Performance of heavy ductile iron castings for windmills

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Abstract: The main objective of the present paper is to review the specific characteristics and performance obtaining conditions of heavy ductile iron (DI) castings, typically applied in windmills industry, such as hubs and rotor housings. The requirements for high impact properties in DI at low temperatures are part of the EN-GJS-400-18U-LT (SRN 1563) commonly referred to as GGG 40.3 (DIN 1693). Pearlitic influence factor (P_x) and antinodularising action factor (K_1) were found to have an important influence on the structure and mechanical properties, as did Mn and P content, rare earth (RE) addition and inoculation power. 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. A correlation of C and Si limits with section modulus is very important to limit graphite nodule flotation. Chunky and surface-degenerated graphite are the most controlled graphite morphologies in windmills castings. The paper concluded on the optimum iron chemistry and melting procedure, Mg-alloys and inoculants peculiar systems, as well as on the practical solutions to limit graphite degeneration and to ensure castings of the highest integrity, typically for this field.

Key words: heavy ductile iron castings; windmills parts; chemistry; structure; treatments; control

CLC number: TG255 Document code: A Article ID: 1672-6421(2010)02-163-08

All over the world, people must prepare for new forms of energy. The sharp rise in energy consumption calls for a sustainable resource that does not create more greenhouse gases, pollution or waste for future generations. Wind power is a renewable, predictable and clean source of energy. Substantial capacity can be built up quickly, offering the energy independence demanded by the world's largest and fastest-growing economies. The wind power industry has experienced fantastic growth in recent years. It is expected that the present wind power share of about 1% of global power consumption will grow to at least 10% by 2020. The targets for renewable power in the EU and China will account for 20% and 15%, respectively, in 2020, and the US is expected to adopt similar targets. These targets mean that installed capacity is set to rise from 75,000 MW in 2006 to at least 1,000,000 MW in 2020, which translates into annual growth of more than 20%. Currently, wind power is the cleanest and best option for reducing CO_2 emissions. Just one of V90-3.0 MW wind turbines can save the atmosphere from more than 5,000 tonnes of CO_2 emissions, every single year [1]. In the spring of 2008, the European heads of states enacted an environment and energy package, which entails that 20% of the European energy consumption by 2020 must come from renewable energy. This binding objective for renewable energy will have a large impact on Europe's future energy supply and at the same time offer peace of mind to investors in renewable energy. At the same time, it is a signal that European leadership is committed to ensure that the positive development in the wind industry continues. Wind power is of course to be competitive on the liberalized market. Production cost per kWh has been reduced by more than 80% within the last 20 years and this trend is expected to continue resulting in a fully competitive technology in 7–10 years. Today wind turbines on good wind sites can already compete with new combined heat and power (CHP) plants, but wind cannot yet compete on the present market terms. The prices at the European power exchanges reflect the current overcapacity and that the majority of the production facilities are already depreciated and paid by the consumers. In addition, health and environmental costs are not calculated into the kWh-price for the individual energy technologies. Wind power would be fully competitive today, if they were [2].

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Male, born in 1948, Professor. **Major research areas**: lamellar, nodular, compacted/vermicular and coral graphite irons-processing and complex characterization; austempered cast irons with LG, NG, CG or coral graphite; cast iron matrix composites; new modifying techniques for cast irons; cupola and electric furnaces operations. **Publications**: 250 published papers (120 in other countries than Romania); 3 Books, about CG Iron (1984), White Irons (1985) and Bainitic Irons (1989); 35 Romanian patents. **Awards**: "Aurel Vlaicu" Award of Romanian Science Academy (1985) for Compacted Graphite Iron contributions; 2 National Awards for scientific and technical creativity in modifying iron area (1987 and 1989); 10 Awards at National Patent Exhibitions; Honor Diploma of POLITEHNICA University of Bucharest for invention activity (1988); Best Paper Awards at the 63rd World Foundry Congress (1998), 106th AFS Casting Congress (2002) and 107th AFS Casting Congress (2003), respectively. **Professional and Scientific Associations:** Romanian Foundry Technical Association (ATTR) [President], American Foundry Society (M), ASM International-The Materials Information Society (M), Romanian Society of Metallurgy (M), Romanian Inventors Association (M), Romanian Steel Producers Union (M), etc.

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Received: 2010-03-10; Accepted: 2010-04-14

1 Ductile iron castings in windmills industry

Ductile iron (DI) castings are playing a key role in this important industry. All of the advantages of DI have contributed to the growth of this engineering material. Some of these castings have come from new applications and designs, but most have come as a result of conversion from another material and possibly another forming method. The primary material that has been replaced is steel, in the form of castings, forgings and fabrications. However, DI parts have also replaced grey iron, malleable iron and aluminium castings as well, proving that DI is very cost effective.

Ductie iron made to German specification DIN 1693, Grade GGG 40.3 is the material of choice for many of the world major wind turbine manufacturers such as for the range of hubs and rotor housing castings (Fig. 1). The need to ensure optimum, consistent and safe performance of these units makes it imperative that only ductile iron castings of the highest integrity and in complete compliance with the specification can be accepted. The requirements for high impact properties in DI at low temperatures for the burgeoning wind energy market are part of the European Standard EN-GJS-400-18U-LT commonly referred to as GGG 40.3. This standard not only has the normal mechanical requirements for ferritic iron but also specifies V-notched Charpy impact requirements at – 20 ℃ (– 4 F) (Table 1). To meet low temperature impact properties the foundry must produce ferritic ductile iron components that need be free of cell boundary phases such as phosphides and carbides. Otherwise the impact properties will not pass.

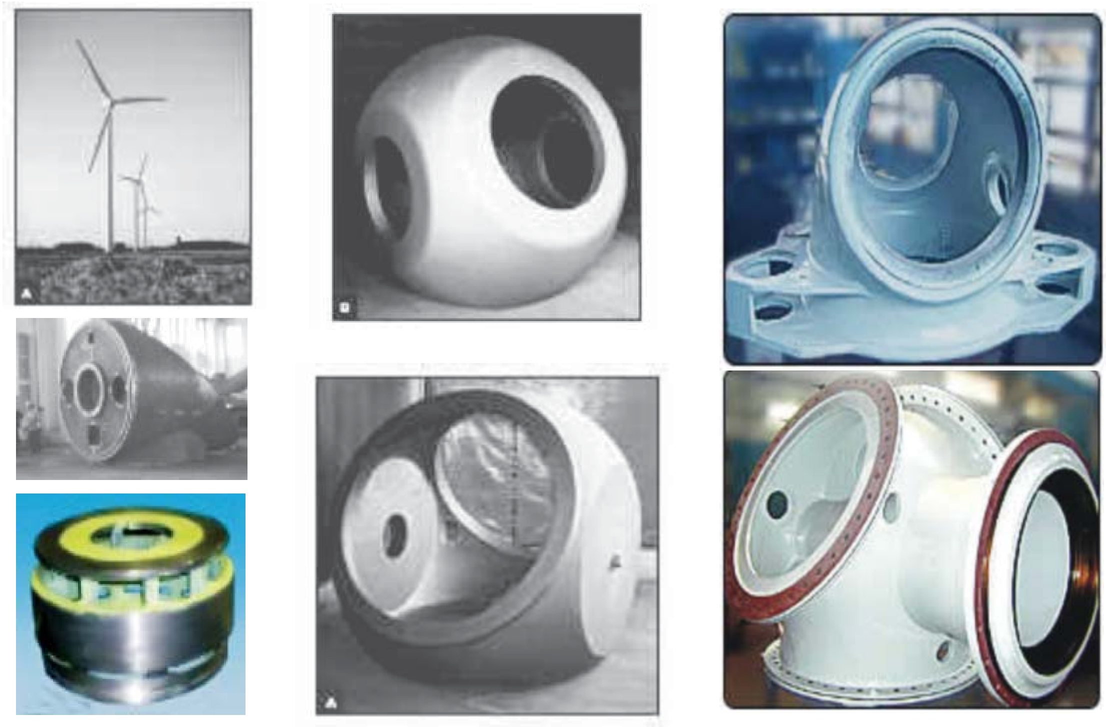


Fig. 1: Typical ductile Iron (DI) castings for windmills

Table 1: Typical ductile iron (DI) characteristics for windmills castings

Test cupons	DI grade (ISO 1083/ SREN 1563)	Charact. casting section, t/e (mm)	Tensile strength (MPa) min	Yield strength (MPa) min	Elongation (%) min	Impact* (J) +23 ℃ (-/RT)	Impact* (J) -20 ℃ (L/LT)
Separately cast (Y_{25})	400-18 EN-GJS-400-18		400	250	18	14 (11)	12 (9)
Attached to castings	400-18A EN-GJS-400-18U	t ≤30	400	250	18	14 (11)	12 (9)
		30 < e < 60	390	250	15		
		60 < e < 200	370	240	12	12 (9)	10 (7)

** V-notched Charpy impact, as average of three tests and as individual value (x), minimum accepted.*

Other metallurgical characteristics such as high nodule counts from effective, late inoculation are key to minimizing detrimental cell boundary phases, but melt composition is a primary consideration. In addition, in that melt is scrap steel that has possible alloying elements such as P, V, Ti, Cr, Mo, B, Mn and Cr, which can result in carbide or phosphide phases which segregate to cell boundaries. This is now a problem to be solved and will be a greater challenge in the future as alloying elements in the steels increase in the years to come [4]. The casting quality standards demanded by wind turbine manufacturers are also high.

Each casting is ultrasonically tested in specified areas to assure free from porosity and inclusion defects. In addition, radiographic examination is performed to further confirm the integrity of each casting. Consistently achieving the specified minimum combinations of tensile and yield strengths, elongation and low temperature impact strength properties in the fully ferritic DI grade EN-GJS-400-18U-LT/GGG40.3 is very demanding. Coupled with the fact, that a full annealing heat treatment of such large castings is very expensive, the foundry must make every effort to achieve the specification directly in the as-cast condition. This requires a high degree of metallurgical control over the preparation of the liquid DI iron to precise composition control as well as the liquid metal processing to ensure the correct nodularity and optimum nodule count, careful mould and core preparation and strict supervision over pouring and casting knockout [4].

2 Chemistry control in ductile iron (DI) for windmills castings

Because ductile irons have complex chemical composition, rigorous control is required for all the elements affecting the structure and behaviour of these materials [5]. A critical factor is the distribution of elements during solidification, either inside the eutectic cells (Si, Ni, Cu) or within the intercellular regions (P, Mn, Ti, Cr, Mo, V). The latter group of elements promotes carbide formation, stabilises pearlite in ferritic irons and affects intercellular lamellar graphite formation. With regard to obtaining ferritic structures in DI, most important are those elements that stabilise pearlite, with a cumulative effect given by the pearlitic influence factor, such as P_x [6] (Fig. 2a). However, other elements also promote pearlite, notably P, which has an effect by one order of magnitude more powerful than Mn, while Ni has the same level of influence as Cr (Fig. 2b) [7,8]. The antinodularising influence of elements must be also considered in ensuring acceptable levels of graphite nodularity, defined for DI as > 80% nodular graphite (NG) and < 20% vermicular graphite (VG), with no lamellar graphite (LG). Compositional control becomes critical when higher values for graphite nodularity are specified (up to 100% NG), such as for windmills castings, and most of all when maximum compactness for NG must be achieved (e.g. for type K-ASTM irons). Generally, in Mg-treated irons, the complex antinodularising (Thielman) factor K_1 should not exceed 1.0, as result of different contributions of representative elements (Fig. 2c) [6,9]. An important group of antinodularising elements are those favouring the occurrence of intercellular LG (Bi, Pb, Sb, As, Cd, Al, Sn, Cu). As regards DI, major influence is exercised by both ferrite forming elements (Si) and pearlite forming elements (Ni, Cu, Sn, Mo, V). The presence of Si strengthens ferrite, but in effect there is a significant decrease in elongation (embrittling effect), whereas Ni increases tensile strength and yield strength, with no obvious negative influence on elongation. Consequently, Ni is frequently present in ferritic DI, when obtaining tensile strength combined with high elongation proves problematic.

It was found [5] that the influence of Mn is dependent on the P and residual elements level. The base conditions to obtain an as-cast ferritic structure, as required by the 400–18 DI grade specification, was P < 0.03%, Mn < 0.2% and P_x < 2.0. At the same low levels of Mn and P, increasing the residual element content (P_x > 2.0) leads to the presence of pearlite in the as-cast structure, although a ferritic structure is obtained after a short annealing heat treatment. High P (0.04% – 0.045%) and Mn (0.25% – 0.35%) contents lead to a stabilised pearlite microstructure, even at low residual element contents (P_x < 2.0). The antinodularising action of residual elements up to a level corresponding to K_1 = 2.0 could be counteracted by rare earth additions, such additions are beneficial for K_1 < 1.2 and can be regarded as compulsory for K_1 > 1.2 [5].

For many foundries steel scrap (SC) is an essential constituent of a charge make-up (Table 2), as it is a lower cost material. However, it is also a major contributor of trace elements. High purity pig iron (HPPI), despite its higher cost, is very attractive

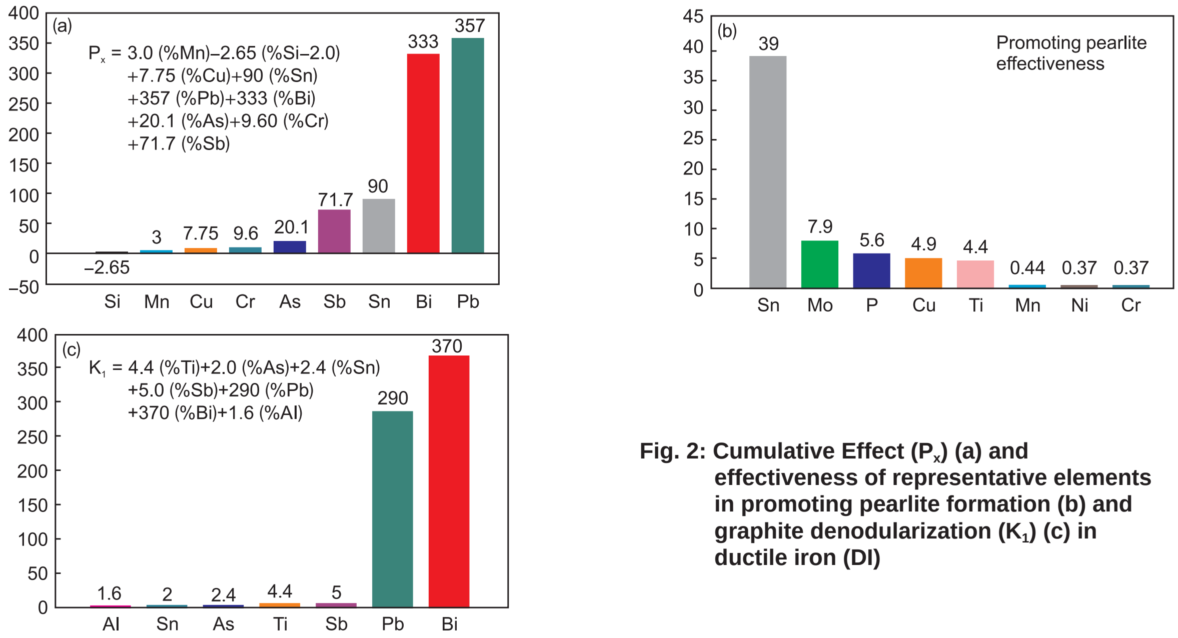


Fig. 2: Cumulative Effect (P_x) (a) and effectiveness of representative elements in promoting pearlite formation (b) and graphite denodularization (K_1) (c) in ductile iron (DI)

Table 2: Typical metallic charge make-up

No.	Material	Arguments	Possible problems
1.	Ductile iron returns (DIR)	• Available material • Special quality: -controlled Mn, P, C -low trace elements level -desulphurized material -deoxidized material	• High Si contribution • Fast dissolution of graphite - carbides occurrence • Possibility of mixed grades • Decreased availability
2.	Steel scrap (SC)	• Lowest cost • Available material • Lower Si contribution • Possible low Mn, P, S level • Possible low Traces level	• Prevalent at > 0.4%Mn • Cr,Ni,Cu,Sn,Cd,Al,Pb,Sb present • Coated steel scrap (Sn, Pb) • Fe and Mn oxides source • Processing cost (>80$/t) • MF-CIF processing specific: -high oxidation risk
3.	High purity pig iron (HPPI)	• Highest C contribution • Lowest Si, Mn, P, S, traces • High metallurgical quality: -graphitization potential • Economic melting procedure • Lower shrinkage defects • Improved DI properties	• Highest cost • Limited availability

as the lowest contributor of trace elements with the potential to improve graphite nucleation/metallurgical quality of the iron melt. It also expands the range of SC that can be tolerated due to its management of the trace element level. The presence of HPPI 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. It was found that the use of HPPI makes it possible to cope with higher P_x levels or less powerful inoculation additions [10-12]. The quality of ductile iron returns (DIR) produced with HPPI transmits benefits to the new production even in periods without HPPI in the charge. It was pointed out that the main influencing factors on the HPPI necessity in the common metallic charge are as follows: (a) Metal matrix: 15%–40% HPPI for ferritic *vs*. 5%–20% for pearlitic/ferritic; (b) DIR share: lower DIR, higher HPPI necessity; (c) Elongation (A) level: higher A, higher HPPI addition; (d) SC quality: lower SC quality, higher HPPI amount (Fig. 3) [11].

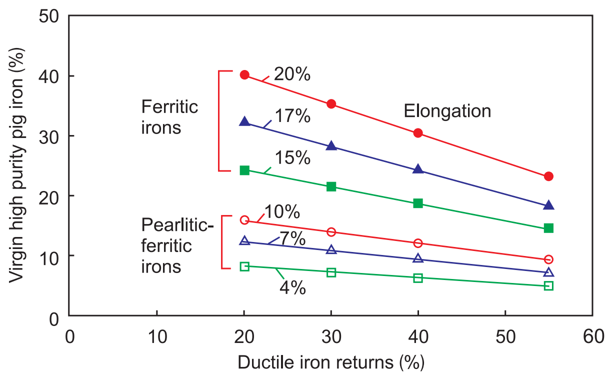


Fig. 3: HPPI – DIR relationships for different elongation levels in ductile irons (DI)

3 Graphite degeneration in heavy ductile iron castings

3.1 Graphite nodule flotation

In the hypereutectic composition range, the first phase formed during solidification should be primary graphite beginning near the graphite liquidus temperature and with growth continuing down to the beginning of the eutectic solidification temperature. Upon reaching a critical size, the graphite spheroids may float in the molten iron and produce flotation layer in the upper regions of a DI casting (Fig. 4.2) [13]. Flotation is normally revealed by the presence of dark patches on the top surface. Usually, it is a greater concentration of nodules (include some exploded hyper-eutectic nodules and dross stringers). As a surface fault comprise a poor surface finish and blowholes in combination with dross, heavy section as slower solidification rate is typically responsible for this defect, which reduces tensile properties. In critical areas, it can have a devastation effect on fatigue properties, extremly important for windmills castings. A correlation of C and Si limits with section modulus is very important. In this respect, lower carbon equivalent (CE) must be considered, to limit nodule graphite flotation tendency.

3.2 Objectionable deviations from spheroidal graphite shape in heavy DI castings

The structure of DI castings usually includes not only spheroidal graphite particles, but also other objectionable deviations from the highest compactness degree, such as irregular (Fig. 4.1), exploded (Fig. 4.3), chunky (Fig. 4.4), spiky (Fig. 4.5), intercellular flake (Fig. 4.6) and vermicular (Fig. 4.7) from many and different causes [13-15]. The most of these graphite morphologies are usually present in heavy DI

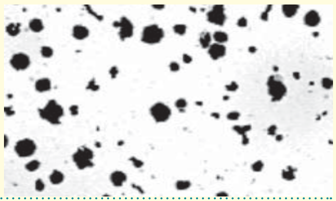
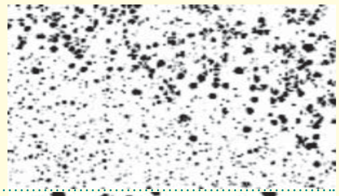
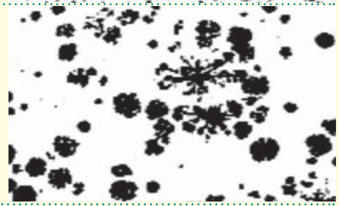
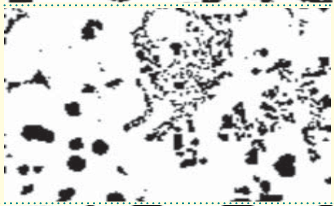
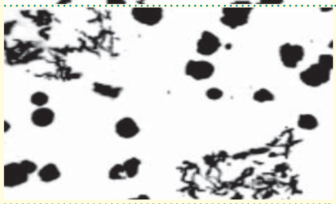
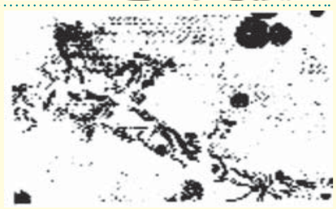
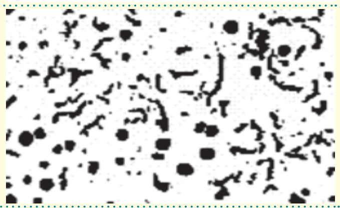
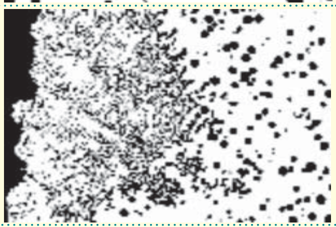
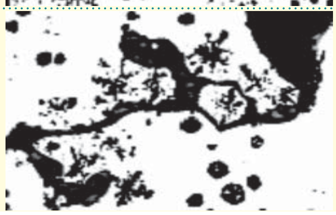
No.	Graphite	Potential causes	Typical aspect
1	Irregular	• High holding temperature/time • Poor inoculation • Excessive fading • Antinodularising elements	
2	Flotation	• High carbon equivalent (CE) • Excessive pouring temperature • Slow cooling rate • Insufficient inoculation	
3	Exploded	• Excessive rare earth (RE) • Particularly high purity charge • Normally in thick castings • Usually for high CE	
4	Chunky	• Usually center of castings • Excessive RE/charge purity • High Si, Ce, Ni, Ca • Within eutectic cells	
5	Spiky	• Antinodularising elements • Typically: Pb, Bi, Ti, Sb	
6	Intercellular flake	• Intercellular strong segregation • Bi, Pb, Sb, As, Cd, Al, Sn • Commonly in heavy castings	
7	Vermicular	• Low residual Mg/RE • Excessive S/O • High temperature/Holding time • Antinodularising elements	
8	Flake/ Surface structure	• Excessive S build-up • Excessive Mg/RE oxidation • Conditioners of moulding sand • High pouring temperature	
9	Dross association	• Inadequate slag control • Excessive slag forming materials • Turbulent mould filling • Metal-mould reaction	

Fig. 4: Objectionable deviations from spheroidal graphite shape in ductile iron

castings, with detrimental effects on the mechanical properties. Chunky-graphite in the thermal center of the castings and surface-degenerated graphite (Fig. 4.8) are the most controlled graphite morphologies in windmills castings.

Chunky graphite occurs in the thermal centers of heavy section castings — those with sections greater than 50 mm. The result of this graphite shape is that the properties in these defective areas are dramatically reduced. The resulting matrix structure is ferritic giving lower tensile strength and yield strength. The close proximity of the graphite particles also reduces the elongation and impact strength. High concentrations (for the section size) of the following elements are the normal cause: Ce, Ca, Si, and/or Ni [13-16]. Excessive Ce, in the absence of tramp elements (those that promote flake graphite), in heavy section regular DI iron will almost always cause chunky graphite. Most MgFeSi alloys contain some level of rare earth (RE), especially as Ce, to counteract the effects of antinodularising elements, to promote high nodule count and to decrease carbides incidence. This is usually fine for thin section parts, but does not work for all section sizes. If the foundry must maintain an excess of Ce and it cannot easily be removed by changing treatment alloys, then adding a graphite flake forming element may be necessary to eliminate the chunky graphite in heavy castings. The addition of either Bi (up to about 0.0030%) or Sb (up to about 0.008%) could prevent the formation of degenerate graphite, and result in increased nodule count and improved graphite nodularity [17].

Superficial layer of DI castings (usually a 0.1 to 3.0 mm thick) can include different variants of graphite morphologies, from a mixture of various graphite shapes [nodular (NG) at variable compactness, vermicular (VG), lamellar (LG), etc] up to a clear transition, such as [13]:

Lamellar (LG) →Vermicular (VG) → Irregular NG → Regular NG

Usually, the surface-layer structure includes three different strata:

- Outside layer: fine graphite flakes;
- Second layer: flakes and/or vermicular particles
- Third layer: nodular graphite, closely to normal structure.

Formation of degenerated graphite accompanies the dross defects (Fig. 4.9), inclusively in surface layer.

Chemically bonded sand moulds (self-set, no-bake, cold box) are commonly used for producing DI castings, especially of large modulus, such as windmills castings. Furan-acid and phenolics-acid no-bake systems are very attractive in DI foundries, due to strong mould occurrence, and directly applied risering possibility, respectively. As favorable for DI casting production, resin mould technology can also contribute to graphite degeneration on the surface of the spheroidal graphite cast iron, as a flake (lamellar) graphite seam. This defect can occur with any moulding technique, but it presents peculiar characteristics for each one, with important contribution of other factors, too. High contaminant and/or low Mg residual produce relatively more graphite flakes. When micro-porosity, non-nodular graphite, dross stringers and other imperfections are at the surface, all properties are reduced, but, fatigue properties are significantly affected.

Sulphur contribution of P-Toluol Sulphonic Acid (PTSA) was identified as the first favorable factor for graphite degeneration at the metal-mould interface. The most important factors to obtain less than 0.15%S in the mould (or even less than 0.07%S) and to decrease the surface layer depth, are as following [13]:

- Lower PTSA addition, ideally less than 50% of the resin;
- Enough nodulizer addition, but usually not elimination of defect;
- Lower pouring temperature, usually less than 1,350 ℃;
- Better maintained and calibrated mixers; lower reclaimed sand rate, usually less than 70%;
- Effective size classification in reclaimed sand system;
- CaO/MgO/talc composition mold coating, with desulphurization contribution;
- High density protective mould coating, but with limited efficiency;
- Phosphoric acid as blending of PTSA, but with possible P-pick up.

Oxygen influence must be also considered in resin mould technology, inclusively for S-included systems, especially due to turbulent flow, water-bearing no-bake binder, Mg-silica reaction or dross formation. MgS-O reaction is possible and resulting S-regeneration will sustain a supplementary Mg loss. Nitrogen bearing resins have a profound effect on the frequency and severity of surface pinholes, but a limited influence on the surface graphite degeneration. An excess of 60 ppm N is suspected to cause flake graphite and pearlitic matrix, but its negative influence can be limited by Ti, RE or Zr addition.

4 Solutions for windmills ductile iron castings production

4.1 The ductile iron (DI) final chemistry

(a) Adverse effects of elements segregation associated with slowly cooled large section casting can be reduced by controlling the purity of the charge materials and increasing the graphite nodule number or eutectic cell count, respectively.

(b) A balance between carbon equivalent (CE) and Si content has to be achieved; high enough to provide satisfactory nodule count (usually more than 60 nodules/mm^2), but low enough to prevent graphite flotations and chunky-graphite formation in the thermal center of castings. Generally, a range of 4.2% to 4.3%CE (3.4wt.% to 3.6wt.%C and up to 2.2wt.%Si) is recommended.

(c) In order to obtain a high quality heavy section DI castings it is necessary that the P content be limited to 0.03wt.%, the Mn content to 0.2wt.%, the Cr content to 0.05wt.%, the Ti content to 0.025wt.% and the cumulative pearlitic influence factor (P_x) to 2.0.

(d) A range of initial S content, before nodularization treatment, of 0.005wt.% to 0.015wt.% is beneficial to control

Mg-treatment recovery, nodular graphite nucleation and inclusions phase formation.

(e) A range of final Mg content of 0.04wt.% to 0.05wt.% should be obtained in the heavy castings; higher Mg favours the degeneration of graphite and increase in the amount of intercellular carbides.

(f) The antinodularising action of residual elements (Bi, Pb, Sb, As, Al, Sn, etc) up to a level corresponding to K_1 = 2.0 could be counteracted by rare earth (RE) additions: such additions are beneficial for $K_1 < 1.2$ and can be regarded as compulsory for $K_1 > 1.2$.

4.2 Metallic charge materials

(a) There has to be a compromise between using a charge which is sufficiently pure to avoid severe segregation effects, and the use of a charge which is only too pure to result in chunky graphite or exploded graphite.

(b) Control of steel scrap (SC) chemistry, that has possible alloying elements such as P, V, Ti, Cr, Mo, B, Mn, and Cr which can result in carbide or phosphide phases which segregate to cell boundries. This is now a problem to be solved and will be a greater challenge in the future as alloying elements in the steels increase. Up to 50wt.% of thin plate steel scrap (Mn < 0.2wt.%) in the charge is a reference.

(c) Special high purity pig iron (HPPI) (“Sorelmetal” type), as resulted from ilmenite ore (Ti-Fe oxides) reduction plays an important role in enabling the foundries to consistently achieve the quality and full specifications of GGG 40.3/ EN-GJS-400-18U-LT DI castings directly in the as-cast condition. The high purity and consistency of this peculiar pig iron is highly valued in addition to the other known benefits, especially to improve the ‘metallurgical quality’ of the iron melt. About 30wt.% –40wt.% of this type of high purity pig iron addition in the furnace charge shoud be considered as reference.

(d) Up to 30wt.% ductile iron returns (DIR), typically as ferritic DI products, are usually used.

4.3 Correction materials

(a) Usually, up to 1.2wt.%C addition in the iron melt is recorded, as graphitic re-carburiser, at higher C-recovery and lower contribution in detrimental elements.

(b) Depending on the metallic charge make-up and later treatments (Mg-treatment and inoculation) parameters, FeSi alloy could be used to control the Si content in the tapped iron, usually at less than 1.0wt.%Si. Foundry grade FeSi must be selected for furnace addition, at lower content of Ca and Al. The holding of the melt at the superheat temperature of min. 1,580 ℃ for 10 min after adding FeSi in the melt is beneficial.

(c) Preconditioning of the base iron during tapping period is useful to improve the nodularity and increase the nodule count, such as 0.1wt.% addition of high purity graphitic carbon material (99.8%C), at -20/+84 mesh particle size, or Al, Zr, Ca-FeSi proprietary preconditioner [19].

4.4 Mg-treatment alloys and procedure

Mg-bearing master alloys used in DI production usually refer to FeSiMgCaAlRE system, at different chemistries, depending on the treatment technique, the base iron melt quality (Si, S, antinodulizing elements, etc), holding time, DI castings characteristics, etc. Typically for heavy DI castings for windmills industry:

(a) Low content of Mg (usually less than 7wt.% Mg in master alloy), according to low S level in the base iron (usually less than 0.02wt.%S).

(b) Low content of rare earth (RE), usually less than 0.5wt.%RE in the master alloy, according to lower occurrence of antinodularising elements in the base iron (high purity charge) and negative effects of excessive RE content, especially for high purity base iron, as chunky and exploded graphite promotion in these cases. The contribution of RE must be considered, for a lower quality base iron production. The avoiding of RE is possible, but only in special conditions.

(c) Low content of Ca (usually less than 0.5wt.%Ca in master alloy), as promoter of chunky graphite in high purity base iron. Ca contribution must be considered for a base iron at lower quality.

Mg-treatment technique must be accorded to the high volume of treated iron, necessity to limit Si contribution (promoter of chunky graphite and ferrite embrittlement at low temperature) and to control Mg-recovery (low but consistent Mg level), to have high fading resistance (long holding and solidification time), and finally, low pouring temperature.

(d)Tundish-Cover method is recommended for this production, as opportunity to treat high liquid iron volume in controlled conditions.

4.5 Inoculation alloys and procedure

In heavy DI castings production, inoculation objectives are totally diferent, compared with medium and especially thin wall castings production. Generally, two important objectives must be considered:

(a) Graphite nodularity recovery, in critical castings production conditions: intensive fading (long holding and solidification time), low level of final residual Mg (typically for heavy castings, with strong graphite morphology control), low pouring temperature.

(b) To promote a minimum nodule count in heavy casting section (more than 60 nodules/mm^2), to limit inter-eutectic cells segregation (lamellar graphite, carbides, pearlite occurrence) and chunky graphite formation, respectively.

Inoculant chemistry must ensure a high fading resistance, graphite nodularity recovery and chunky/exploded graphite avoidance. Special chemistry of inoculants must be considered, for lower iron temperature application (less than 1,350 ℃). Sr-FeSi and Ba-FeSi (limited Ca content) systems are usually used.

Inoculation technique must accorded with the specific of these castings. Usually late inoculation procedures are used, such as In-stream granular inoculant addition (during mould filling, 0.2–0.7mm grain size), pouring basin inoculant addition (granular or insert forms), reaction chamber application (usually granular form). Limited inoculant addition rate is typically: 0.15wt.%–0.30wt.%, referring to treated iron.

4.6 Special chemical interactions in heavy DI castings

Two groups of active elements are usually associated in DI for this application: nodularising elements (Mg, RE) and antinodularising elements (Sb, Sn, Bi or Pb). For a strong balance control of these contradictory inflencing elements, it is possible to capitalize upon the beneficial effects of the presence of rare earth (RE), such as the improvement of the graphite nodularity and nodule count, without the occurrence of chunky and/or exploded graphite. For this reason, at least one element from the second group is added during inoculation procedure, at very low content, such as up to 0.005wt.%Bi or Pb and 0.01wt.%Sb or Sn. Expected effects in windmills castings structure: high graphite nodularity and nodule count and low incidence of objectionable graphite morphologies.

4.7 Moulding and iron pouring

Chemically bonded sand moulds (self-set, no-bake, cold box) are commonly used for producing heavy DI castings, due to strong mould occurrence, and directly applied risering possibility, hence fewer and smaller risers will suffice, or even riserless design can be considered (more than 90% casting yield). In order to decrease the castings defects occurrence, especially as graphite degeneration, inclusively at the surface layer of castings, some solutions are recommended:

(a) Low S content in the mould (less than 0.10%S), especially by lower PTSA (P-Toluol Sulphonic Acid) addition (ideally less than 50% of the resin), better maintained and calibrated mixers, lower reclaimed sand rate (less than 70%), effective size classification in reclaimed sand system, etc.

(b) Phosphoric acid is also considered as blending or even replacing of PTSA, in order to reduce the incidence of S presence in this system, such as a 3-compound acid mix (1/3 of each PTS, phosphoric and lactic acid).

(c) CaO/MgO composition mould coating, with desulphurization contribution, such as CaO/MgO layer for S stop and Zr-oxide for refractory solution.

Low pouring temperature, usually less than 1,350 ℃, is necessary for heavy DI castings, not only to control graphite nodularity but also to capitalize upon graphite expansion action to reduce contraction defects and risering necessity, respectively.

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