Selection of raw materials and control of trace elements for production of high-quality SG iron

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Abstract: During the production of SG iron, the selection of raw materials and control of chemical composition are most important. From the very early days of SG iron production, the effects of trace elements on graphite form and matrix structure have been studied, and the allowable concentration limits for their detrimental influence has been decreased year by year, during the last fifty years. This paper has reviewed some of the suggested SG iron trace elements in the literature and in several Chinese foundries. It was found that for most SG iron castings, rare earth elements are still required to neutralize the harmful effects of trace elements and improve SG iron quality. It also found that the use of high purity and ultra-high purity base iron melts enabled integrated, safety-critical and complicated SG iron castings of varying thickness, and heavy-section, to be produced successfully. These SG iron castings have surprisingly good structures, and their mechanical and dynamic properties are vastly superior to those specified in current international SG iron standards. Further study is required on the effects of using high purity and ultra-high purity base melts on the structure and properties of SG iron.

Key words: trace elements; anti-nodulizing and pearlite factors; chunky graphite; high and ultra-high purity pig iron; high quality SG iron

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Production of SG iron includes the selection of raw materials and control of base iron composition, the spheroidizing treatment, inoculation and pouring processes. Among these, the selection of raw materials and control of base iron composition are of major importance. The elements in SG iron can be divided into four groups: primary or major, spheroidising, alloying, and trace elements. The primary elements are iron, carbon, silicon, manganese, phosphorous and sulphur; spheroidizing elements are magnesium and rare earth elements such as cerium; alloying elements are typically copper, molybdenum and nickel; trace elements are those whose contents are very low and unintentional; they normally originate from the charge materials and may or may not have an effect on the quality of the casting^[1-3].

Since the early years of SG iron production, the effects of trace elements have been studied^[4-8]. In 1952, Morrogh H.^[4] pointed out the damaging effect of trace elements such as Ti, Pb, Sb, Bi, As, P, As, etc. on the nodular graphite shape of magnesium-treated SG iron. He also found that a small amount of rare earth elements could

neutralize the harmful effect of these trace elements on nodular graphite shape. These effects are complicated and some of them have multifold influences. Some trace elements, such as Bi, Ti, As, Sn, Pb, Al and Sb, inhibit graphite spheroidization and promote the formation of flake graphite, vermicular graphite, or other undesirable, degenerate types of graphite. Such elements are often called 'tramp' or interfering elements. Some of these (Bi, Sb, As and Pb) have an additive effect when they exist simultaneously, and have a stronger influence on graphite morphology. Figure 1 shows the flake graphite caused by tramp elements when using a pure magnesium spheroidizing treatment^[5].

Some trace elements (Sn, Pb and Bi) are strong pearlite promoters; other elements (Cr, V, Mo, Ti and B) are strong carbide promoters. All these elements are positive segregation elements and segregate to the last solidified areas, to form intercellular carbides and inclusions. Figures 2 and 3 show the intercellular carbides and inclusions due to high Mn, S and other minor elements^[6]. The presence of these carbides and inclusions will decrease mechanical properties of SG iron, especially impact and fatigue properties. Thus, for safety-critical SG iron castings and for SG iron castings requiring high, low-temperature impact properties used for high-speed trains, wind power, storage containers for spent nuclear fuel, etc., all the tramp elements must be strictly controlled.

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Fig. 1: Flake graphite caused by high titanium content^[5]

Fig.2: Inclusions and carbides at cell boundary^[6]

Fig. 3: Inclusions at cell boundary^[6]

In order to evaluate the influence of trace elements on graphite spheroidization, Thielemann, in 1968, developed a trace element evaluation number K_1 for assessing the ability of a charge to produce well-formed graphite nodules^[3,7]. This equation is only valid for calculations on base iron melts incorporating steel scrap, pig iron and returns, and not for the final composition.

$$K_1 = 4.4 (\%Ti) + 2.0 (\%As) + 2.3 (\%Sn) + 5.0 (\%Sb) + 290 (\%Pb) + 370 (\%Bi) + 1.6 (\%Al) \quad (1)$$

The above equation (1) was developed during the 1960s by experimenting on castings with wall thicknesses of 8–45 mm, using different pig irons (37 different variants from around the

world, with 17 of these specifically intended for producing SG iron), in combination with SG iron returns and steel scrap. The work was based on 200 industrial heats and 163 laboratory melts, by different experimental groups, having varying levels of Bi, Sb, Sn, As, Sb and Ti.

It can be seen from equation (1) that Pb and Bi have the strongest anti-nodulizing effect, followed by Sb, Ti, Sn, As, and Al. It is reported that Se is also an anti-nodulizing element, but it is not included in the equation. Thielemann suggested that when $K_1=1\pm0.0625$, no correction of the charge composition is necessary for obtaining an SG iron with a nodularity above 85%^[3,7]. Equation (1) is sometimes found in the literature with the denomination ‘anti-nodulizing action factor’ and is always used for the final composition, instead of the charge composition^[3,9-10].

Several relationships have been proposed to relate the composition of cast irons with the amount of ferrite and/or pearlite in the matrix structure. Among them, Thielemann focused on pearlitic grades, the effect of impurities, and also the effect of Si. He expressed the Pearlite Influence Factor (P_X) as follows^[3,7,9-10,20]:

$$P_X = 3.0 (\%Mn) - 2.65 (\%Si-2.0) + 7.75 (\%Cu) + 90 (\%Sn) + 357 (\%Pb) + 333 (\%Bi) + 20.1 (\%As) + 9.60 (\%Cr) + 71.7 (\%Sb) \quad (2)$$

This P_X value is often called the Quality Index (QI) in literature, especially when referring to ferritic grades of SG iron^[9-10,20]. The P_X value expresses the relative tendency of elements to promote the formation of pearlite, and the tendency to form carbide, as elements Mn and Cr are carbide promoters. The P_X value also indicates the purity of an SG iron; the lower the P_X value, the purer the SG iron.

In the following sections, some SG iron trace elements reported in the literature and in several Chinese foundries were evaluated by applying the K_1 formula; elimination of the harmful effects of tramp elements by using rare earths was also discussed. The control and prediction of structure and properties of SG iron by controlling K_1 , P_X and Sum Pearlite Elements (the sum of Pearlite-stabilizing elements) were reviewed. Chunky graphite and its prevention, and the production of high-demand SG iron castings by using high purity and ultra-high purity pig iron were also described.

1 Selection and control of trace elements for final composition of SG iron

Gundlach suggested that when $K_1 < 1.0$, spheroidal graphite is possible; when $K_1 > 1.0$, degenerate graphite is likely to be formed, and rare earth additions are required to neutralize the effect of deleterious trace elements^[13]. Tables 1 to 5 show the final maximum content of trace elements in SG iron according to the literature. Table 1 shows only the maximum levels of Sb, As and Pb, by D. S. White of Elkem^[11]. It can be seen that the maximum levels of these elements have decreased significantly during a period of 40 years.

Table 1: Lowering of trace element levels (wt.%) over time by White of Elkem ^[11]

Year	1967	1998	2007–2009
Sb	0.0002–0.0090	0.0080	0.0031
As	0.0010–0.0380	0.0160	0.0053
Pb	Up to 0.0050	0.0043±0.0011 (max. 0.0080)	0.0011

Table 2 shows the maximum level of trace elements that can adversely affect SG iron properties, graphite formation and matrix structure, by Sorelmetal ^[12]. Table 3 shows the tolerances for trace elements suggested by Gundlach of Element Materials Technology, Wixom ^[13]. Table 4 shows the suggested targets and typical control ranges for the production of ADI ^[14]. Table 5 shows the maximum content of minor elements in SG iron, suggested by FOSECO ^[15].

Table 2: Maximum level (wt.%) of trace elements that can adversely affect SG iron properties, graphite formation and matrix structure, by Sorelmetal ^[12]

Element	Maximum level
Al	0.03
As	0.01
B	0.002
Bi	0.002
Cd	0.002
Pb	0.002
Sb	0.003
Se	0.002
Te	0.002
Zr	0.01

Table 3: Tolerances (wt.%) for trace elements suggested by Gundlach of Element Materials Technology Wixom ^[13]

Element	Maximum allowed content
Pb	0.002
Sb	0.002
Sn	0.002
Bi	0.002
Te	0.02
Al	0.04
Ti	0.05
Zr	0.01
Se	0.01

Table 4: Suggested targets and typical control ranges (wt.%) for production of ADI ^[14]

Element	Maximum level
Sn	0.02 (only as needed) typically control range ±0.003
Sb	0.002 (only as needed) typical control range ±0.0003
P	0.04
S	0.02
O	0.0050
Cr	0.1
Ti	0.040
V	0.10
Al	0.050
As	0.020
Bi	0.002
B	0.002
Cd	0.005
Pb	0.002
Se	0.030
Te	0.020

Table 5: Maximum content (wt.%) of minor elements in SG iron by FOSECO ^[15]

Element	Maximum
Al	0.01
As	0.01
B	0.002
Cr	0.05
Mo	0.01
Sb	0.004
Bi	0.001
Pb	0.0004
N	0.005
P	0.04
S	0.02
Sn	0.01
Ti	0.02
V	0.03

In Table 2, ten (10) trace elements are listed, except Sn and Ti. In equation (1), assuming Ti to be 0.04% (normally in SG iron, Ti is required to be below 0.04%) and neglecting Sn, the calculated K_1 value is 1.579. Table 3 gives values for nine (9) elements but omits As; by neglecting As in equation (1), the calculated K_1 value is 1.619. Table 4 shows sixteen (16) trace elements including all the detrimental ones in equation (1), the calculated K_1 value is 1.672. Table 5 shows values for fourteen (14) trace elements including all the detrimental ones in equation (1); in this case the calculated K_1 value is 0.653. It can be seen that by using the values in Table 5, K_1 is well below 1.0, whilst using those in the other Tables, K_1 is between 1.5–1.7.

It is believed that in practical foundry production, not all the

trace elements shown in these tables will reach the maximum level; however, it is quite possible that some of them will reach or even exceed the maximum level, therefore the K_1 value can exceed 1; in this case it is necessary to add rare earth elements to neutralize the detrimental effects of harmful trace elements.

2 Elimination of harmful effects of trace elements by using rare earths

Generally, if $K_1 > 1.0$, graphite degeneration is possible, and high-quality SG iron may not be produced. In this case, rare earths such as Ce or La are needed to neutralize the tramp elements and eliminate their harmful effects.

The harmful effects of subversive trace elements in magnesium-treated SG iron can be divided into three types: 'consuming', 'segregation' and 'mixing' types. The consuming-type elements include Se and Te, which can react with Mg and rare earths to form compounds that reduce the effective amount of Mg and rare earths available, and therefore inhibit the formation of spheroidal graphite. The segregation-type elements like Sn, Sb, As, B, Ti, Al, Bi and Se have a very small equilibrium distribution coefficient in austenite and can increase carbon activity in molten iron. During eutectic solidification, these elements segregate at intercellular boundaries and promote deleterious graphite shapes (chunky or thick flake graphite). If the amount of segregation-type elements is relatively high, degenerate graphite can form in the middle stage of solidification. For the mixing-type elements such as Al and Bi, if their amount is small, they act in the same way as segregation-types; if the amount is high, they consume the effective spheroidizing elements to promote degenerate graphite shapes. The heavier the atomic weight, the stronger the subversive effect. For segregation-type elements, the smaller the equilibrium distribution coefficient of the elements in austenite, the stronger the subversive effect; therefore, the allowed critical amount in iron is smaller. The effect of subversive elements is influenced by many factors, and different studies suggest different allowed critical amounts for SG iron. Normally, the critical amount refers to the amount when only one element is present in the iron. If more than one subversive element is present, the influence on spheroidal graphite is increased. The thicker the casting, the stronger the harmful effect of subversive elements on spheroidal graphite^[1,13,16].

Rare earths can react with deleterious tramp elements to form complicated, high-melting point metal-bond compounds; this reduces their effective amount in liquid iron and decreases or eliminates their segregation to intercellular areas^[1,13,16-17].

A great number of experiments have been carried out, and results show that different amounts of tramp elements require different amounts of rare earths to neutralize them. There are optimum ratios between tramp elements and rare earths^[3,11,16-19]; these ratios are generally between 0.8–1.1, depending on the prevailing conditions^[3, 11, 16-19]. The amount of rare earths needed to neutralize tramp elements is derived from experimentation and is not an exact science^[12].

For most situations, 0.01% Ce is usually sufficient to counteract the harmful effect of tramp elements. For castings less than 37 mm thick, an excessive amount of Ce may cause degenerate graphite and carbides to form, especially when little or no tramp elements are present^[12]. Normally, the more different tramp elements present in the base iron, the more rare earth is needed; also, the thicker the section of the SG iron, the more rare earth is needed.

In practice, foundries tend to add more rare earths than required to eliminate the harmful effects of tramp elements. In addition to neutralizing tramp elements like Ti, Pb, Bi, As etc., rare earths can also assist in nodulizing and provide a supplementary effect to Mg; this assists in nucleating graphite and makes the graphite shape more spheroidal. However, rare earth elements are strong carbide promoters, and excessive amounts may cause rare earth-containing inclusions and carbides, which would lead to high shrinkage tendency. Due to these negative influences, and because rare earths have become more and more expensive, their content in spheroidizers has been reduced over the years^[13, 18].

However, when high-quality SG iron (>90% nodularity) or high strength and high impact values at low temperature are required, more strict control of composition is needed as K_1 needs to be very low. As pointed out by Riposan etc., the presence of high purity pig iron in the charge is extremely beneficial, not only to control the complex factors P_X and K_1 , but also to improve the 'metallurgical quality' of the iron melt^[9-10, 20].

3 Control and prediction of structure and properties of SG iron by controlling K_1 , P_X and Sum Pearlitic Elements

Riposan etc.^[9-10] used different metallic charges, including high purity pig iron such as Sorelmetal, to study the effect of trace and alloying elements on as-cast and heat-treated, grade 400-18 SG irons. Anti-nodulizing Action Factors (K_1) of 0.3–2.4 and Pearlite Influence Factors (P_X) of 0.1 to 5.1 were used in the study. They found that the anti-nodulizing action of deleterious trace elements up to a level corresponding to $K_1 = 2.0$ (Thieleman factor) could be counteracted by Rare Earth (RE) additions. In relatively high purity base irons, in terms of anti-nodulizing trace elements ($K_1 = 0.7$ to 0.8) and using 0.04% to 0.05% Mg, higher RE contents increased carbide tendency, for both uninoculated and inoculated irons. So, a low content of RE (0.005 to 0.01%) for $K_1 < 0.8$ is practical and sufficient in a Ca-bearing FeSi alloy inoculated iron. The RE addition from a Ca, RE-FeSi alloy appears to be unnecessary, or even undesirable, due to the increased risk of forming chill (carbide). Rare earth elements are beneficial when $K_1 < 1.2$ and essential when $K_1 > 1.2$, especially due to the presence of Pb in these SG irons. It was found that Pb-contaminated steel scrap is extremely dangerous in higher ductility irons.

It was also found that the Pearlite Influence Factor (P_X) and the Anti-nodulizing Action Factor (K_1) have an important

influence on the properties of 400-18 SG irons, depending on the Mn and P levels, the metallurgical quality of the iron melt, rare earth (RE) addition and efficiency of the inoculation. It was found that the influence of Mn depended on the phosphorus and other residual element levels in SG iron. Less than 0.03% P, and 0.2% Mn, with $P_X < 2.0$ are the base conditions to obtain an as-cast ferritic structure. At the same lower levels of Mn and P, but an increase of residual elements ($P_X > 2.0$), pearlite will be present in the as-cast structure; however, a ferritic structure can be obtained after a short annealing heat treatment. Lower levels of phosphorus ($P < 0.025\%$) and other residual elements ($P_X < 2.0$) allow the use of relatively high Mn contents (0.32%–0.38%), when a ferritic structure is required in the as-cast state. For a grade 400-18 iron with high P (0.04%–0.045%) and Mn (0.25–0.35%), the required properties can still be obtained provided that the level of residual elements is low ($P_X < 2.0$) [9-10].

It was also found that the presence of high purity pig iron in the charge is extremely beneficial, not only to control the complex factors P_X and K_1 but also to improve the “metallurgical quality” of the iron melt; the use of high purity pig iron allows a higher P_X level or lower inoculation level [9-10].

Grenier, et al. [20] studied the low-temperature impact resistance (-40°C) of an as-cast SG iron block ($19 \times 19 \times 20 \text{ cm}^3$) with different percentages of high purity pig iron in the charge. Charpy bars were machined from a vertical slice cut through the center of the block from top to bottom, thus the influence of location (solidification time) and SG iron purity on the impact values could be obtained. The average impact values obtained from 12 SG iron heats ($\text{C}=3.20\%\text{--}3.45\%$, $\text{Si}=2.00\%\text{--}2.25\%$, $\text{Mg}=0.035\%\text{--}0.050\%$) were 5.5 J to 15.8 J.

They also developed a QI factor, Sum Pearlite Elements (the sum of Pearlite-stabilizing elements), to evaluate the low temperature impact resistance properties [20]:

$$\text{Sum Pearlite Elem.} = \text{Cu} + \text{Mn} + \text{P} + \text{Cr} + \text{Sn} + \text{Sb} + \text{Ti} \quad (3)$$

The P_X factor on the test-pieces from different locations was between 0.1 and 2.9, and the Sum Pearlite Elements Factor was between 0.09 and 0.55.

Figures 4 and 5 are graphical representations of the linear regression analysis of the average impact resistance [20]. It was found the impact resistance is linearly related to the P_X value and Sum Pearlite Elements.

It can be seen from Figs. 4 and 5 that the lower the Factor P_X and Sum Pearlite Elements, the higher the average low-temperature impact resistance. These figures also indicate that the lower the Factor P_X and Sum Pearlite Elements, the lower the spread of impact resistance values. In order to ensure impact values exceed 12 J, the P_X value should be kept lower than 1.0 and the Sum Pearlite Elements should be kept below 0.25.

This shows that the more high-purity pig iron in the charge, the better the metallurgical quality and the ductility in heavy section SG iron castings. Foundries are now able to control trace elements and reduce the total impurities, to improve the quality of SG iron.

Fig. 4: Linear regression fit between average impact resistance at -40°C and P_X factor [20]

Fig. 5: Linear regression fit between average impact resistance at -40°C and Sum Pearlite Elements parameters [20]

4 Chunky graphite and its prevention in heavy-section SG iron

For relatively thin section SG iron, the worst result of too high a content of rare earths is the appearance of rare earth-containing inclusions, carbides and shrinkage defects. For thick section SG iron, too high a rare earth content can cause chunky graphite, whilst too little may lead to flake graphite. This makes heavy-section SG iron much more difficult to produce.

Chunky graphite is interconnected, frequently branches, and displays clustered pyramidal segments. Spiral growth from the base plane is clearly revealed at the end of segments. Chunky graphite has a negative effect on the mechanical properties of the iron. For example, the tensile properties can be reduced by 25% and elongation can be reduced by 80%–85% [21]. Chunky graphite continues to be a serious defect in heavy-section SG iron castings and has been intensively and continuously studied [1,3,19-29].

There are several explanations for the formation of chunky graphite; however, the formation mechanism is not clearly understood. Some of the mechanisms are controversial. Generally, chunky graphite is related to heavy sections ($>50 \text{ mm}$), slow cooling rate, insufficient inoculation and too high a level of carbon, calcium, silicon, nickel, and especially, rare earths.

A Ce concentration of around 0.02% promotes fast growth of graphite and leads to chunky graphite clusters; however, there are examples where amounts up to 0.02% Ce could be

tolerated elsewhere^[24].

Recently, Torre, et al.^[22] studied chunky graphite formation in Y2, Y3 and Y4 SG iron blocks (as per standard EN1563) with different levels of silicon, carbon and rare earths, and different inoculants; no conclusion could be drawn for the effect of nodule count on chunky graphite formation. This is in contradiction to many other researchers who studied the effect of melt inoculation on chunky graphite. It was found that the most evident result was the positive effect of RE addition on decreasing the amount of chunky graphite. The highest chunky graphite fractions were found when no RE was added to the melt. This observation apparently contradicts the generally accepted view that RE favors the formation of chunky graphite. It should be stressed however that the amount of residual RE in the present alloys is very low. The workers checked if there was an optimum amount of cerium or RE present; they also checked for the appearance of chunky graphite. A general trend was obtained for this casting size with a minimum area affected by

chunky graphite, for a cerium content of 0.004–0.005 mass%. Such a value is in the low range of the optimum values reported by Skaland^[29] and would further decrease with an increase in the casting section size.

In order to eliminate chunky graphite in heavy-section SG iron, RE are normally added, together with trace elements Bi, Sb, Pb etc., but the addition of rare earth and trace elements must be balanced. ASK developed an SMW INSERTTM which offers a balance of Bi and Ce to increase nodule count, thereby reducing the occurrence of chunky graphite^[23].

However, tramp elements Bi, Sb, Pb and Sn are all strong pearlite stabilizers (see Table 6) and their addition can result in pearlite formation^[3]. Therefore, care must be taken to ensure addition rates are accurate and consideration must be given to the potential build-up of Bi and Sb in foundry SG iron returns.

It is certain that the formation mechanism of chunky graphite is not fully understood, and further research needs to be carried out to produce high quality heavy-section SG iron castings.

Table 6: Mn-equivalent for several elements favoring (+) or preventing (-) pearlite^[3]

As	Bi	Cr	Cu	Mo	Ni	Pb	Sb	Si	Sn	Ti	V
6.7	111	3.2	2.6			119	24	-0.9			
48			2.0						24		
		1.0						-0.9		5.2	1.2
			2.2			148	29				
		4.0	0.5		1.5						10
			1.7						13.3		
				1.7	0.9			-0.6			

5 Production of high-demand SG iron castings by using high purity and ultra-high purity pig iron

In 2010 and 2017, Hebei Longfengshan (LFS) Casting Industry Co., Ltd. developed high purity and ultra-high purity pig irons respectively; a typical composition of these pig irons is shown in Tables 7–9. The sum of 12 trace elements in the high purity pig iron is <0.05% (Table 8) and that in the ultra-high purity pig iron is <0.025% (Table 9). These pig irons lay down the foundation for the development of high-quality SG iron.

5.1 High-strength, high low-temperature impact, ferritic SG iron

For many years, Changzhou Huade Machinery Co., Ltd. has produced high-quality SG iron castings for high-speed trains, grade QT400-18AL (-40 °C)^[30]. Huade has paid special attention to the charge materials. By strictly controlling the base iron composition, and using a low magnesium (5.5%–

6.5%) and low rare earth (0.5%–0.8%) spheroidizer with an addition rate of only 1.1%, Huade successfully manufactured the axle box castings for high-speed train bogies with the nodularity exceeds 90%. Figure 6 shows the typical graphite and matrix structures of this high strength, low-temperature impact, ferritic SG iron.

By using high purity pig iron, the rating number for assessing graphite spheroidization $K_1 < 0.6$, the Pearlite Influence Factor $P_\lambda < 0.9$, and the sum of all 12 trace elements in the SG iron reaches very low values ($\sum T \leq 0.09\%$). Thus, intercellular flake graphite, inclusions and pearlite were eliminated, as can be observed by optical microscopy (Fig. 6).

The actual mechanical properties of the SG iron were: tensile strength 400–420 MPa, yield strength 260–290 MPa, elongation 24%–26%, impact value at -40 °C is 14–16 J·cm⁻², hardness 140–180 HB. Recent tests have shown that the SG iron achieved the properties of grade QT400-18AL (-40 °C), at -60 °C, i.e. at 20 °C lower than the specification^[30].

It has been found by Japanese scientists through over 60 years of tracking and analysis, that the service life of 60%–70% of

Table 7: Maximum content of main elements in high purity pig iron (wt.%)

Grade		C05L	C08L	C10L	C12L
C		≥3.80			
Si		≤0.70	0.70–0.90	0.90–1.10	1.10–1.30
	Super grade	≤0.010			
Ti	Grade 1	0.010–0.020			
	Grade 2	> 0.020 and ≤0.030			
Mn	Super grade	≤0.05			
	Grade 1	> 0.05 and ≤0.10			
P	Super grade	≤0.020			
	Grade 1	> 0.02 and ≤0.03			
S	Super grade	≤0.015			
	Grade 1	> 0.015 and ≤0.020			

Table 8: Maximum content of trace elements of high purity pig iron (wt.%)

Element	Cr	V	Mo	Sn	Sb	Pb	Bi	Te	As	B	Al
Max. limit	0.015	0.015	0.008	0.003	0.0008	0.001	0.0005	0.0005	0.0018	0.001	0.01

Table 9: Typical content of main and trace elements of ultra-high purity pig iron (wt.%)

Element	C	Si	Mn	P	S	Ti
Content %	3.5-3.8	≤0.50	≤0.02	≤0.008	≤0.01	≤0.005
Element	V	Cr	As	Mo	Sn	Sb
Content %	≤0.005	≤0.01	≤0.0008	≤0.002	v0.0002	v0.0001
Element	Pb	Bi	Te	B	Al	Cu
Content %	≤0.0001	≤0.0001	≤0.00005	≤0.0001	≤0.001	≤0.008

Fig. 6: Typical graphite morphology (L) and matrix structure (R) of axle box for high-speed train bogie

castings is adversely affected by internal inclusions, and that low mechanical properties is only one of the reasons for failure, not the main reason^[27-28]. The good service life of Huade SG iron castings is due to the absence of internal inclusions, which results from the high purity of the base iron melt.

5.2 Elimination of chunky graphite in thick-section SG iron castings with high purity pig iron

Figure 7 shows the comparison of graphite in blade castings made from a fully scrap steel charge and from a 60% high purity pig iron, respectively. These large blade castings weigh

approximately 110 kg and have a length of 1,500 mm; the thinnest section is approximately 3 mm and the heavy sections have a thickness of 80–90 mm. These castings require a very high-quality and should have no shrinkage defects or degenerate spheroidal graphite. However, during production, chunky graphite often appears in the thick sections.

Previously, the furnace charge for SG iron blade castings consisted mainly of scrap steel. Subsequently, 60% high purity pig iron was used as the furnace charge, which resulted in chunky graphite being eliminated and the customer's demand being satisfied.

Fig. 7: Graphite morphology in blade castings made from a fully scrap steel charge (L) and from a 60% high purity pig iron (R)

Although high-quality scrap steel may have low manganese, other alloying elements may not be sufficiently low. The addition of high purity pig iron to the melt can dilute the concentration of tramp elements, which can be the reason for eliminating chunky graphite in the thick sections.

5.3 Experiments with extra-heavy section SG iron castings using ultra-high purity pig iron

In order to meet the requirements of producing extra-heavy section SG iron castings, experimental studies on such castings utilizing ultra-high purity pig iron have been performed by several organizations.

The experimental SG iron melts were prepared using 100% ultra-high purity pig iron (only carbon and a small amount of ferrosilicon alloy were added) and treated with low rare earth Si-Fe-Mg alloy (6% Mg, 0.5% Re), without any addition of Pb, Bi or Sb. The SG iron melt was poured into test blocks $\Phi 800$ mm $\times$ 1,000 mm; the total poured weight of the block and gating system was approximately 4.3 tonnes. Solidification time in the block center was very long, approximately 13 h. After the block had solidified and cooled down to room temperature, it was sectioned through its center. The nodule number in the center was 20–40 mm², the graphite was of very good spheroidal shape, and no evidence of chunky graphite was found. At the same time, a comparable experimental block was cast with base iron made from a different pig iron, using chills to increase the cooling rate; the solidification time was much shorter at only 3–4 h. Apart from these two differences (pig iron type and chills), the other

experimental conditions were the same. After the comparable experimental block was cooled down and sectioned, large amounts of chunky graphite were found in the central area.

These results demonstrate that the use of ultra-high purity material can eliminate chunky graphite in thick-section SG iron and results in excellent properties. One of the main reasons for these very good results is the purity of the base iron. Since only ultra-high purity pig iron was used as the raw material, K_1 is only 0.09216, which is far lower than 1.0; also, the sum of 12 trace elements including tramp elements, pearlite promoters and carbide stabilizers is <0.025%; the Pearlite Influence Factor P_x is also very low. The factor of Sum Pearlite Elements is only 0.0533. Thus, intercellular flake graphite, inclusions and pearlite were all eliminated due to the ultra-high purity of the melt. Further study is needed on the effects of ultra-high purity base iron and rare earths on very heavy-section SG iron.

The examples of castings described above are only a few applications for high-quality, heavy-section SG iron made from high purity and ultra-high purity pig irons. More practical applications have shown that using these pig irons can produce SG iron castings with properties better than those specified in ISO standards and that good spheroidal graphite can be obtained in heavy-section SG iron.

6 Summaries

(1) During the last fifty years, the maximum limits of trace and tramp elements in modern, high-quality SG irons have

become lower and lower; in addition, the purity required for base iron has become higher and higher. However, for most SG iron castings in production over the world, rare earth elements still need to be added to neutralize the harmful effects of trace elements and improve SG iron quality.

(2) The use of high purity and ultra-high purity pig iron is a very efficient and beneficial method to obtain high purity base iron. Low tramp element content allows less spheroidizer to be added, ensuring high nodularity with few inclusions, and enables the consistent production of high-quality SG iron.

(3) The use of high purity and ultra-high purity pig iron can prevent chunky graphite forming in very heavy-section SG iron castings.

(4) The influence and effect mechanism of spheroidizing elements, trace and tramp elements on the structure and properties of SG iron, especially those with a heavy-section and those that operate at low temperatures, requires further intensive study.

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