EFFECT OF RARE EARTHS ON THE PROPERTIES OF CAST IRON

by

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I. INTRODUCTION

The discovery of producing nodular shaped graphite[1,2] in cast irons occurred approximately 23 years ago. The majority of nodular graphite iron produced today is with the magnesium process.

However, in the past several years new interest has developed in the use of rare earth elements for producing nodular iron. Several commercial processes are now using rare earths in conjunction with magnesium to produce this iron. One process uses a cerium-silicon alloy with a magnesium-silicon alloy. The ratio of cerium to magnesium used in this process is one to two weight per cent.

It is the purpose of this investigation to evaluate the effects of rare earth additions on the graphite shape and matrix of a commercial base iron.

II. LITERATURE REVIEW

The separate discoveries of producing nodular or spheroidal graphite were achieved by the additions of magnesium[1] and cerium[2]. The development of nodular iron over the past twenty years has been with magnesium treatment. Recently the use of rare earth metals, mainly cerium, has become economically feasible. The following sections review some of the developments and problems of rare earth additions in the production of nodular iron.

Producing Nodular Iron With Rare Earths

At this writing, the author is not aware of any production foundry producing nodular iron purely with the rare earth elements. However, because of the nickel shortage for producing magnesium-nickel alloy, and the lower cost of cerium alloys there has been new interest in producing nodular iron with rare earths. Foundries are now using cerium alloys along with their magnesium-silicon alloys.

Cerium Treatment of Iron. Morrogh and Williams[3] demonstrated that at least 0.02 per cent retained cerium and sulphur below 0.02 per cent, spheroidal graphite could be produced in a hyper-eutectic iron. The carbon equivalent above 4.33 per cent is considered hyper-eutectic. The carbon equivalent equals the per cent total carbon plus one third per cent silicon.

These experiments indicated that there was considerable carbide stablization with the hypo-eutectic iron, carbon equivalent below 4.33 per cent. This led to treatment of hyper-eutectic iron which reduced the carbide tendencies and gave better graphite configuration.

It was also determined that hyper-eutectic nodules[4] formed before the eutectic solidification and that this graphite served as nuclei for the eutectic graphite.

Part of the conclusion that hyper-eutectic nodules formed was based on segregation of nodules at the surface of a centrifugally cast liner. Morrough and Williams reasoned that this could only happen by existence of spherulites before eutectic solidification.

It was also noted that in heavy sections the graphite would deteriorate to what Morrogh called "quasi-flake graphite"[5]. This is graphite flake that is not interconnected in the cell.

With the hyper-eutectic iron, there were problems of carbon flotation in the heavier sections. In the areas of flotation, the graphite was considerably larger and deteriorated.

Recently Mickelson and Merrill[6] used a low cost cerium alloy in order to develop a suitable commercial practice for the cerium process. The work pointed out the problem of carbon flotation which tends to be more severe than in the magnesium process. As Morrogh pointed out, the iron must be hyper-eutectic, preferably above 4.4 per cent carbon equivalent. Generally, most of the problems

associated with the cerium process stem from the carbon flotation. In Mickelson and Merrill's[7] work, deterioration of the graphite occurred where there was flotation. It also appears that the cerium process does not completely nodularize all of the graphite. There is always some quasi-flake graphite present.

These investigators concluded that cerium could nucleate nodular graphite on the hyper-eutectic graphite but not readily on the graphite expelled during the eutectic solidification. The eutectic graphite deposits on these hyper-eutectic spherulites. Eutectic graphite any distance from the hyper-eutectic spherulites would precipitate as vermicular graphite.

Cerium treatment may also produce cementite but this can be overcome by adequate post inoculation, which also improved graphite structure.

Nevertheless, good physical properties can be achieved with the cerium process. It also offers no flash reaction, higher recoveries, no fume, and very little dross compared to the magnesium process.

Other Rare Earth Treatments. Along with cerium, other rare earths can produce nodular graphite, for example lanthanum, neodymium, praseodymium, yttrium and others.

The Russians[8] have studied the effects of cerium, neodymium, and praseodymium on cast iron. The additions were made to pure iron with less than 0.01 per cent impurities. Their specimens contained 3.35 per cent carbon and 2.15 per cent silicon. The range of rare

earth additions was 0.0035 to 0.035 weight per cent. Generally as these rare earth elements increased, the hardness increased along with eutectic cementite and pearlite. Cerium favored the greatest amount of eutectic cementite, then praseodymium, neodymium, and lanthanum. At 0.03 per cent cerium, the amount of cementite was massive.

The ability of lanthanum to produce nodular graphite was not as great as cerium for a given amount of residual element. Increases in lanthanum increased the amount of nodules along with an increase in pearlite. The effects of neodymium and praseodymium on the structure fell between those of cerium and lanthanum.

These authors also mention the sharp difference of graphite form of the lanthanum containing alloy. There were sharp zones of nodules and pearlite, and zones of flake graphite and ferrite similar to the original iron matrix.

Yttrium. Some work has been done with yttrium[9] treatment of iron for producing nodular graphite. The advantages of yttrium over cerium and magnesium were high melt point(2748°F) and low propensity to chill the iron. Yttrium can be added up to 0.50 per cent without producing abnormal chill.

There is also some retention of yttrium on remelt. The investigators found that with a small addition of nodularizer on the remelted iron, elongations up to 10 per cent were achieved. This retention is of value to the foundrymen. The single disadvantage is that the cost of the element makes its use prohibitive.

Present Use Of Rare Earths

In the early development of nodular iron, problems arose in producing the desired graphite shape. It was found by investigators that certain trace elements deteriorated the nodular graphite to a flake form or affected the metal matrix. These elements were listed as tin, lead, antimony, bismuth, arsenic, selenium, aluminum, titanium, and zinc. Morrogh[10] was one of the first to work on neutralizing the effects of some of these elements.

Morrogh's work involved the additions of the various listed elements to magnesium treated irons. He concluded that lead, antimony, bismuth, titanium, and aluminum inhibited nodule growth. The adverse effects of these elements could be neutralized with small additions of cerium. For example 0.005 per cent residual cerium[11] was enough to over come the effects of 0.019 per cent lead and 0.08 per cent titanium. It was demonstrated that arsenic and tin did not effect graphite formation. However, these were powerful pearlite stablizers, and cerium had little effect on these two elements. This discovery has led to the commercial practice of treating nodular irons with small amounts of cerium usually in the form of mischmetal or cerium contained in the magnesium-silicon alloy. The amount of cerium added is in the range of 0.01 to 0.02 per cent which is sufficient to over come adverse effects of deleterious elements.

Later work[12] has shown that cerium contents of approximately 0.3 per cent in a magnesium-ferrosilicon alloy will inhibit cementite formation in this section castings. It also promotes high nodule count and good nodule shape.

It should be mentioned here that there are some contradictions as to what are deleterious elements. Heine[13] found that bismuth was helpful in promoting high nodule count particularly if the carbon equivalent was below 4.35 per cent and there were low pouring temperatures.

Also in heavy sections tellurium[14] may be helpful in improving nodular shape while lowering nodular count.

Other investigators[15] have found that rare earths in combination with titanium improved nodule shape, and with antimony reduced the amount of pearlite and improved elongation.

The contradictory findings are probably correct, the problem being the complete understanding of the variables involved. For example chemistry, pouring temperatures, section sizes, amounts and combination of these deleterious elements, and interdependence of all of these on the structure and graphite configuration need to be considered for complete understanding of the effects of these elements.

Simultaneous Additions of Mg and Rare Earth Metals. Homma and Ichimura[16] have shown that mixing 46.6 per cent calcium- 21 per cent silicon- 24 per cent magnesium alloy (Ca-Si-Mg) with a 17 per cent rare earth- 16 per cent calcium- 51 per cent silicon (R-Ca-Si) in

the proper ratio will give good physical properties while allowing the use of lower grade raw materials. The rare earths in the R-Ca-Si alloy consisted of lanthanum and cerium.

Treating with these alloys will cause lower hardness in the thinner sections of the casting. The ratio of magnesium alloy to the rare earth alloy should be in the range of one to five to one to two. The combinations of these alloys in the proper ratio will give good properties at 0.6 per cent total alloy addition.

As the R-Ca-Si alloy increases above a ratio of one to one, some of the graphite reverts to plum-blossom like[17] shape. At the same time the physical properties decrease as the R-Ca-Si alloy increases above the one to one ratio.

The Ca-Si-Mg alloy and the R-Ca-Si alloy additions for the production of nodular graphite is now a commercial practice.

The simultaneous additions of cerium-ferrosilicon alloy (11 per cent cerium and 45 per cent silicon) and magnesium-ferrosilicon alloy(9 per cent magnesium and 45 per cent silicon) is another commercial practice. The approximate additions of these alloys are 0.08 per cent cerium and 0.16 per cent magnesium.

The advantages of a rare earth process would be no violent reaction, no fume, no dross, and higher recoveries of the additions. It would also reduce the amount of equipment needed for pollution control.

III. EXPERIMENTAL METHOD

The successful use of cerium-silicon alloy to complement the magnesium alloy is not without problems. These problems are greater tendency toward cementite formation in the castings, and micro-structure correlation with strength. The latter problem arises when the process involves micro-structure evaluation for quality control purposes. Even though the structure may be acceptable, the physical properties could be on the low side of the specification.

It is the purpose of this investigation to compare the effects of cerium, lanthanum, mischmetal, and didymium on the properties of cast iron.

Materials

The following list of materials used in this investigation are commercial products used in the foundry industry, the exception being the rare earth metals which are high purity compounds.

Rare Earths. The rare earth metals involved in this investigation are cerium, mischmetal, lanthanum, and didymium. The analysis of these are listed on Table I, page 24.

Base Iron. The base metal for this investigation was from a commercial foundry. Approximately 700 pounds of desulphurized iron

was pigged into molds which produced blocks 2.5 pounds apiece. The blocks were shot blasted to remove sand and any slag. The analysis of the base metal(weight per cent) are: 3.53 total carbon, 1.06 Si, 0.27 Mn, 0.031 P, 0.011 S, 0.010 Ni, 0.18 Cu, 0.04 Mo, 0.022 V, 0.023 Ti, 0.01 Sn, and 0.073 Cr.

Refractory Material. The induction furnace had a pre-baked alumina crucible. The treating ladle was rammed with a mullite plastic cement.

Ferrosilicon. The ferrosilicon was of commercial grade containing 76.48 per cent silicon, 1.09 per cent aluminum, and 0.60 per cent calcium.

Tensile and Micro-structure Molds. The molds were made of baked oil sand. The tensile molds, one inch modified keel blocks, were made to ASTM A 396-68 specification. The micro-structure molds were made to Lynchburg Foundry Company's design[17].

Melting Procedure and Sampling

The experimental procedures were kept as simple as possible in order to achieve consistency. The treating and pouring temperatures used were in ranges that would be expected in a commercial foundry practice.

Each heat consisted of melting twenty pounds of the base metal in a high frequency induction furnace. The only additions to the

furnace were silicon and graphite.

The molten metal was super-heated to approximately 2740°F. The metal was then tapped into the treating ladle onto the rare earth metal. A one per cent ferrosilicon addition was added to the stream of metal for inoculation. The treated metal was then stirred with a steel rod.

The heats were done in series of four identical treatments except for the change in the rare earth metal. Table II, page 25, gives the amounts of silicon, graphite, and rare earth added to each heat.

The treated iron was then poured into the molds in a temperature range of 2480° to 2540°F. The samples poured were: modified keel block, pin samples for carbon and silicon analysis, chilled wafer for spectrographic and X-ray analysis, and a Tectip, Leeds and Northrup determinator for carbon equivalent. The phase change of the metal is determined by an expendable type K thermocouple in a molten metal reservoir. The thermocouple is connected to a Speedomax H instrument, and the arrest is recorded. The arrest point, liquidus temperature, is a function of the carbon equivalent.

The total time involved from treatment to pour-off was approximately five minutes.

The temperature measurements were made with an optical pyrometer at the furnace, set on 0.4 emissivity range, and an immersion thermocouple, plantinum-10% plantinum rhodium thermocouple at the

treating ladle. All of the temperatures are recorded on Table II, page 25.

Tensile Bars. Two bars were poured in each heat. One of the bars was tested in the as-cast condition. The other bar was subjected to an annealing heat treatment cycle before testing. The tensile bars were machined and tested in accordance with ASTM A 395-68 Specification.

Heat Treatment Cycle. The bars were heated up to a temperature of 1650°F and held there for two hours. After the two hour hold, the bars were air quenched from a temperature of 1650°F. The bars were then tempered at a temperature of 1350°F for two hours holding time. The bars were then cooled at a temperature rate of 100 degrees per hour, and at 650°F the bars were pulled from the oven.

IV. RESULTS AND DISCUSSION

The tests were made in series of four heats with identical carbon and silicon additions. The rare earths were added in equal amounts, but each heat had a different rare earth metal. Table II, page 25, gives the additions for each heat and Table III, page 26, gives the final chemistry results.

All of the tests, except series one, had carbon flotation. This was the major cause of the low elongation values. Figure 1, page 28, shows a plot of the carbon equivalent(C.E. = % total carbon plus 1/3 % silicon) of the pin samples versus the carbon difference between the pin samples and the tensile specimens. It is apparent that as the carbon equivalent increases, the carbon flotation increases.

The didymium metal contained 2.25 per cent magnesium, and this resulted in noticeable flash when the molten metal was poured onto this rare earth. In the cerium, lanthanum, and mischmetal addition tests, there were no signs of flash reaction.

Carbon Structure

On page 29, Figure 2, are the types of graphite structures that resulted from the rare earth addition tests. Figure 2a is the nodular graphite which was present in all of the tensile

specimens in varying amount. The nodular graphite was usually in the lower portion of the bar. The feathery type graphite, Figure 2b, was always found in the extreme top portion of the tensile bar. Figure 2c, vermicular type graphite was generally found in the top portion of the bar. However, the specimens with lanthanum metal additions usually had vermicular type scattered throughout the micro-structure. The undercooled graphite, ASTM classification type D, Figure 2d, was evident only in several of the micro-structures examined.

Figure 3, page 30, shows a typical fracture of a cast tensile bar which was poured horizontally. The dark area at the top is the area of carbon flotation and is at the riser connection. The dark area can be readily correlated with strength, the larger the dark area the lower the strength. Figure 4, page 31, shows the micro-structure of the tensile fracture at the light and dark area of Figure 2.

Untreated Sample. Figure 5, page 32, shows a sample with no rare earth additions or inoculation. The chemistry of this sample is 3.72 per cent total carbon and 3.15 per cent silicon. Most of the graphite is in the form of undercooled with some flake type. The matrix is essentially ferritic.

Series One Test

The carbon equivalents in these heats were similar to that of the magnesium process for producing nodular iron. The physical properties are given on Table IV, page 27. The rare earth metal didymium gave the highest physical properties in this test.

Figure 6a, page 33, shows a typical micro-structure of the as-cast iron in this test. All of the tensile specimens had cementite scattered throughout the matrix and there was about 30 to 40 per cent pearlite. In the heats containing cerium, lanthanum, and mischmetal only about 5 per cent of the graphite was in the nodular form. The didymium tensile specimen had approximately 15 per cent nodular graphite. The rest of the graphite in the tensile specimens was in the vermicular form.

The micro-structure on the annealed specimens retained approximately 5 per cent pearlite with some cementite in the pearlite. Figure 6b shows a typical annealed tensile specimen.

Series Two Test

A carbon addition of 0.05 per cent was made in this test in order to make the iron hyper-eutectic, carbon equivalent about 4.33 per cent. The rare earth additions were also raised from 0.08 to 0.15 per cent addition. Both of these changes were made to improve physical properties and graphite structure.

The only significant increase in physical properties was in the cerium addition heat, C-2, Table IV. The graphite structure was approximately 80 per cent nodules, 50 to 60 per cent pearlite, and 5 per cent cementite. There was no feathery type graphite in the micro-structure. Figure 7, page 34, shows the micro-structure of the as-cast and annealed tensile specimens. It also shows the micro-structure of the 3/8 inch metal section specimen which has considerably more cementite than the tensile bar specimen. This was the case throughout all of the tests, except test four.

The lanthanum addition test had massive cementite at the bottom portion of the bar and scattered cementite at the top. Figure 8, page 38, shows the micro-structure of these two conditions.

The mischmetal and didymium addition heats had approximately 20 to 30 per cent nodular graphite, 10 to 30 per cent pearlite, and scattered cementite throughout the matrix. In the top portions of all the bars there were vermicular and feathery type graphite. The micro-structures are similar to those in Figure 9, page 39.

Series Three Test

A further increase in rare earth additions was made, from 0.15 to 0.20 per cent, to improve physical properties. There was a slight improvement in the lanthanum, mischmetal, and didymium additions while the cerium addition heat had lower physical properties than the series two test. Typical micro-structures are

shown in Figure 9. Again all of the heats had deteriorated graphite in the top portion of the tensile specimens.

Series Four Test

The rare earth additions for this test were lowered to 0.15 from 0.20 per cent since the increase in series three did not result in any significant improvement of physical properties. The silicon addition at the furnace was raised in order to increase the final silicon content of the iron above 2.70 per cent. This was done in an attempt to improve the elongation values.

The significant result of this test was that there was no cementite present in either the tensile specimens or the 3/8 inch micro-structure specimens. Figure 10, page 37, represents a typical micro-structure of the lower portion of the as-cast bars.

There was 30 to 50 per cent nodules present and approximately 30 per cent pearlite. The top half of the specimens had both verimcular and feathery types of graphite.

Series Five Test

This test was conducted with 0.08 per cent magnesium additions along with the 0.15 per cent rare earth additions. The purpose was to improve graphite structure and reduce flotation. The results were the lowest elongation values of any of the tests.

The micro-structure consisted of 20 to 30 per cent nodules. The top portion of the bars had approximately 30 per cent more feathery type graphite than the other tests. All of the micro-structures had scattered cementite throughout the matrix, while the lanthanum addition heat had massive cementite scattered throughout the matrix, Figure 11, page 38.

Physical Properties

The as-cast tensile and yield properties were comparable to those reported in the literature. The elongation values were low.

The annealed physical properties are low compared to magnesium treated irons. However, the properties are comparable to ferritic malleable iron, cupola melted. A possible advantage of rare earth treatment of irons over the ferritic malleable would be a reduction in the time for heat treatment.

Rare Earth Analysis

The rare earth analysis, Table III, shows some of the cerium and neodymium values higher than what was added. This was due to the high background count for the X-ray determinations. See the appendix for more detailed information. However, the increased rare earth additions did not increase the tensile properties.

V. CONCLUSIONS

The rare earth metals cerium, lanthanum, mischmetal, and didymium were added to irons in ranges of 0.08 to 0.20 per cent. The irons were made from one base composition. Graphite and silicon were added at the electric furnace to change the carbon equivalent. The irons for series one test were approximately at eutectic composition with 0.08 per cent rare earth additions. In series two test 0.50 per cent graphite was added with 0.15 per cent rare earth additions. In series three tests 0.20 per cent rare earth additions were made with the same graphite and silicon additions as in test two. Test four had 0.50 per cent graphite, 1.47 per cent silicon and 0.15 per cent rare earth additions. Test had the same additions as test four, except for a 0.08 per cent magnesium additions. In the series two through series five tests, the irons were hyper-eutectic.

The 20 pounds of metal were poured from the furnace into the treating ladle in a temperature range of 2740° to 2780°F. The metal was then poured from the treating ladle into the sampling molds, temperature range of 2490° to 2530°F. The following conclusions were drawn:

1. As the carbon equivalent increased, the carbon flotation increased.

2. All of the tensile specimens with carbon equivalent above the eutectic had carbon flotation.

3. In the top portions of the bars the graphite was deteriorated from the nodular. In the bottom portions of the bars the graphite was essentially nodular in form.

4. All of the tensile specimens had cementite scattered throughout the matrix, except those in test four. The silicon level in test four was raised above 2.70 per cent.

5. The irons with lanthanum additions had the largest amount of vermicular graphite, and the lowest physical properties.

6. The irons with didymium additions gave the most consistent results of physical properties and they were usually the highest.

7. The low elongation values were a result of carbon flotation.

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VII. FUTURE WORK

From the results of this experiment, it appears that future work should involve using a rare earth alloy to develop an iron just above the eutectic that would produce a nodular graphite structure. The advantage of this should be reduced tendency for graphite flotation. The problem would be the cementite formation in the matrix. However, this could be over come with inoculation treatment to the iron.

The nodularizing alloy should consist of combinations of rare earth metals, other than mischmetal, or rare earth metals with various amounts of magnesium not to exceed five per cent of the total alloy content.

TABLE I

Analysis of High Purity Rare Earth Metals

Elements	Mischmetal	Cerium	Lanthanum	Didymium
	wt %	wt %	wt %	wt %
Grade	99.9	99.9	99.9	97
Ce	53	N.D.	0.10	1.40
La	23	0.03	N.D.	1.98
Nd	16	0.07	0.05	75.2
Pr	5	----	0.12	12.7
Dy	Tr	----	----	----
Gd	2	----	----	4.6
Cr	0.034	----	0.002	----
Cu	----	0.016	----	----
Fe	0.035	0.014	0.043	0.35
Mg	0.032	0.030	0.010	2.25
Mn	0.006	0.023	0.004	0.010
Si	0.010	0.005	0.029	0.070
C	0.008	0.001	0.001	0.044

N.D. - Not Determined
--- - Not Traced
Tr - Trace

TABLE II

Heat Identification and Alloy Additions

For Rare Earth Comparison Tests

Heat No.	Additions to Furnace Carbon	Fe-Si	Ladle Additions R.E.	Fe-Si	Treatment Temp.	Pour Temp.
	wt %	wt %	wt %	wt %	°F	°F
C-1	---	0.80	0.08	1.0	2710	2500
L-1	---	0.80	0.08	1.0	2690	2490
M-1	---	0.80	0.08	1.0	2740	2480
D-1	---	0.80	0.08	1.0	2740	2520
C-2	0.50	0.80	0.15	1.0	2740	2480
L-2	0.50	0.80	0.15	1.0	2740	2500
M-2	0.50	0.80	0.15	1.0	2740	2490
D-2	0.50	0.80	0.15	1.0	2735	2480
C-3	0.50	0.80	0.20	1.0	2740	2500
L-3	0.50	0.80	0.20	1.0	2740	2500
M-3	0.50	0.80	0.20	1.0	2740	2500
D-3	0.50	0.80	0.20	1.0	2745	2495
C-4	0.50	1.47	0.15	1.0	2740	2530
L-4	0.50	1.47	0.15	1.0	2740	2520
M-4	0.50	1.47	0.15	1.0	2740	2480
D-4	0.50	1.47	0.15	1.0	2740	2500
C-5	0.50	0.80	0.15	1.0	2770	2540
L-5	0.50	0.80	0.15	1.0	2760	2490
M-5	0.50	0.80	0.15	1.0	2780	----
D-5	0.50	0.80	0.15	1.0	2780	2540

C - Cerium Metal
L - Lanthanum
M - Mischmetal
D - Didymium

Series test five had 0.08 per cent Magnesium addition.

TABLE III

Final Chemistry Results of Rare Earth and Alloy Additions

Heat No.	Pin Samples T.C. %	Pin Samples Si %	Tensile Specimens T.C. %	Tensile Specimens Si %	Wafer Specimens Ce %	Wafer Specimens La %	Wafer Specimens Nd %	Wafer Specimens Pr %
C-1	3.48	2.26	3.44	2.30	0.093	-----	-----	-----
L-1	3.58	2.33	3.60	-----	-----	0.036	-----	-----
M-1	3.57	2.37	3.62	2.34	0.08	-----	-----	-----
D-1	3.53	2.33	3.60	-----	-----	-----	0.11	0.013
C-2	3.82	2.28	3.72	2.34	0.14	-----	-----	-----
L-2	3.88	2.28	3.78	-----	-----	0.043	-----	-----
M-2	3.90	2.31	3.79	-----	0.073	-----	-----	-----
D-2	3.88	2.28	3.78	2.27	-----	-----	0.11	0.013
C-3	3.95	2.36	3.74	2.32	0.152	-----	-----	-----
L-3	3.88	2.56	3.76	-----	-----	0.046	-----	-----
M-3	3.91	2.40	3.72	-----	0.10	-----	-----	-----
D-3	3.88	2.42	3.72	-----	-----	-----	0.12	0.014
C-4	4.00	2.78	3.84	2.73	0.149	-----	-----	-----
L-4	3.96	2.93	3.83	2.84	-----	0.043	-----	-----
M-4	4.04	2.76	3.73	2.67	0.08	-----	-----	-----
D-4	3.94	2.88	3.52	-----	-----	-----	0.11	0.012
C-5	4.02	2.66	3.56	-----	0.146	-----	-----	-----
L-5	4.02	2.62	3.54	2.60	-----	0.048	-----	-----
M-5	4.02	2.59	3.68	-----	0.078	-----	-----	-----
D-5	4.02	2.80	3.62	-----	-----	-----	0.10	0.011

Series five test had 0.08% magnesium addition. The retained magnesium: C-5, 0.014; L-5, 0.010; M-5, 0.012; D-5, 0.019.

TABLE IV

The Effects of Rare Earth Additions on the As-Cast and Annealed Iron Properties

Heat No.	As-Cast Properties U T S	Y S	Elong.	Hard-ness	Annealed Properties U T S	Y S	Elong.	Hard-ness
	psi	psi	%	bhn	psi	psi	%	bhn
C-1	61,900	44,000	2.5	187	48,400	35,000	6.5	137
L-1	55,000	42,000	2.5	170	44,800	35,000	5.0	137
M-1	55,600	43,500	4.5	166	46,200	35,000	6.0	137
D-1	68,700	51,000	3.0	217	46,600	35,000	7.0	137
C-2	79,600	50,500	9.0	192	56,200	36,000	15.5	143
L-2	55,300	42,000	5.5	163	49,000	36,000	7.0	149
M-2	60,400	48,500	3.5	179	51,000	36,000	8.5	143
D-2	63,300	46,500	4.0	192	48,800	35,000	8.5	140
C-3	62,200	49,000	3.0	179	47,200	37,500	2.5	143
L-3	60,000	48,500	2.0	187	49,300	39,000	4.5	143
M-3	65,300	51,000	6.0	187	49,900	35,000	9.0	143
D-3	70,200	49,000	7.5	202	53,100	37,000	12.0	143
C-4	60,000	51,000	2.0	179	54,000	42,000	5.5	156
L-4	59,000	48,000	3.5	166	54,600	45,000	3.5	163
M-4	58,300	48,000	1.5	170	48,400	47,000	6.0	153
D-4	87,200	57,000	3.5	212	57,000	42,500	10.5	149
C-5	58,700	52,500	1.0	196	48,800	44,000	1.5	149
L-5	56,200	50,000	1.5	196	43,300	43,000	None	149
M-5	60,900	52,000	1.5	207	46,300	46,000	2.0	166
D-5	70,000	56,500	3.0	202	44,300	44,000	2.5	156

The annealed tensile bar D-5 was flawed.

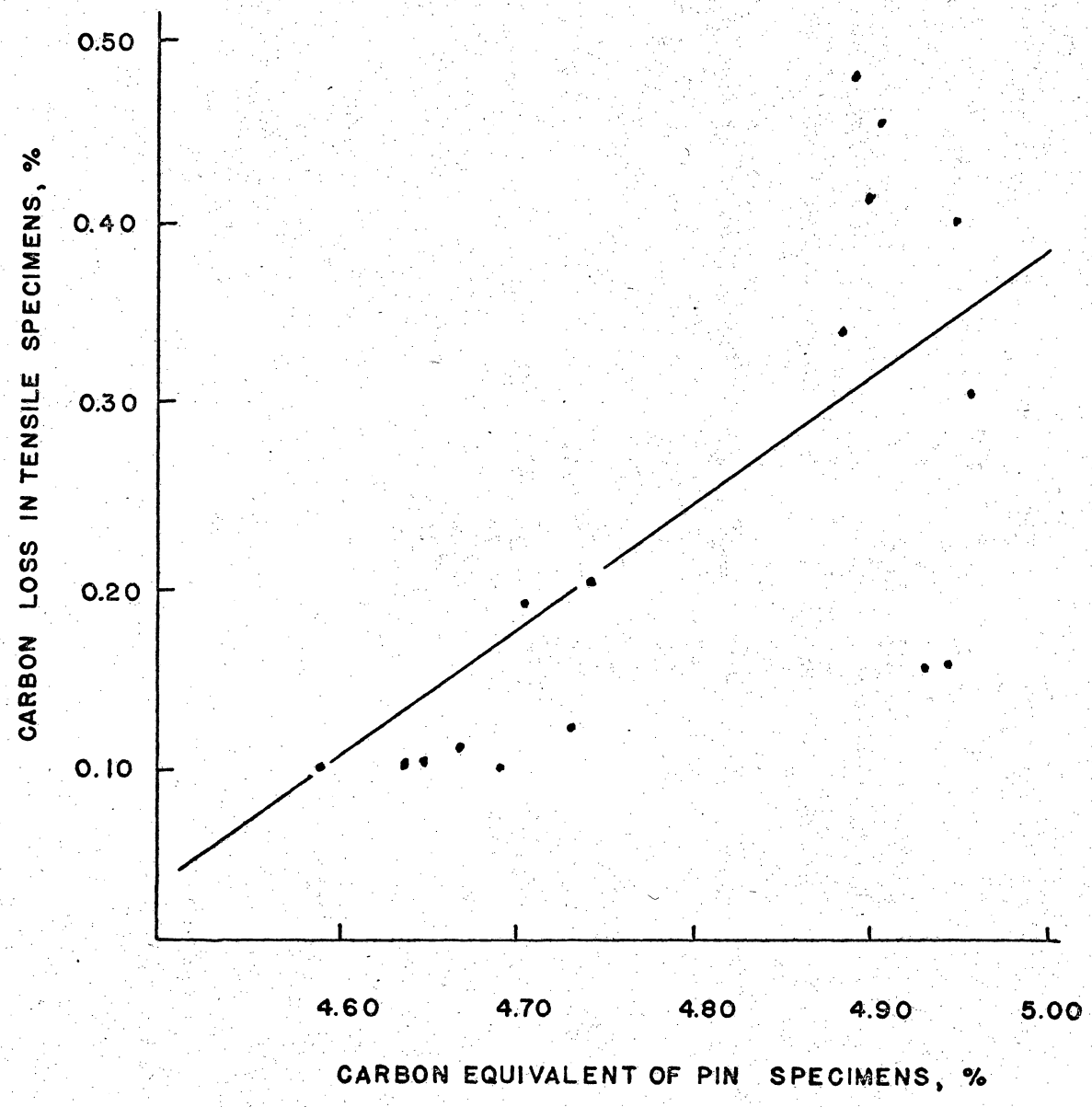


FIGURE I. CARBON FLOTATION IN ONE INCH KEEL BLOCKS OF RARE EARTH TREATED IRON

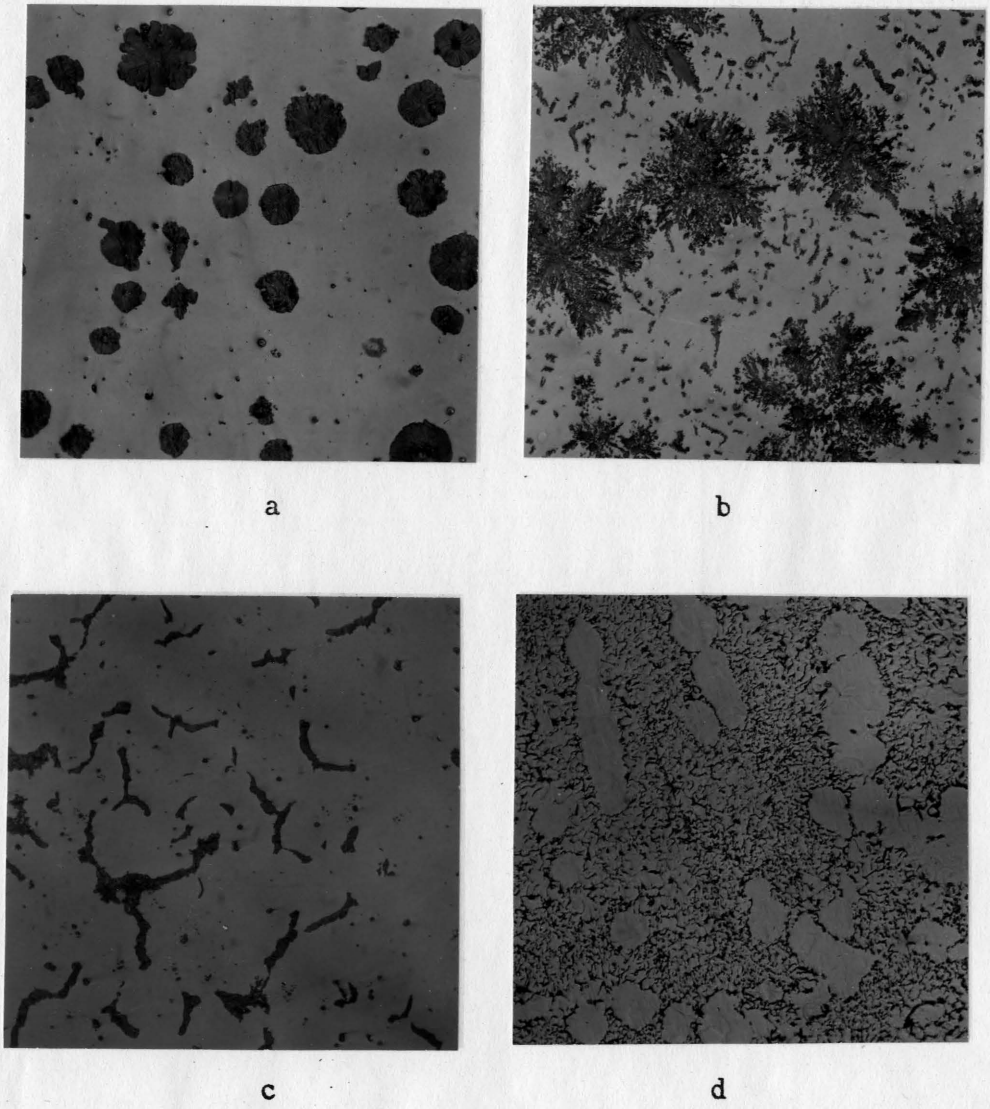


Figure 2. Graphite structure that resulted from rare earth additions, unetched, 200X. a) nodular. b) feathery. c) vermicular. d) undercooled, or type D.

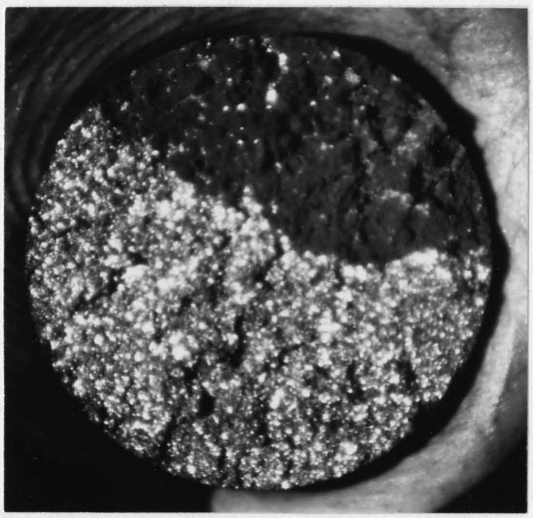


Figure 3. Fracture of cast tensile bar showing carbon flotation, black area, 5X.

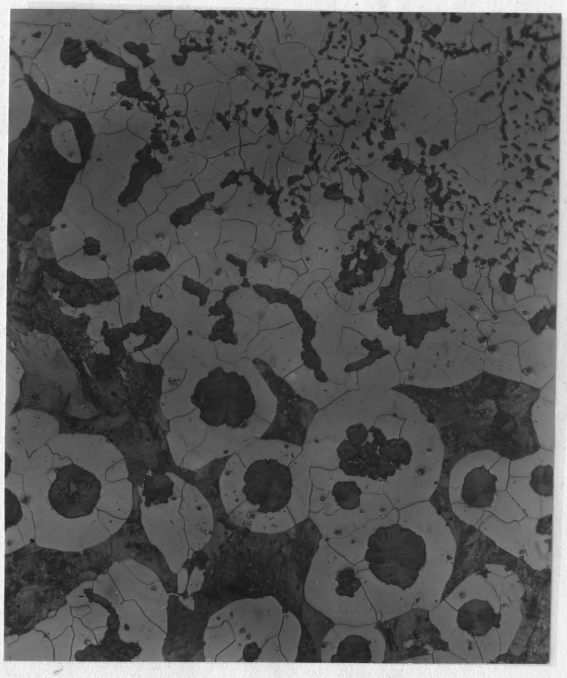


Figure 4. Micro-structure of tensile fracture at the white and black area in Figure 2, 5% nital etched, 200X.

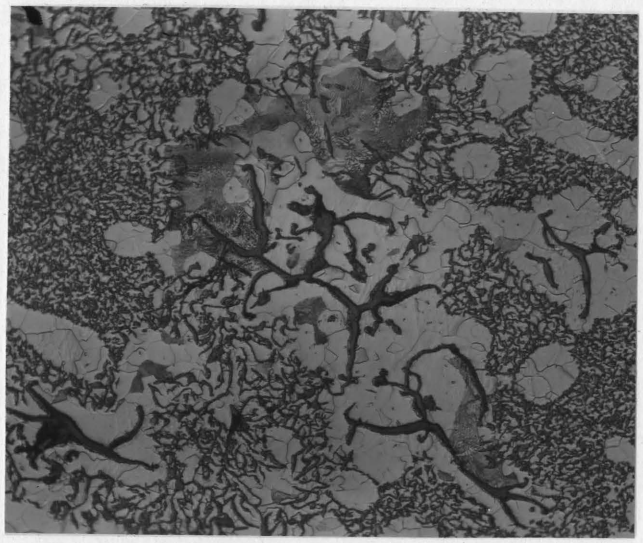
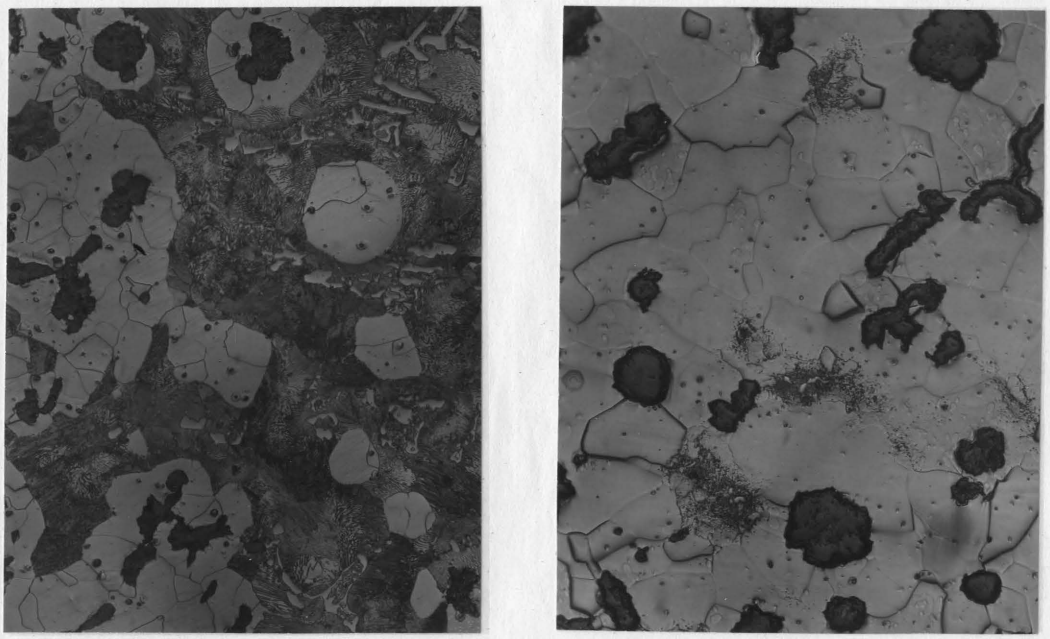
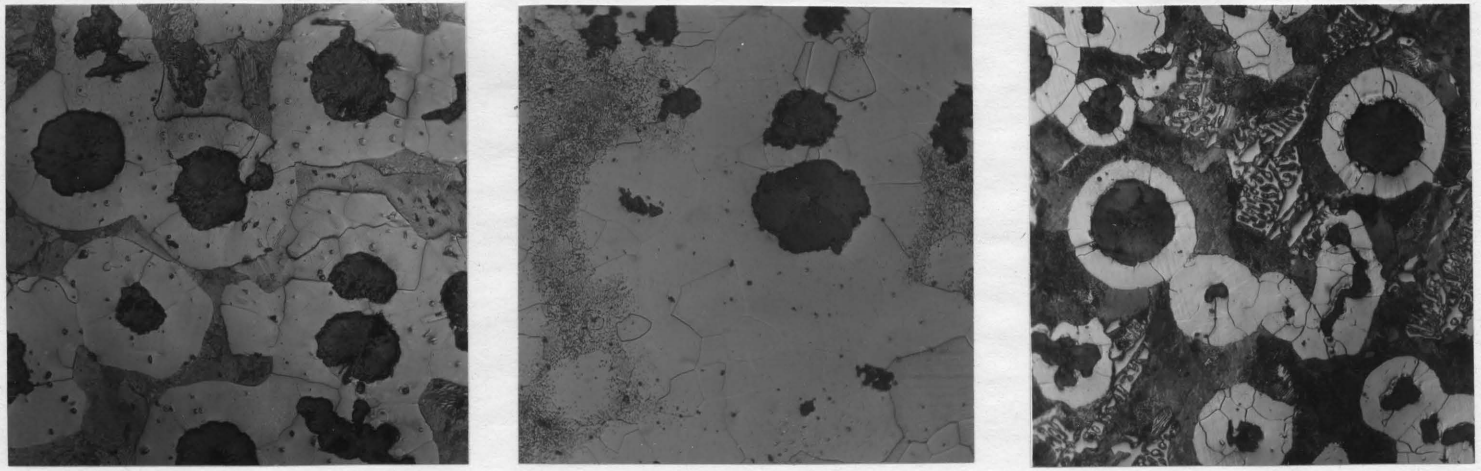


Figure 5. Micro-structure of untreated and uninoculated iron specimen, 5% nital etched, 200X.



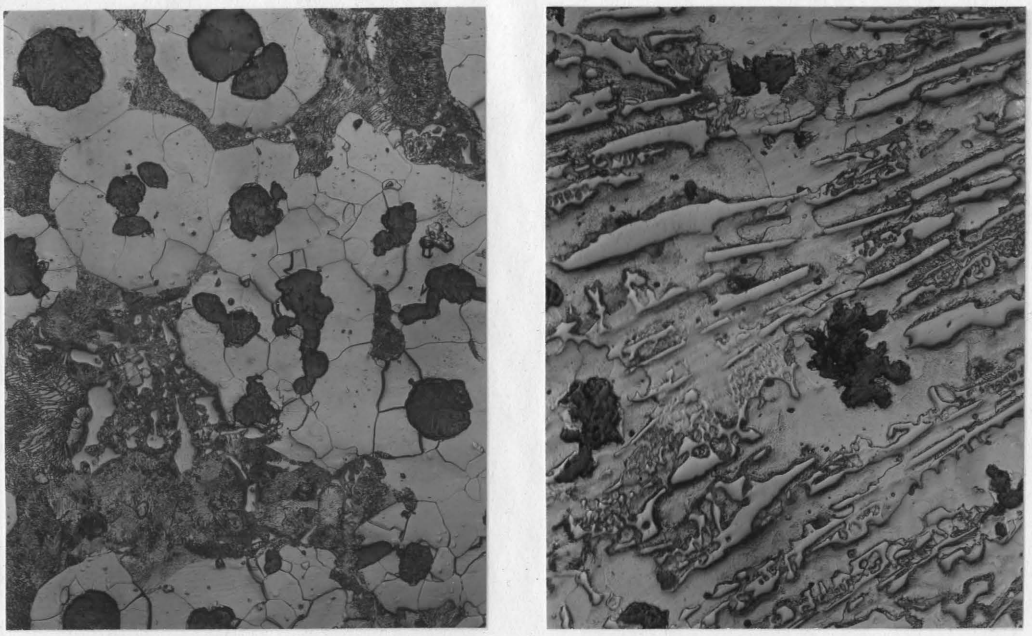
a b

Figure 6. Typical micro-structure of tensile specimens in series one test, 5% nital etched, 200X. a) as-cast tensile specimen. b) annealed tensile specimen.



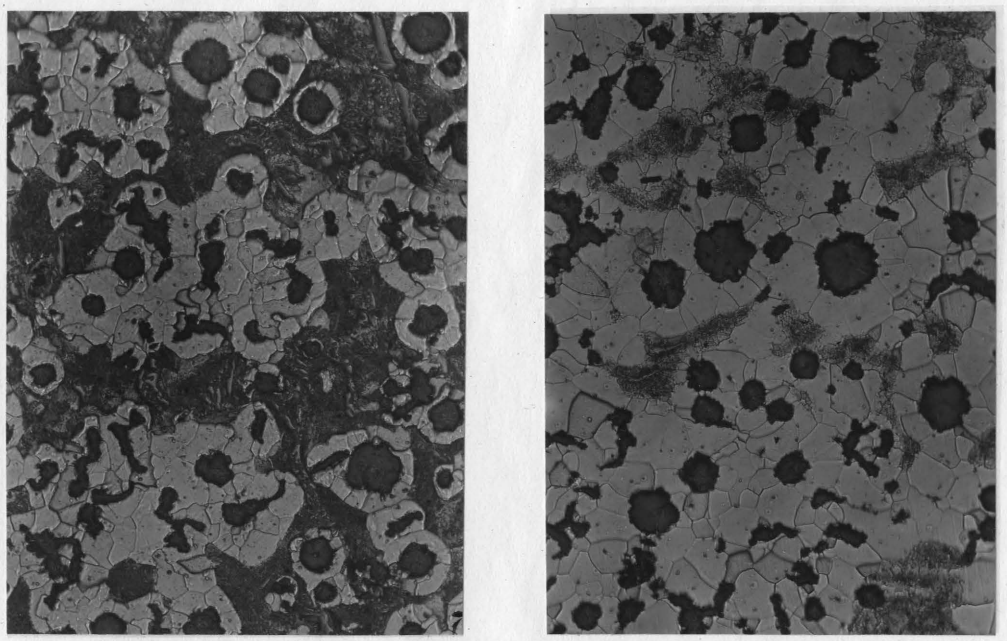
a b c

Figure 7. Micro-structure of cerium addition specimens in test two, 5% nital etched, 200X. a) as-cast tensile specimen, b) annealed tensile specimen. c) 3/8 inch metal section specimen, as-cast.



a b

Figure 8. Micro-structure of lanthanum addition of tensile specimen in test two, 5% nital etched, 200X. a) top of bar. b) bottom of bar.



a b

Figure 9. Typical micro-structure of tensile specimens in test three, 5% nital etched, 100X. a) as-cast specimen. b) annealed specimen.

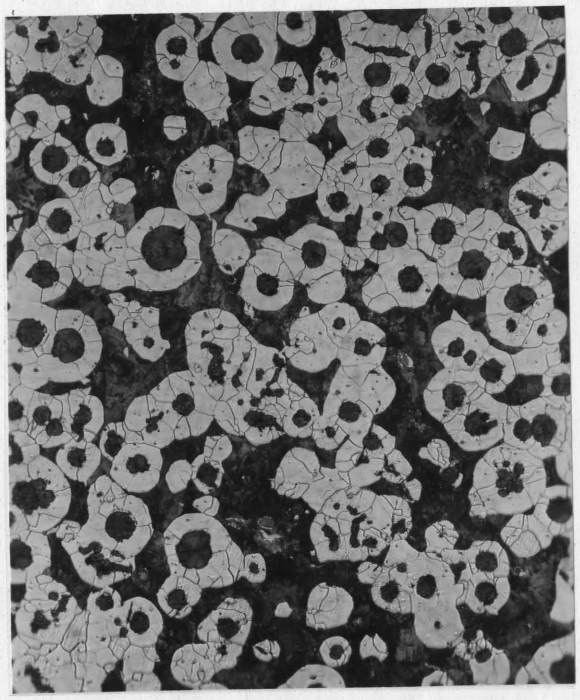


Figure 10. Typical micro-structure of lower portion of tensile specimen in test four, note absence of cementite, 5% nital etched, 100X.

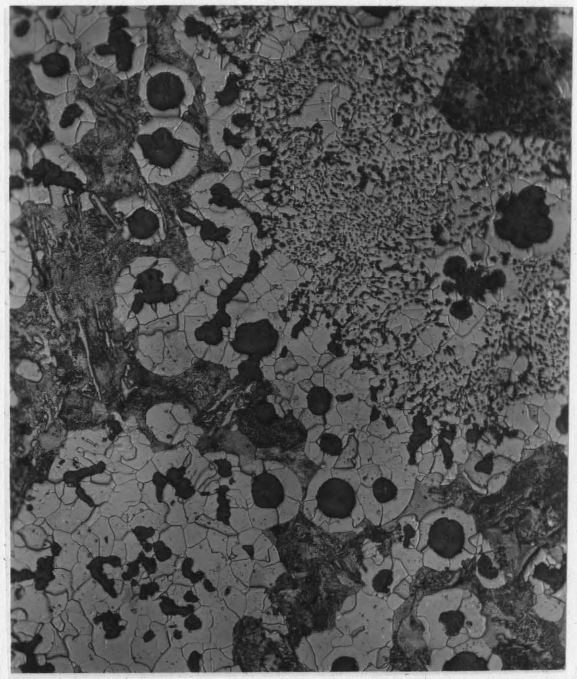


Figure 11. Micro-structure of tensile specimen with lanthanum addition in test five, 5% nital etched, 100X.

VIII. APPENDIX

Rare Earth Analyses

Rare earth analyses are extremely difficult, particularly when the iron contains a large number of elements such as the iron used in this experiment. The large number of elements present caused high background count and this is the reason for values of cerium and neodymium being higher than some of the additions. The background count was as high as 0.008 per cent. The precision of the analyses was plus or minus 0.003 per cent. Taking this into account the recoveries were quite good on cerium and neodymium.

The lanthanum analyses on the mischmetal addition could not be made because of very low radiation readings. It is believed that there was some interference by another element.

The lanthanum recoveries in the lanthanum additions were low. The micro-structures examination revealed poor graphite form in most of the tensile specimens.

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EFFECT OF RARE EARTHS ON THE PROPERTIES OF CAST IRON

by

William Andrew Thomas, Jr.

Abstract

The rare earth metals cerium, mischmetal, lanthanum, and didymium were added to irons in the amounts of 0.08 to 0.20 per cent. Silicon and graphite were added to the iron at the electric furnace to change the carbon equivalent of the base metal.

The base metal was super-heated to temperatures of 2740° to 2780°F. The molten metal was poured onto the rare earth with a one per cent silicon addition for inoculation. It was then poured into the tensile molds in a temperature range of 2490° to 2540°F.

The appearance of the tensile fracture indicated the presence of carbon flotation. The chemical analysis and micro-structure examination verified this. All of the tensile specimens with carbon equivalent above the eutectic had flotation. As the carbon equivalent increased the carbon flotation increased.

The graphite structure in the carbon flotation region was deteriorated from the nodular, and the graphite was nodular in form in the lower portions of the specimens. Cementite was scattered throughout the matrix of all samples except those with silicon contents above 2.70 per cent.

The metal with didymium additions had the most consistent physical properties, while lanthanum produced the lowest physical properties. The tensile and yield values where comparable to those reported in the literature for similar additions. However, the elongation values were low due to the carbon flotation.