Recent development of ductile cast iron production technology in China

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Abstract: Recent progress in the production and technology of ductile cast iron castings in China is reviewed. The manufacture and process control of as-cast ductile iron are discussed. The microstructure, properties and application of partial austenitization normalizing ductile iron and austempered ductile iron (ADI) are briefly depicted. The new development of ductile iron production techniques, such as cored-wire injection (wire-feeding nodularization) process, tundish cover ladle nodularizing process, horizontal continuous casting, and EPC process (lost foam) for ductile iron castings, etc., are summarized.

Key words: ductile cast iron; production technology; recent development


With the constant growth of national economy, the castings output in China increases quickly. China has been ranked the top manufacturer of casting production in the world since 2000. The casting output had reached 24,420,000 tons in 2005, accounting for about 28.5% of the world's total output [1]. In addition, the output of ductile iron had also developed rapidly, which reached 5,838,000 tons in 2005, increasing to 2.46 times of output in 2000. The ratio of ductile iron castings to total castings increased from 18% in 2000 to 23.9% in 2005. Over the past five years, the production of centrifugal-cast iron pipe had achieved an average 40% growth in China, to 1.9 million tons in 2004. Moreover, huge quantities of various centrifugal-cast iron pipes have been exported to Southeast Asian countries. However, the ratio of ductile iron castings to total castings in developed countries, such as France (40.8%), the United States (32.88%) and Japan (28.9%), is still beyond that of China in 2005.

With the development of automotive and cast pipe industries, as well as the gradual improvement of ductile iron casting quality in China, the applications of ductile iron castings will be continuously expanded. In the "11th Five-Year Plan," the production of ductile iron in China will be greater than that of the world's average level, and will continue to be an important casting alloy for various engineering fields in the future. Therefore, further stabilizing ductile iron production process, improving ductile iron quality, exploiting and introducing new technologies for ductile iron production, are still an important task for Chinese casting manufacturing industry.

1 Development of as-cast ductile irons

The as-cast ductile irons own many advantages, such as energy-saving, equipment investment decreasing, production cycles shortening, production costs reducing and competitiveness promoting, compared with heat treated ductile irons. Moreover, some defects from heat treatment, such as high temperature oxidation and deformation, can be avoided in the as-cast ductile irons. About 80% ductile iron casting components in automotive applications aboard are manufactured in as-cast. Thus, the research and development in producing as-cast ductile irons for heavy-duty applications are the major tendency in future.

1.1 Thin-wall as-cast ferrite ductile iron

Thin-wall ferrite ductile iron is comprehensively utilized for making castings for some of safety critical automotive components, such as knuckle, front and rear control arms with overall section thicknesses about 10 mm. This kind of castings has the solidification characteristics, such as, high cooling rate, serious white tendency, formation of the intergranular carbide and pearlite microstructure under metastable system. So, appropriate measures should be adopted to control its metallurgical conditions.

Eutectic solidification time can be effectively decreased by increasing the number of nodule graphite, which can promote the formation of eutectic graphite. The relationship between the number of white critical nodule count and the cooling rate is as follows [2]:

\[ N = 0.58R^2 + 19.07R + 1.01 \]  \hspace{1cm} (1)

Where, \( N \) – white critical nodule counts per square mm; \( R \) – cooling rate \(^{({}^\circ\text{C}/\text{s})}\). It is shown that there is the minimum graphite nodule count in a different thickness ductile iron under various cooling rate, where white cast iron would not be formed.
Measures increasing nodule count mainly include:

(1) The content of C and Si should be as high as possible when carbon equivalent (CE) is no more than 5.0%. However, ductile-to-brittle transition temperature of ductile iron will be significantly increased by Si, and the brittleness of ductile iron will significantly increase when Si content extends to a certain extent. Therefore, the final content of Si ought to be controlled between 2.4% and 2.8% for thin-wall ferrite ductile iron.

(2) Activity of C is weakened by some elements, such as Mn, Cr, V, Ti, etc., which should be as low as possible. It is generally considered that no more than 0.3% Mn is the key to produce ductile iron with high toughness \[^{[3]}\]. Mn content should be 0.2% according to the trial conducted by BCIRA in Britain. But it is difficult to achieve such a low level to the domestic manufacturers because of poor quality pig iron resource.

(3) Control of trace element content. It is as shown in the experimentation conducted by J. W. Cheng \[^{[4]}\] that not only spheroidization rate and the toughness of ductile iron were decreased, but also graphite morphology was influenced by the trace elements Pb and Sb existed in raw materials. Disadvantageous effect of Pb and Sb on the microstructure and properties of the thin-walled ferrite ductile iron can be eliminated by both increasing RE content in spheroidizer and using inoculant containing Bi.

(4) Ratio of RE to S in the molten iron should be 3<RE/S<6. RE and Ca should be introduced at the same time, and Ca content should be controlled between 0.02% and 0.08%. Mg content should be as low as possible under full spheroidization. It is reported that NC series of special spheroidizer, consisting of RE combination with Ca, for thin-wall ductile iron, had been developed by the RE institute in Japan.

(5) Intensiﬁng inoculation. The amount of graphite nodule can be increased by adding Bi to inoculant. However, graphite spheroidizing would be hindered using excessive Bi, because the best scope of content Bi was narrow. Inoculation effect and the amount of graphite nodule can be improved using either stream inoculation or wire-feeding inoculation technique.

Chemical composition, microstructure and mechanical properties of thin-wall ductile iron parts (for automotive safety critical casting components), which were produced by Dongfeng Automobile Company (DFAC) for Guangzhou Honda and Shenlong Company, were as follows: C 3.40%–3.80%, Si 2.3%–3.0%, Mn<0.2%, P<0.03%, S<0.02%; spheroidizing rate >95%, the content of ferrite>75%, the content of carbides ≤2%; \( R_m > 420 \text{ MPa}, R_{p0.2} > 275 \text{ MPa}, A > 12\%, \gamma > 12 \text{ JC/cm}^2\), HB156–197. In recent years, many research and development works on as-cast thin-wall ductile iron were carried out by DFAC, and as-cast ductile iron parts with wall thickness of 3 mm and weight of 0.3 kg has been produced, which has high toughness \[^{[5]}\], QT400-18 as-cast ductile iron with spheroidizing rate >90% and ferrite content >90% was developed by Shandong Institute of Mechanical Design and Zhucheng Shilong Valve Ltd., using the molten iron containing Si 2.4%–2.8%, Mn<0.2%, low P and S content, and through appropriate spheroidization and inoculation operations. The technology was applied to produce the components of reflux device assembly \[^{[6]}\].

At present, there is a misunderstanding in high toughness of ferrite ductile iron. It is thought that performance of ductile iron was strongly related to its toughness. Actually, that is inaccurate. The casting deformation is not generally permitted during its service. Therefore, certain strength can maintain precision of parts, prolong service life of castings, enhance deformation resistance, and reduce deformation during its service under appropriate toughness conditions since toughness is inversely proportional to strength. The casting components to export are usually requested with a mixed matrix in microstructure. For example, the spring bracket produced for Ford Company, only requested \( R_m > 525 \text{ MPa}, A > 5\%\), and HB149–187, without particular requirement for matrix \[^{[13]}\].

Some problems in casting production, speciﬁcally those with complex shape such as high cooling rate, poor graphitization ability, and higher tendency of shrinkage and porosity existed in thin-walled ferrite ductile iron. In addition to applying extensive detecting measures (such as X-ray and ultrasonic inspections), it is the fundamental and important approach to solve the problem through systematic study and integrated management in its solidiﬁcation characteristic and process control. Besides general solidiﬁcation characteristics of ordinary ductile iron, the ductile iron with thin sections also has the following characteristics:

(1) High cooling rate due to thin wall, resulting in inadequate graphitization and formation of free carbide (reverse chill), makes the overall volume shrinkage tendency increase. Mr. Zhang Bo indicated that the actual contraction rate in solidiﬁcation was bigger than one from the calculation of equilibrium when the modulus of medium and small-sized ductile iron castings satisfy \( M < t/2=2.5 \text{ cm} \) ( \( t \) as casting thickness), and the total expansion volume caused by casting graphitization could not be enough to compensate the total shrinkage volume. This means that a riserless casting process is not suitable for thin section castings.

(2) Austenitic dendrite developed. It is shown in the latest research \[^{[7]}\] that developed divorced austenitic dendrite comes into in the course of the solidiﬁcation and growth process of ductile iron, and divorced dendrite becomes more developing with section thickness of casting decreasing. Moreover, small ductile iron casting usually has more complex shapes, which makes the liquid metal feeding channel choked easily, increasing the sensitivity to shrinkage and porosity and difficulty to control. For production process of castings, shrinkage void and shrinkage porosity may be solved by comprehensive treatment involving both metallurgical factors and casting process factors.

The metallurgical factors include: (1) Adjusting suitable chemical composition of iron melt (including trace elements from pig iron, etc.), wherein it is particularly important to control silicon content; (2) Controlling charging recipe and source of raw material (such as scrap steel); (3) Using multiple inoculation and stream inoculation technique; (4) Choosing low-RE spheroidizer and improving spheroidizing technique; (5) Adopting reasonable holding time and holding temperature.
of the molten iron; (6) Adopting higher pouring temperature.

The factors of casting process are as follows: (1) Choosing suitable solidification mode (simultaneous solidification or directional solidification) and optimizing gating system design, making temperature distribution over casting more uniform; (2) orientation and layout of casting and gating/riser system on board; (3) application of chills or chilling molding materials; (4) Good molding methods and mold stiffness, etc. In the early stages of casting trial production, such as prototyping stage, the casting process design, especially the gating system design of small thin-wall ductile iron casting, is particularly important.

1.2 As-cast pearlite ductile iron

Pearlite ductile iron is widely used in the mechanical manufacturing industry, due to its various advantages, such as the higher strength, hardness and better toughness. As-cast pearlite ductile iron can be directly prepared by adding the alloy elements into the molten iron. Good quality iron would be fabricated by adding copper element, which can stabilize pearlite and not promote the formation of free carbide. This has been successfully applied in No.1 Foundry Plant of DFAC in the early 1980s, and manufactured ductile iron used for 6-cylinder engine crankshaft with 150 hp, where the performance of ductile iron reached the grade of QT600-3. The crankshafts in SANTANA were fabricated by Shanghai St. Dormann using copper alloying technique. In addition, pearlite ductile iron with $R_m$ 800 MPa, A 3%–5%, HB 280–350, was manufactured by Mr. Zhu Xianyong [9], using alloy elements with 0.5% Cu and 0.02% Sb.

As-cast pearlite ductile iron is also produced using compound inoculant instead of alloying. There are many plants which used the SPI inoculant [10] developed by Huazhong University of Science and Technology, and good results have been achieved. The inoculant has two functions of inoculating and microalloying. An application of combining low rare-earth magnesium spheroidizer and stream inoculation technique can improve matrix pearlite and graphite roundness. A ductile iron with high hardness and toughness, whose tensile strength and elongation are more than 700 MPa and 5%, respectively, was developed by Mr. Guo Zhenting [10] through choosing the low-rare earth spheroidizer, using tundish spheroidization process technique and compound inoculant consisting of Sb and Ba. Its performance can achieve the grade of QT700-2. The 4-cylinder ductile iron with the grade of QT800-2 crankshaft was fabricated in the Jianglin Casting Plant [11] by using sand-lined permanent mold. The composition of spheroidizer is 5%–6% Mg, 2%–3% RE, 0.65%–1.23% Sb.

Shell moulding is also a good method to produce as-cast pearlite ductile iron. The ductile iron whose properties reached the grade of QT600-3 was produced by Zhu Xianyong [12] using combination 0.6% Cu with 0.4% Mn. It is recognized that the technology of shell mould backing with iron shot beads is good for increasing the number of the graphite nodules, graphite roundness and the content of pearlite in matrix, reducing the tendency of shrinkage and porosity, and improving the surface accuracy and the performance of ductile iron.

The crankshaft is mainly subject to the bend and torsion loading in its working process, whose main damage form is fatigue. The relationship between the fatigue strength in bending and the diameter of graphite nodule for as-cast ductile iron can summarize as follows [13]:

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\sigma_w = 2287/d_{max}^{0.46}
$$

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\sigma_w = 668.3/d_{avg}^{0.92}
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Where, $\sigma_w$ — bending fatigue strength, $d_{max}$ — maximal diameter of the graphite, $d_{avg}$ — average diameter of the graphite. From the formula above, we can find that the reduction in the diameter of the graphite nodule can effectively improve the fatigue strength of ductile iron. So it is important to adopt corresponding ways to refine the graphite nodule to increase the working life of crankshaft of as-cast pearlite ductile iron.

1.3 Ductile iron components with heavy-section

With the development of the heavy machine manufacturing industry and the nuclear power industry, the research and application of the thick section of ductile irons are promoted. Many studies on the solidification characteristic of thick section ductile irons, the formation mechanism of the chunk graphite and its prevention, as well as their process controls, were carried out. In the early 1980s, Wo29 ductile iron casting case, with a dimension of 2,880 mm × 2,370 mm × 3,200 mm as well as the section thickness of 200 mm, weight to 28 tons, was produced by the Wuhan Heavy-Duty Machine Tool (Group) Co. Ltd. (former Heavy-Duty Machine Tool Plant). A large ductile iron end cover, with a dimension of φ 4,400 mm × 1,860 mm and a weight of 37 tons as well as the largest section thickness of about 300 mm, was fabricated by the QiQihar Heavy CNC Equipment Corp., Ltd. (former QiQihar First Machine Tool Works) in 1984. It is the largest ductile iron casting in China by now. Thereafter, nuclear fuel containers, with a weight of 20 tons and the section thickness of 330 mm, were also successfully produced in the plant [14].

A series of defects, such as decrease of the graphite nodules, large diameter of graphite, spheroidization fading, graphite degeneration, graphite flotation, segregation of alloying elements and intergranular carbide [15], frequently occur in heavy section ductile iron castings due to slow cooling rate and long solidification time. Fading in spheroidization process is a phenomenon that the molten iron with good spheroidization previously is oxidized, re-sulphurized or other reasons. Due to a long time held under the liquid state, the residual content of spheroidizing element in the molten iron is less than the amount as requested, resulting in the grade of the spheroidization reduced. Graphite degeneration usually happens at the heavy sections. The graphitization at the places is degenerated due to slow cooling rate and long eutectic solidification time. There are two reasons that can be

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attributive to the formation of chunk graphite originated from graphite degeneration. One is fragmenting graphite; the other is weakening in the stability of the austenitic shell. The heat flow and alloying elements, etc. could cause austenite shell breaking and changing the growth mode of graphite. It is clear that the formation of chunk graphite is usually due to slow solidification rate of heavy section casting.

The methods to restrain spheroidization fade and graphite degeneration are as follows:

1. Increase castings’ cooling rate
   Rapid cooling is an effective way to prevent the graphite from degeneration. Iron chill, with the high heat conductivity, especially the strong thermal storage capacity, is the most widely applied molding materials. The graphite mould has even higher heat conductivity, three times higher than that of cast iron. But the heat storage capacity of graphite mould is weaker, which is very appropriate as molding material under the forced cooling conditions.

2. Control silicon content
   The silicon, like cerium, calcium and nickel, can drop the melting point of austenitic shell and promote the formation of chunk graphite. So the content of silicon must be controlled in the production of the heavy section ductile iron. Generally, the carbon equivalent is controlled at 4.2% to 4.3 %, and the content of silicon should be limited at 1.8 % – 2.2 %, in which it is good to prevent the formation of massive chunk graphite. When Sb of 20 to 100 ppm is added to molten iron, there will be no massive chunk graphite found in an 8-inch cube casting even the content of silicon is as high as 2.5%. The elongation of the central area is more than 20%, while the content of ferrite reaches 90% – 95%[14].

3. Desulfurize
   The content of sulfur in the liquid iron after spheroidization is controlled no more than 0.01 %, which can effectively prevent spheroidization fade.

4. Joint use of the Ce and Y rare earth spheroidizers
   The anti-fading ability of Y-Mg-Si spheroidizer is stronger than that of RE-Mg-Si spheroidizer. It should be emphasized that lowering pouring temperature and shortening the holding time after spheroidization as short as possible, not only prevent spheroidization fade, but also prevent the graphite degeneration. It is good for the heavy section ductile iron anti-fading to use yttrium spheroidizer. Of course, there are also some successful examples to apply Ce rare earth to produce the heavy section ductile iron castings. According to raw materials resources and melting conditions in China, the joint use of Ce rare earth and Y rare earth is an economic choice. The content of the rare earth used for spheroidization is controlled in 0.015% – 0.025% and magnesium controlled at 0.04% – 0.06% [15].

5. Increase graphite nodule counts
   Increasing the number of graphite nodule and reducing the diameter of graphite nodule can counteract the adverse effect caused by the slow solidification rate. There are two main ways to increase the number of the graphite nodule and refine the nodular graphite: one is to add trace alloying elements, the other is to strengthen the instantaneous inoculation. Adding a small amount of Sn, Sb or Bi to the heavy section ductile iron can prevent graphite degeneration and increase the number of graphite nodule as well as improve the mechanical properties. Not only the roundness of the graphite is improved, but also graphite degeneration is prevented by adding 0.03% Sn and 0.05% Sb into the heavy section ductile iron[16]. Inoculation can effectively increase the number of nodular graphite in heavy section ductile iron. However, excessive inoculation will promote the formation of the chunk graphite, while inadequate inoculation can make the roundness of the graphite poor, appeared as degraded graphite nodules with cluster-shape plus some carbides. The inoculation should be in action right after pouring. Therefore, in-mould inoculation, pouring-basin inoculation, wire-feeding inoculation and in-stream inoculation are the best choices.

At present, the technology producing heavy section ductile iron is gradually developed abroad. A typical example, such as the supporting frame of press machine, with a dimension of 11,300 mm × 3,300mm × 3,000 mm and a weight of 160 tons as well as the maximum section thickness of 630 mm, produced by Siemplkamp Corporation in West Germany, is the maximum ductile iron casting in the world. The highest level technique of heavy section ductile iron production can be counted on nuclear fuel containers, which need to pass 9 m falling damage experiment and 850℃ burning test. And the requirements are also high for the performance in the low-temperature toughness. TN1300 nuclear fuel container was fabricated by Thyissen Company in West Germany, whose dimension is ø2,500 mm × 5,967 mm, with a weight of 115 tons and the section thickness of 400 mm. The properties of samples sliced from the container is $R_m \geq 300\,\text{Mpa}$ and the low-temperature impact toughness (– 40℃) ≥ 12 J/cm². TN1300 type nuclear fuel container with a weight of 115 tons and the section thickness of 500 mm was also manufactured by Thystem Company in France, while nuclear fuel container with a weight of 100 tons and the section thickness of 425 mm was successfully produced in Japan in 1998. Therefore, there is tremendous potential in the production of heavy section ductile iron in China.

2 Heat treatment of ductile irons and austempered ductile irons

2.1 Incomplete austenization normalizing
Ductile iron is heated to (G + F + A) three-phase region, held and then cooled in air, a dual phase ferrite-pearlite microstructure will form in matrix of ductile iron[17]. High soundness of nodular graphite could be obtained due to partial precipitation of carbon around the graphite in the matrix. The ductile iron with high hardness, high fatigue strength and good low-temperature toughness is mainly used for the chassis parts of truck.

One successful example for the application of ductile iron is the axon of front-wheel-drive in the car. In the past, the axon and the trunnion tube annulus in two ends were respectively...
fabricated by steel sheet stamping and steel casting, and then were welded together by using 13 parts. Now, it can be fabricated by casting in one step, as a result, the production cost and weight of the component are greatly reduced.

High-duty ductile iron crankshaft was manufactured by Mr. Guo Zhenting [18] using incomplete austenitization normalizing. The heat treating process was: firstly heating crankshaft to 600 °C, holding for 1 h, then to 800 °C for 2 h, after that, it was rapidly heated to 900–910°C, then it was cooled by spraying. The microstructure of ductile iron matrix could transform to the fine pearlite and chunk ferrite. Finally, ductile iron with tensile strength of 840 MPa and elongation of 5.2% to 7.4% can be obtained by tempering at 580 – 600 °C and holding for 2 h.

### 2.2 Austempered ductile iron

Because Austempered Ductile Iron (ADI) has some characteristics, such as high strength, good ductility, high dynamic load performance like bending fatigue and contact fatigue, good shock-absorbing ability, excellent wear and abrasion resistance, it has become a kind of important engineering material [19, 20] since the 1980s. The study of ADI began from the late 1960s in China. From the early 1970s to 1990s, many fundamental researches around ADI metallurgical processes, such as its production technology and control of casting and heat treatment, static and dynamic mechanical properties and its influencing factors, performance and applied scope and so on, had been carried out. Also, four seminars on ADI had been successfully held in Beijing in 1987, Jilin in 1991, Dalian in 2002, Suzhou in 2006, respectively, which promoted the production and application of ADI in China. The main development is as follows [21]:

1. Exploitation and introduction of advanced heat treatment furnace and establishment of specialized heat treatment center.

ADI specialized furnace, developed by Zhejiang Jiashan Sanyong Industrial Furnace Co. Ltd., was successfully produced in 2006 and was used to manufacture ADI umbrella gear. The seal-boxing controllable multifunction atmosphere furnace was introduced from American AFC by Suzhou Aipu Parts Manufacturing Co. Ltd. in 2006 that is the most advanced in the world. In addition to the furnace, an austempered continuous production line of ADI production for railway parts was also manufactured by Nanjing Guangying Furnace Ltd. Through improvement on the former austempering device by Hubei Machinery and Electron Research and Design Institute and use of the intelligent manipulator, the austempering process could be accurately implemented. The establishment and introduction of such equipment lay well foundation for development of ADI.

2. Progress of ADI production technology

The prominent development of ADI includes those for dual phase ADI and carbide ADI. Dual phase ADI, or called as Duplex ADI, has more development done abroad in recent years. Duplex ADI is also defined as partial austenitization austempered ductile iron, with austenitizing temperature between $A_{C1}$ and $A_{C2}$, where pro-eutectoid ferrite coexists with the $\gamma$-phase. It is also called incomplete austenitization austempering, to utilize the pro-eutectoid ferrite in matrix to increase plasticity and toughness of ADI, decrease hardnes and improve machinability, while the tensile strength, yield strength and bending fatigue strength are without sacrificing reduction obviously. It is reported that the material was applicable to produce crankshaft in United States. The yield strength, elongation and Brinell hardness of dual phase ADI are 835 MPa, 5.3% and 241, respectively. Similar tests were also conducted by Mr. Wang Huailin, a senior engineer in Dalian Sanming Foundry Company, and good results were achieved.

Carbidic ADI (CADI) shows better wear-resistance than the general ADI. The wear-resistance of CADI is close to that of high alloyed cast iron, but the plasticity and toughness are higher than that of the latter. CADI is suitable for mining parts, agricultural machinery parts and so on.

In addition to dual phase ADI, CADI, austempering treatment process was improved and alternated into two-step austempering method so that the parts attained high strength, high hardness and high plasticity and toughness to meet the requirements of their working conditions.

3. Great progress on the research and development of ADI crankshaft

As the turbocharger technology was used, the load-bearing of the crankshaft for diesel engine had been increased by 45% – 67%. Bending fatigue properties of ordinary ductile iron crankshaft have been unable to meet service requirements, which faced to be replaced by low-alloy forged steel crankshaft. ADI crankshaft treated by fillet rolling, whose fatigue strength and structure fatigue strength had been substantially improved to satisfy service requirements, as a result, the crankshaft made of ductile iron can be continuously applied. Owing to lack of large forging equipment, ADI crankshaft was widely employed by automobile factory in China. Four-cylinder and six-cylinder crankshaft of turbocharged diesel engine were produced by Dalian Sanming Foundry Company. Because existence of some key problems, such as casting quality of crankshaft, deformation in austempering, rolling process, are solved basically, the crankshaft safety factor can achieve 1.8 and even above 2.0. So the ADI has optimistic application prospect.

4. Expanding application areas of ADI

The expansion is at the market demand for the applications of various components in heavy truck, bus chassis and railway industries. In recent years, quotation of various ADI vehicle chassis parts was inquired by many foreign companies. Some foundries have produced the casting components in small volume for large vehicle like Mercedes-Benz. The ADI gears applied for the supportive stand of trailer, exported to Germany, was recognized in their quality by the buyer basically. In addition, the demands for railway accessories have been continuously expanded.

5. Enhanced technological communication and constant replenishment of ADI performance database

About 5,600,000 tons of ductile iron was produced in China in 2004, of which 2,000,000 tons was used to fabricate pipe.
The output of ADI is estimated at 60,000 to 80,000 tons, accounting for 2% of ductile iron (except for ductile iron pipe). Among ADI castings, low wear-resistance parts, such as grinding ball, liner, hammerhead, etc., accounted for 35%; accounting for more than 5% was the railway wedge, bushing, filler plate, scaffold, chassis scaffold of the truck, pothook, the shell of general machinery, pneumatic pick housing, machine head, squeezing sleeve mini-diesel crankshaft, camshaft, and cylinder sleeve; higher precision gear less than 5%; other parts balance.

Industrialization of ADI in China can be promoted through preferentially solving following questions:

1. National specifications or standards on ADI need to be established as soon as possible. Of course, a lot of work ahead for the standard establishment should be carried out, and the manufacturer should have a few representative products and certain scale production. To the goal is difficult to be achievable in a short time. According to the characteristics of economic globalization and entering WTO, the most effective method is to establish an equivalent specification to ISO standard. In addition, static and dynamic mechanical properties of ADI, service performance, physical performance and typical example analysis on the application areas should be more reported in the relevant publications, and added into mechanical design, metal material manual. It is important for engineering personnel, particularly the designer to deepen the understanding of ADI.

2. Promoting the establishment of specialized ADI heat treatment center. Heat treatment cost maybe account for 20% of ADI production cost. Moreover, the less treatment capacity is, the higher the cost. The establishment of ADI special heat treatment plant can not only guarantee product quality and reduce production cost, but also save investment. It is benefit to promoting development of ADI.

3. Through conducting essential technical reconstruction on existing ductile iron production plants to meet the requirements of ADI, making more ductile iron production plants can produce ADI castings, because of higher quality requirements and more strict control.

4. A comprehensive and correct understanding for performance characteristics, application scope and production condition of ADI should be obtained, when ADI was recommended and used. Only in this way, the production cost can enable to reduce gradually, the economic benefit of ADI production can be discovered fully and the application scope of ADI can be expanded widely.

5. The specialized production lines for those critical parts like crankshaft and gear should be build for a certain industrial scale. The industrial chain of crankshaft and gear production should be set up through solving major critical projects related to the technology, which would promote the establishment of self-independence intellectual property for the production and enhance the ADI production technical level in China.

3 New production process of ductile irons

3.1 New technology of spheroidization

(1) Cored wire injection spheroidization

Ductile iron could be treated by means of cored wire injection process, which has several advantages, such as better desulfurization and deoxidization functions, higher absorption of magnesium, less slag, higher alkalinity of slag, less dust and weaker magnesium light, and automatic production possible. So this method will have a bright prospect, being applied sufficiently in the cast pipe industry [22].

Cored wire is usually packed by using alloy. Alloy with high magnesium (25%–30% magnesium), instead of pure magnesium, has been used as spheroidizer abroad. According to domestic condition of the molten iron, it is suitable for choosing high magnesium alloy spheroidizing powder containing 25% – 30% magnesium. When it is added into melt, relative stability of the process and sufficient quantity of magnesium dissolved can be guaranteed. If magnesium content is too low, more spheroidizer needed to add, the treatment cost will be raised [21].

Regarding to the rate of feeding wire, for example, the feeding speed can enable to approach about 20 m/min in 500 kg melt iron at 1,500 °C. The more melt iron and the higher temperature treated, the faster speed needed, otherwise, slower speed applicable. The injected wire amount is related to the sulfur content in melt iron. It’s reasonable that 0.7% (wt. %) feeding wire packed with 25% magnesium can be recommendable to treat liquid iron containing 0.03% sulfur. About 1.1% the cored wire needs to be added when 0.06% sulfur exists in melt iron. In general, the weight of liquid iron should not be less than 300 kg. If liquid iron is deficient, spheroidization effect will be affected [24].

In order to achieve satisfactory spheroidization by using cored-wire injection process, some points must be taken into account [25].

Firstly, magnesium absorption rate is directly associated with the structure of pouring ladle. For cored wire injection process, more absorption rate of magnesium can be achievable when the ratio between height and diameter of ladle increases. This ratio should be over 1.4 or 1.5 and even up to 2. Some difficulties on maintenance of the ladle would be generated using higher ratio between height and diameter of ladle. But the special ladle structure is very necessary to increase magnesium absorption and guarantee spheroidization quality.

Secondly, it is also necessary to use the covered ladle. Magnesium-light pollution and melt iron splashing can be greatly reduced with the suitable cover on the ladle. So, this method is adopted by researchers domestic and abroad, which also brings some operating troubles.

Moreover, a special processing station for the wire-feeding process was constructed abroad. Covering the treatment ladle, feeding wire and removing drag are automatically performed at the station, following the pouring ladle with liquid iron delivered to the location. Moreover, injected wire amount can be adjusted automatically, through online of processing station and bath analysis, based on the temperature and sulfur content of melt iron. The processing station is also equipped with a collection system, by which the leakage quantity of smoke, dust and light can be decreased to the least. However, this
system is only in its infancy stage in our country. Some simple operating methods, such as the ladle transferring to the wire-feeding machine by a lifter, manually covering of the ladle and manually feeding the wire injection, made the operation more inconvenient and less efficient, comparing to ordinary pouring technology. Variations from the manual operations and deficiency of the collection system make the injection feeding system with many advantages less functional. In order to popularize this new technique in China, it is necessary to construct processing station and improve relevant hardware equipments.

Besides cored wire injection spheroidization, the cored wire injection desulfurization technique has been studied by China Institute of Agricultural Mechanical Engineering, and the better results and extending application of this process has been achieved.

(2) Tundish ladle nodularizing process

Tundish ladle process is a technique that melted iron was spheroidized in the ladle covered under a certain gas pressure and relative anoxic atmosphere. Generally, spheroidizer is filled in the groove at the bottom of ladle, so that absorption of spheroidizer could be gained, compared to that in the pit at the bottom of ladle, shown in Fig.1. The kinds of treating ladle are as follows: removable covered treating ladle (Fig.2 and Fig.3), semi-stationary treating ladle (Fig.1 and Fig.4), teapot-type treating ladle (Fig.5 and Fig.6).

(3) Study of pure La spheroidizer with the low-chiller and low shrinkage tendency

Serious tendency of white and shrinkage porosity of ductile iron is a difficulty in production, especially in thin-walled ductile iron production. Chilling tendency is crucial relation to the content of Mg and Re in nodulizer. A comparison of some
different nodulizer was made by Skarander in Denmark. The results show that:

◊ When MgSiFe nodulizer containing La utilized for spheroidization, the amount of nodular graphite is 2–3 times more than that treated by nodularizer containing Ce, and the spheroidization rate increases about 10%–20%.

◊ The chilling tendency of the molten iron obviously decreases when the MgSiFe spheroidizer with La is used for spheroidization. The ductile iron treated by LaMgSiFe spheroidizer containing 0.5% La, has no free carbide and shrinkage porosity found at the hot spot of 5 mm thickness of sample under the condition of no inoculation. This finding was also supported by thermal analysis result.

◊ Compared with CeMgSiFe spheroidizer, the amount of pearlite decreases by 50% in ductile iron treated by using LaMgSiFe spheroidizer.

Recently, LaMgSi spheroidizer (5.5% Mg, 44.52% Si, 1.11% La, 0.92% MgO) was developed by Hubei Zijin Foundry Charging Company. Experimental comparisons between common RE5Mg8 nodulizer and LaMgSi nodulizer were finished in the No.2 Foundry Plant of DEAC. The results were listed in Table 1 (Data from attached casting specimen in mould).

It is observed that the LaMgSiFe nodularizar can reduce chilling and shrinkage porosity tendency effectively, and the cost of LaMgSiFe nodularizer is the general same as that of RE5Mg8 spheroidizer. So, there are still many improvements on the LaMgSiFe spheroidizer. Development of the spheroidizer is a very good approach for improving the quality of ductile iron castings, especially for middle and small-sized castings.

### 3.2 Horizontal continuous casting ductile iron

The fundamental of the horizontal continuous casting process was illustrated in Fig.7 [27,28]. The molten iron, with correct chemical composition and temperature, is poured into a holding furnace, and then solidified in a crystallizer installed under the holding furnace. The solidification shell forms and is stepped forward to ensure the shell not broken-out and the molten iron not leaked-out by means of starting traction machine. The molten iron continuously enters into the crystallizer under the gravity force and solidifies in crystallizer. Ductile iron is fabricated by the repeated operation. Diversified products with various structures are manufactured by cutting and shearing.

<table>
<thead>
<tr>
<th></th>
<th>Rc</th>
<th>Rp0.2</th>
<th>A</th>
<th>HB</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaMgSiFe first pouring</td>
<td>466</td>
<td>313.9</td>
<td>18</td>
<td>166</td>
</tr>
<tr>
<td>LaMgSiFe last pouring</td>
<td>418</td>
<td>277.7</td>
<td>19</td>
<td>158</td>
</tr>
<tr>
<td>RE5Mg8 first pouring</td>
<td>515</td>
<td>364.7</td>
<td>6</td>
<td>174</td>
</tr>
<tr>
<td>RE5Mg8 last pouring</td>
<td>510</td>
<td>350</td>
<td>11</td>
<td>172</td>
</tr>
</tbody>
</table>

**Table 1 Comparison of experiment result between two nodulizers**

Due to high cooling rate and nucleating rate, the nodular graphite with small diameter, soundness microstructure and good properties can be obtained in shape ductile iron by means of horizontal continuous casting. More than ten production lines of horizontal continuous casting were introduced and developed by Xi’an University of Technology and Shenyang Research Institute of Foundry, etc. The annual output reached 20,000 tons, among them, 30% for ductile iron. The ductile iron produced by horizontal continuous casting process is widely used in casting components such as the bushings for high-speed trains, small gear, high pressure hydraulic valve and other important components.

### 3.3 Negative pressure EPC technology of ductile iron

EPC technology has been grown in China rapidly since the last decade of the 20th century. Because the castings fabricated by EPC have many advantages, such as high casting...
surface finishing and dimensional accuracy, good working environment and low manufacturing costs, various scales of EPC production lines or simplified production device have been established in many enterprises through the introduction of technology or cooperation with domestic research institutes.

Some characteristics favorable, such as mould with high compactness and molten iron with rapid cooling rate, could be achieved, when liquid iron solidified under negative pressure. So, ductile iron castings could be manufactured by negative pressure EPC, a casting process of EPC technology combining with sealed molding under negative pressure. Ductile iron castings produced by EPC have high dimensional accuracy, good surface finish, and low reject rate, which would bring better economic benefits. At present, ductile iron castings like shaped tube [29], valve [30], automotive differential cases [31], etc. are fabricated by EPC in some factories in China.

3.4 Permanent mould and sand coated permanent mould casting technologies

Permanent mould casting process of cast iron has been developed and applied in the casting production for a long time [32, 33]. Most of castings produced by permanent mould casting process are those with relatively simple geometry and with a weight range of 5–15 kg. The key technologies for permanent mould casting process are basically resolved and gradually matured due to continuous research and development since the 1970s. The castings produced by permanent mould casting process exceed those by sand casting process in the surface and internal quality. The surface finish accuracy with ± 0.5 to 0.8 mm and surface roughness with Ra 6.3 µm can be obtained. So, permanent mould casting technology has become an advanced, economic and efficient new technology in the production of iron castings, especially for ductile iron.

Now, many works on the selection of mould materials and varieties of product development are fulfilled in China, including: (1) Rapid cooling rate is obtained, which makes significant fine graphite and matrix structures due to the application of copper alloy mould. Moreover, alloying elements are added to improve the mechanical properties. While the thermal stress in copper alloy would become smaller than that of casting iron mould when it is repeatedly poured. Therefore, using copper alloy mould is more favorable than cast iron mould in the production of gray iron and ductile iron, and the mechanical properties of gray iron and ductile iron are slightly improved [34], (2) The thin-walled ferrite ductile iron with as-cast ferrite content more than 98%, small graphite nodule with the average diameter of 12 µm, the number of nodular graphite per unit area above 900 / mm², spheroidizing rate beyond 90% and cast mechanical properties up to QT450-15 was produced using copper permanent mould casting. In addition, as-cast austempered ductile iron can be prepared by permanent mould casting and with the appropriate annealing process. The tensile strength of as-cast ADI reached 1,080 MPa with insignificant drop in the hardness [35].

Sand coated permanent mould casting with the characteristics of both metal and shell molding is particularly suited to fabricate ductile iron such as valves, cylinder head, crankshaft and disc tooth castings, etc. Through consistent research and extension by Zhejiang Institute of Electrical and Mechanical Design in recent years, the sand coated permanent mold casting is gradually developed, and becomes a new process for ductile iron casting production with China's special characteristics. This process has been applied in ductile iron casting production by dozens of foundry enterprises in China by now. More than 30 kinds of castings have been manufactured with output about 100,000 tons, among them, crankshaft accounts for about 80%. Wanli Mechanical Co. Ltd. in Jiangsu province has six sand coated permanent mold casting production lines, which are used for producing single, three, four, six-cylinder crankshaft with high performance. The shaking ladle desulfurization technology is utilized in this plant.

3.5 Investment casting of ductile iron

The investment casting technology of ductile iron has been developed rapidly abroad since the 1960s. It has been significantly grown up in its production, variety of products and geometric complexity in recent years in China. For example, many ductile iron castings are fabricated in Dongfeng Precision Casting Plant.

But some differences in their casting productions between investment casting and sand casting exist (shown in Table 2), as follows: (1) Poor ability in slag removal and difficulties in feeding with investment casting process because of incomplete gating system; (2) The microstructure and properties are affected by slow solidification rate because of its hotter mould shell; (3) High density of mould shell may cause gas permeability difficult. The blowholes, which reduce the internal and external quality of castings, easily form. All of these gave an increase of reject rate in its production.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Sand casting</th>
<th>Investment casting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear shrinkage</td>
<td>0.8% –1.5%</td>
<td>Paraffin mould shrinking 0.8% –1.2%</td>
</tr>
<tr>
<td>Gating system</td>
<td>Considerable ability of pushing off the slag</td>
<td>Without ability of pushing off the slag</td>
</tr>
<tr>
<td>Mould stiffness</td>
<td>Higher in baked mould, lower in greensand mould</td>
<td>Higher, powerful ability of self-feeding</td>
</tr>
<tr>
<td>Atmosphere inside mould pouring</td>
<td>Reduction atmosphere</td>
<td>Weak oxidization atmosphere</td>
</tr>
<tr>
<td>Gas permeability</td>
<td>Better</td>
<td>Bad</td>
</tr>
<tr>
<td>Dimensional accuracy</td>
<td>General</td>
<td>Better</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>General</td>
<td>Better</td>
</tr>
</tbody>
</table>

Table 2 Comparison of several key characteristics between sand and investment casting processes
At present, quite a number of ductile iron castings with thin wall and complex geometry cannot be cast well with investment casting process. Therefore, the further research and development on the process, such as selection of mould shell material, melting techniques, solidification of casting, the spheroidization and inoculation process and pouring technology, are needed.

4 Summaries
The significant progress in the technological development for ductile iron production has been made in China. Moreover, there is still greater potential for further development. In the "11th Five-Year Plan" period, the production and technology of ductile iron in China will make much greater achievement through the efforts of the foundry community.

References