the large graphite nodules with trend toward vermicular graphite.

4. The presence of grain boundary segregation in the form of carbides caused by the precipitation residual carbide stabilizing elements.

5. The presence of complex magnesium compounds in the form of orthorhombic crystals which only occur when irregular shaped nodules or compacted (chunky) forms of graphite are present.

These are the factors associated with extended solidification time which lead to a decline in the overall mechanical properties of ductile iron.

THE USE OF CONTROLLED SOLIDIFICATION makes it possible to produce large heavy section castings with properties equivalent to those of steel castings, along with a 5.0% weight reduction, excellent machineability, and the high level of casting mold yield only possible in ductile iron.

A. F. Spengler
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ADENDUM PROJECT NO. 23

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PRIOR TO 1961

During the period from 1946 to 1961 the INCO Research Group was aware of the reduced properties problems in heavy section ductile iron castings. It was assumed to be the normal decline in mechanical properties which normally occurs in heavy section castings along with the ever present possibility of low free magnesium content in the metal. Their recommendations at that time were usually these:

1. Increase the nickel content, and in some situations add small quantities of molybdenum.

2. Increase nodule count by increasing the size of the inoculant addition.

3. In circumstance when large amounts of residual elements were thought to be present add cerium.

3. Increase the size of the treating alloy addition.

Based on the general knowledge available at that time, it was the opinion that even though the properties of heavy section ductile iron casting were below the standards of light section castings; they were far superior to alloy gray irons. There were some, however; brief references to an improvements in mechanical properties which occur when chills were used to control feeding in large castings. This information was from private communications between Millis and Spengler.

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