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DUCTILE IRON PRODUCTION TECHNOLOGY: A REVIEW

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ABSTRACT

Ductile iron castings have proven to be the cost-effective materials of choice and/or potential alternatives to other competing materials (e.g. malleable iron, steel and aluminum castings) and manufacturing processes (forgings, fabrications, etc.) with either an improvement in service performance or lower production cost or both. The outstanding growth in the use of ductile iron castings in engineering applications including those in which the casting properties are critical to lower energy utilization, safe operations and in safety related components such as automobile steering knuckles and brake calipers, gears, valves, pumps, etc., has occurred because of the tremendous improvement in production capabilities resulting in quality consistency and freedom from imperfections, obtained through stringent microstructure control. This paper is a review of the production technology and development (in terms of the metallurgical, chemical composition, heat treatment, microstructure and mechanical properties and design parameters) of this unique class of engineering purpose cast irons and highlights niche applications where ductile irons excel over conventional materials.

1. BACKGROUND INFORMATION ON DUCTILE IRON

The increased demand for improved performance output and fuel efficiencies, decreasing noise and pollution and reduced costs in automobiles and other dynamic-load bearing systems have led to the development of novel cast iron materials with superior strength to weight ratios that add up to more strength for less expense. In recent years, ductile (also known as spheroidal or nodular graphite) cast iron, the base material for the uniquely versatile austempered ductile iron (ADI), has become one of the most important engineering materials, in view of its excellent combination of good castability, machinability and mechanical properties with significant savings in cost and weight compared with equivalent steel components. The material can be tailored to fit an unusually broad diversity of needs, which remarkably, has opened new vistas for its application in the manufacture of automobile, construction, agricultural, mining, heavy-machine, military and railroad components, which are traditionally produced by expensive forging and fabrication processes involving high grade alloy steels (crs-latestream.pdf, 1999; Lerner, 2004; Bockus and Dobrovolskis, 2006; Palmeira *et al*., 2006; Ductile Iron Data for Designers – Section 2, 2010).

Ductile irons have strength, impact toughness and ductility comparable to those of many grades of steel, while exceeding by far those of standard gray irons. It has the same advantages of design flexibility and low-cost casting procedures of gray irons (Nicoletto *et al*., 2002). Their corrosion resistance is equal or superior to that of gray cast iron and cast steel in many corrosive environments. The wear resistance is comparable to some of the best grades of steel and superior to gray iron under heavy load or impact situations. Ductile irons are considerably less expensive than cast steels to produce and only moderately more expensive than gray cast irons since the production procedures are similar. Ductile iron has a clear advantage over malleable iron for applications where low solidification shrinkage is required or where the section is too thick to permit uniform solidification as white iron (Ductile Iron Data for Designers – Section 2, 2010).

Ductile iron castings have advantages of isotropy of properties and homogeneity without laminations as in the case of steel forgings and fabrications. Ductile iron offers substantial cost savings, particularly with respect to the reduced requirement for feed metal, production cost (in terms of material and energy requirements) and mechanical properties. Again, the use of the most common grades of ductile iron "as-cast" eliminates heat treatment costs, thus offering a further advantage.

The most important single step in the production of ductile iron is the addition of graphite nodularizing agents in the treatment of the iron melt. This gives an as-cast structure containing graphite in the form of small rounded, "spheroidal", "globular" or "nodular" particles in a ductile metallic matrix (Figs. 1(a)-(d): (Imasogie, 1994; Imasogie *et al*., 2000; Adetunji *et al*., 2008; Olusunle, 2008). Ductile iron results from a suitable treatment of the molten iron with magnesium and/or calcium containing treatment agents, prior to casting, which causes the graphite to precipitate as tiny spheroids or nodules rather than as flakes, as obtains in the case of gray cast iron.

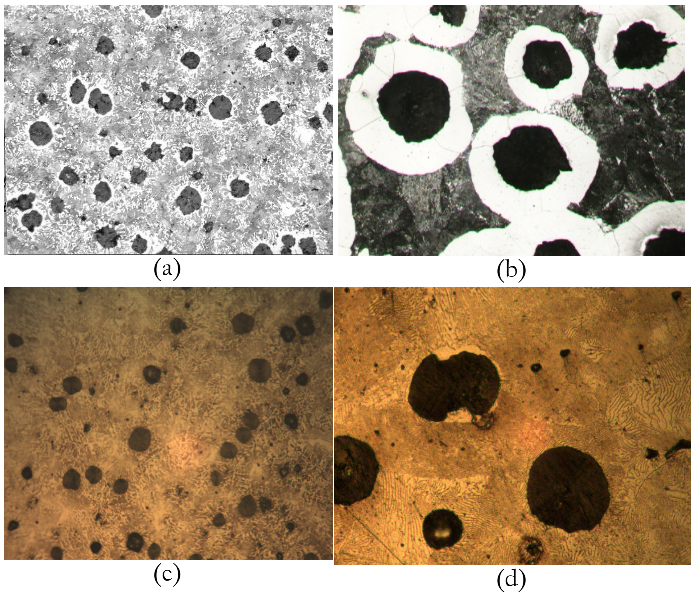


Fig. 1: Micrographs of nital etched, as-cast ductile irons: (a) Mg-Ca-Fe-Si treated iron, graphite nodules (dark grey) in ferrite envelopes, in fine pearlite matrix with some free carbides, x70 (Imasogie, (1994); (b) the enlarged form of (a) showing the 'bull's-eye" graphite nodule-free ferrite pair, x 500; (c) Rotary Furnace-Melted FeMgSi treated iron; graphite nodules (dark grey) in fine pearlite matrix, x70 (Adetunji et al., 2008); (d) Ni-Cr alloyed FeMgSi treated iron, showing graphite nodules in fine pearlite matrix with free carbide (light irregular particles), x 500 (Olusunle, 2008).

The graphite spheroids or nodules in ductile iron, unlike the random lamellae of graphite flakes in ordinary gray cast iron, create much fewer and less severe discontinuities in the metal matrix, thus producing a stronger, more ductile cast material. Thus, the spherical shape of the graphite removes its "crack" effect, while as spheroids, they act as "crack-arresters" in the system. A number of variables including chemical composition (charge and alloying, graphite nodularizing treatment and inoculating agents, etc.), melting conditions and practice, graphite nodularizing treatment and inoculation method and practice, temperature, cooling rate, section size, etc., affect the graphite and matrix structures. It has been established that all of the mechanical and physical properties characteristic of ductile iron are as a result of the graphite being substantially or wholly in the spheroidal/nodular shape. The bulk mechanical properties are thus determined primarily by the steel-like matrix and any departure from this shape/form or in the proportion of the graphite will cause a drastic deviation from these properties (Fuller *et al.*, 1980; Emerson and Simmons, 1976; Fuller, 1977; Imasogie *et al.*, 2000; 2001).

The presence of graphite contributes directly to lubrication of rubbing surfaces and provides reservoirs to accommodate and hold lubricants. This means good resistance to mechanical wear. Graphite also contributes to machinability because it acts as a lubricant during cutting and also tends to break up chips. Like gray iron, ductile iron has inherent corrosion resistance. In addition, the nodular graphite has desirable lubricating and crack arresting effects in the system (Imasogie, 1994; Imasogie *et al.*, 2000; 2001)).

Ductile iron is a eutectic alloy, which means that it has a low melting point, high fluidity and good castability especially for intricate, complex-shape castings with light sections. Expectedly, the automotive industry has expressed its confidence in ductile iron through the extensive use of the material in safety related, functional and structural components such as steering knuckles, brake calipers, etc., which are used mostly as cast.

This paper reviews developments in ductile iron production technology and highlight some notable applications of the material. Section 2 describes briefly, the major types of ductile irons and their applications. The graphite nodularizing action can be regarded as a simultaneous desulphurization and deoxidation treatment where elements with strong affinity for sulphur and oxygen are added (Anderson and Kaysay, 1985; Heine, 1987; Imasogie, 1994; Imasogie *et al.*, 2000; Imasogie, 2003). A detailed review of graphite nodularizers and theories of nodularization mechanisms is presented elsewhere (Imasogie *et al.*, 1991, 2001). Section 3 reviews ductile iron production metallurgy in terms of the evolution of graphite nodularizing treatment and post treatment inoculation methods and practices (open ladle, sandwich, tundish cover, in-mold, plunger, converter, injection, etc.,). The choice of a treatment method depends to a large extent on prevailing circumstances such as the level of technological advancement (expertise and installed capacity) and available foundry equipment. Section 4 highlights recent improvements in ductile iron technology and describes briefly how to achieve high-volume-continuous-casting production of near-net-shape high quality casts. Section 5 discusses the microstructure in relation to the fracture characteristics of ductile irons. Section 6 highlights niche areas of applications where ductile iron materials compete and are even preferred to conventional engineering materials such as forged steels, wrought steels, aluminum, etc.

2. TYPES OF DUCTILE IRONS

There are three major types of ductile iron castings (Ductile Iron Society, 2010):

i. Ferritic Ductile Iron (60-40-18); with graphite spheroids in a matrix of ferrite. It has high impact resistance, relatively good thermal conductivity, high magnetic permeability, low hysteresis loss, good corrosion resistance and good machinability.
ii. Pearlitic-Ferritic Ductile Iron (80-55-06); with graphite spheroids in a mixed matrix of ferrite and pearlite. It is usually produced in a normal production of ductile iron and it is less expensive to the ferritic grade. It has good machinability.
iii. Pearlitic Ductile Iron (100-70-03); with graphite spheroids in a matrix of pearlite (i.e. a fine aggregate of ferrite and cementitie (Fe_3C)). It is relatively hard, with moderate ductility, high strength, good wear resistance, moderate impact resistance, relatively lower thermal conductivity, magnetic permeability and higher hysteresis loss. It has good machinability. Pearlitic grades of ductile irons are good candidates for applications requiring only high strengths and limited ductility and toughness and are generally not recommended for use in applications requiring impact toughness.

There are some other emerging special grades of ductile irons:

i. Martensitic Ductile Irons: these are tempered martensitic ductile irons having very high strength and wear resistance.
ii. Austenitic Ductile Iron; with outstanding features including good corrosion and oxidation resistance, magnetic properties, strength and dimensional stability at elevated temperatures. It is also known as Ductile Ni-Resist.
iii. Heat Resisting Ductile Irons: these are alloy ductile irons containing 4-6% silicon (Imasogie *et al.*, 2001), Ductile Iron Data (2010)) developed to meet the increasing demands of high strength ductile irons capable of operating at high temperatures in applications such as exhaust manifolds, turbocharger casings, etc. The primary properties required for such applications are oxidation resistance, structural stability, strength and resistance to thermal cycling. Alloying with Si and Mo significantly improves the high temperature performance of ferritic ductile irons while maintaining many of the production and cost advantages of conventional ductile irons.
iv. Austempered Ductile Iron (ADI): This is the most versatile set of ductile irons. ADI offers a remarkable combination of strength, toughness and wear resistance; almost double the strength of conventional ductile iron, but with comparable percentage elongation (ε %) and toughness characteristics. It has exceptional wear resistance and fatigue strength and compared to equivalent high alloy steels, it offers reduced component weight, costs and improved service performance.

    ADI is subjected to the austempering process to produce mechanical properties that are superior to conventional ductile iron, cast and forged aluminum and steel. In addition, ADI weighs only 2.4 times more than aluminum but it is 2.3 times stiffer. ADI is also 10% less dense than steel. For a typical component, ADI costs 20% less per unit weight than steel and half that of aluminum (Johansson, 1977).

3. DUCTILE IRON METALLURGY

3.1. Graphite Nodularization Treatment and Practices

The vital characteristic of ductile iron (DI); the base material for ADI, is the globular structure of the graphite component and this is traditionally produced by adding small quantities of magnesium and/or cerium under highly controlled conditions. However, magnesium is expensive and dangerously reactive. Violent agitation of the molten metal causes undesirable pyrotechnics, splashing, and low recovery of reagent, the low boiling temperature and volatility of magnesium being the cause. The cerium process is even more expensive because of the very high cost of misch-metal used as an additive. A greater residual content of cerium than magnesium is needed for an equivalent nodularity and the iron produced is more susceptible to chilling (Davis and Magny, 1978). Also, the graphite spheres given by cerium treatment are in general not so perfect, while a heavy inoculation is essential for good nodularity in thick sections, where graphite flotation tends to be more serious. Thus, the growing interest of metallurgists in finding cheaper, safer, and equally effective substitutes is understandable.

Among other identified potential nodularizers, calcium and calcium containing compounds have been successfully used as modifiers before in-mould nodularizing treatment with magnesium (Horuichi, 1957; Krzemien, 1979; Kurganov *et al.*, 1981; Petrichenko *et al.*, 1981). However, only modest properties have been obtained for irons inoculated with Ca-CaC_2 (Imasogie, 1994; Umoru *et al.*, 2005) and CaSi-CaF_2 (Imasogie *et al.*, 2001) as primary nodularizers. An extensive study was carried out by the present author working with the ductile iron research group based at the Department of Materials Science and Engineering, Obafemi Awolowo University, Ile-Ife, and at the Engineering Materials Development Institute, EMDI, Akure, Nigeria, to find a cost-effective treatment route for the production of standard ductile irons using locally available materials and foundry equipment. The research was focused on the possibility of harnessing the positive and additive aspects of appropriate calcium alloy combinations used together with magnesium; that is as master alloys with the added advantage of better treatment control and ultimately improved ductile iron. The research effort yielded a special Ca-CaC_2-Mg master-alloy formulation, selected on the basis of optimum results (Imasogie, 1994, 2002, 2003; Imasogie *et al.*, 2000). Results of investigations of the effectiveness of the multiple calcium-magnesium based master alloy nodularizer and the properties of the ductile iron produced have been extensively reported (Imasogie, 1994, 2002, 2003; Imasogie *et al.*, 2000; Imasogie and Afonja, 2003).

One of the emerging hypotheses of the mechanism of nodularization of graphite in cast iron is based on the removal or neutralization under special conditions, of some surface active elements such as sulphur, phosphorus, oxygen, etc. Results of the above mentioned research (Imasogie, 1994, 2002, 2003), established that the removal and/or neutralization of both sulphur and phosphorous in particular, in the iron melt through reactions with the nodularizers employed, is indeed necessary for the production of ductile iron. Sulphur, phosphorus and to some extent oxygen are known to be surface active and by reducing the graphite/iron interfacial energy, through their segregation on the graphite/iron interface and selective adsorption on the graphite prism planes, can promote the extended interfacial characteristics of flake graphite (Franklin and Stark, 1984; Takita and Ueda, 1979; Imasogie, 2002). The nodularizers ensure that the graphite basal planes would now have the lower surface energy in contact with molten iron and nodular graphite is formed. It was observed that the degree of this apparent neutralization of the surface active elements was relatively higher with the multi-material Ca-CaC_2-Mg master-alloy treatment than with the traditional Mg or Mg-FeSi treatment (Imasogie, 2002). Figs. 2(a) – (d) show typical photomicrographs of two sets of as-cast ductile iron specimens obtained using the multi-material Ca-CaC_2-Mg master-alloy and the conventional FeMgSi nodularizers. Figs. 2(a) and 2 (b) illustrate the microstructural features of the two irons in the as-cast conditions; respectively.

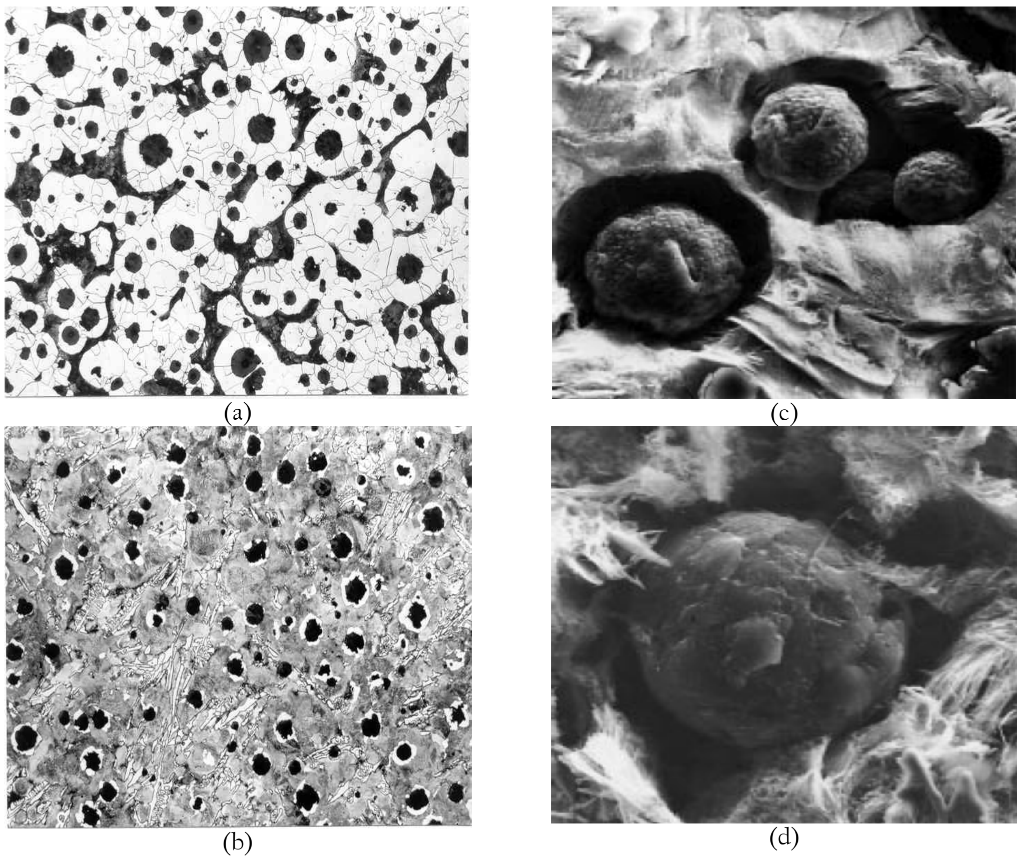


Fig. 2: Micrographs of irons in the as-cast state, nital etched; (a) Ca-CaC_2-Mg masteralloy treated iron; showing graphite nodules (dark grey) and some fine pearlite (irregular dark areas) in a ferrite matrix; (b) FeMgSi treated iron; showing excessive amount of free carbide (light columnar particles), other phases, with graphite nodules enveloped in ferrite, in a pearlite matrix; (c) and (d): irons in ((a) and (b), respectively, showing SEM of the as-cast specimens with matrix etched away to show the different 3-D graphite nodule forms (Imasogie, et al 2000).

The iron treated with MgFeSi (Fig. 2(b)) has a much larger pearlitic phase, confirming the tendency of magnesium to stabilize carbide. The microstructure also exhibits significant phosphide eutectic and other hard phases. However, in the iron treated with the special masteralloy nodularizer (Fig. 2(a)), the graphite spheroids appear almost uniform in size and distribution in the matrix, which appears to have none of these hard phases. Up to 96% nodularity was obtained using the special Ca-CaC_2-Mg masteralloy compared with 98% using magnesium alone. The mechanical properties were also comparable. Figs. 2(c) and 2(d) illustrate SEM observations of the form and/or morphology of graphite in these specimens, respectively, where the matrix has been etched away. Here, striking distinctions exist between graphite morphologies obtained using the aforementioned master-alloy (Fig. 2(c); which shows colonies of graphite spheroids each of which appears to be built up of several tiny spherulites), compared with that produced using the conventional magnesium ferrosilicon (Fig. 2(d); which shows the graphite as lumpy and solid with a relatively rough surface).

The first step in the production of a sound ductile iron is the careful selection of charge materials as well as graphite nodularization treatment process parameters. The amount of each alloying elements required should be such as will give castings that are free of carbides as much as possible; particularly in as-cast ferritic ductile irons (Bockus and Dobrovolskis, 2004). For instance, manganese and chromium should be in the range 0.5 and 0.1 % respectively. Manganese and chromium usually come in from steel scrap, iron units and returns or they can be deliberately added as alloying elements. In particular, the graphite structure as well as the matrix is affected by the carbon content and/or C/Si ratio (as increasing this ratio decreases the proportion of ferrite to pearlite phases in the system). Generally, to achieve a ferritic casting in as-cast condition, chemical composition of charge material should not contain more than 0.01%Sn, 0.02%As, 0.1% Σ(V + Mo), 0.04%Cr, 0.02%S and 0.05%P (Bockus and Dobrovolskis, 2004).

In all cases, the sulphur content must be kept below 0.02% through melting and desulphurization processes for the treatment to be effective with the above mentioned nodularizers. In the case of the use of the traditional pure magnesium, the material is introduced into the molten iron either in the open-ladle (or in-ladle) method or the pressure-container (converter) method. In both cases, special (mostly proprietary) techniques have been developed and numerous patents have been taken out regarding most of the techniques.

Lerner and Panteleev (2002; 2003) have carried out a comprehensive review of magnesium and magnesium-based-alloy treatment agents in ductile iron production. Fig. 3 presents a typical classification of Mg-treatment alloys and treatment methods currently in use for producing ductile iron castings.

In general, apart from the deployment of special equipment or devices to control the violent reaction rate and maximize Mg recovery, the use of pure magnesium as a treatment agent presents several challenges. Most of these have had something to do with the undesirable effects of significant undercooling, high chill rate and Mg "fading". Its major advantage is the fact that the necessary desulphurization process can be carried out in the same ladle before or during treatment.

Two of these traditional processes; the 'plunging' and the sealed pressure/autoclave ladles (Figs. 4(a) and (b)), have stood the test of time. Apart from its simplicity, the plunging process can utilize the full range of nodularizing materials and has the ability to treat iron with relatively high sulphur content. However, it suffers from considerable temperature losses, as a result of plunging the large cold plunging bell with the nodularizing agent, as well as a significant pyro-effect. In addition, due to the extreme working conditions of the plunging bell, it is seldom reusable. On the other hand, the pressure ladle/autoclave technique has a pneumatically or hydraulically operated pressure head that plunges the Mg billet into the ladle and finally seals it. Since the magnesium is introduced into the liquid iron under excessive air pressure, it melts, but does not vaporize. A special stirring device mixes the liquid metal layers, resulting in improved nodularizing treatment. The advantages of this latter process include up to 70% Mg recovery and an adequate residual Mg content. Nowadays, the process is fully automated and environmentally safe. However, the process still suffers from significant temperature losses, a relatively high cost of equipment and the necessity for regular maintenance during operations.

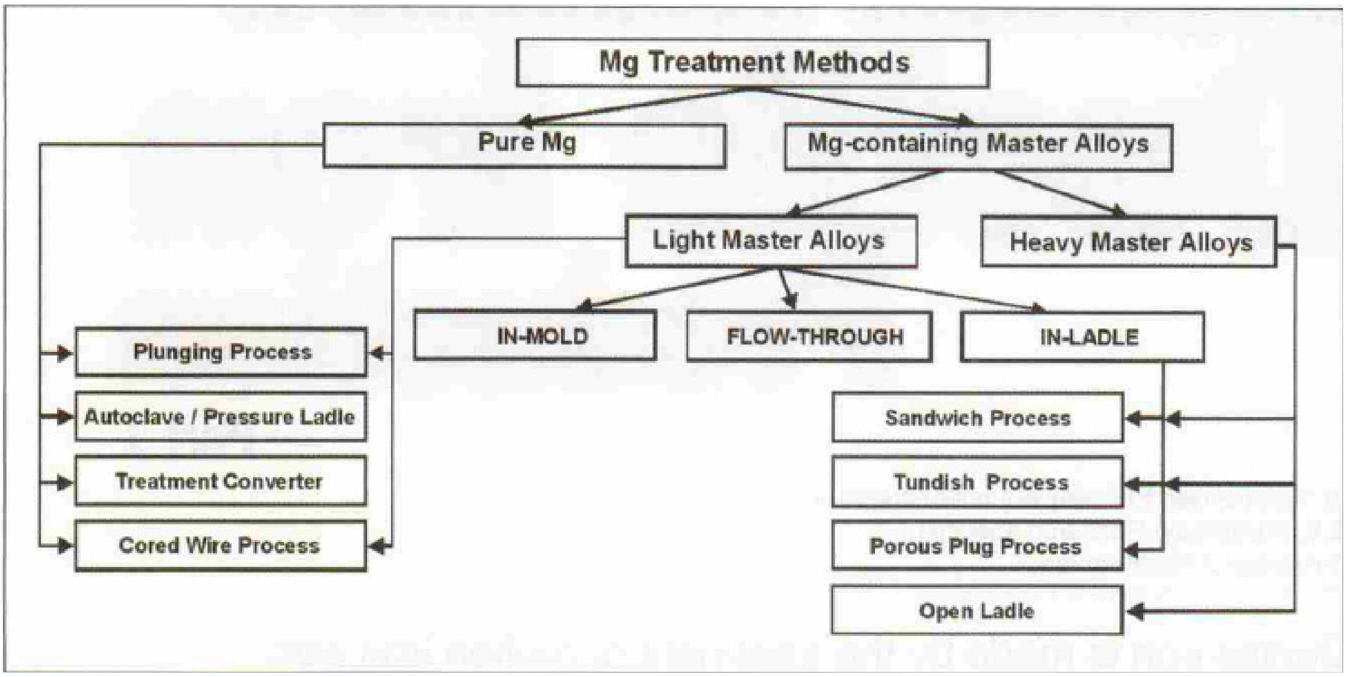


Fig. 3: Classification of Mg treatment alloys and methods currently used for ductile iron castings (Lerner and Panteleev, 2002)

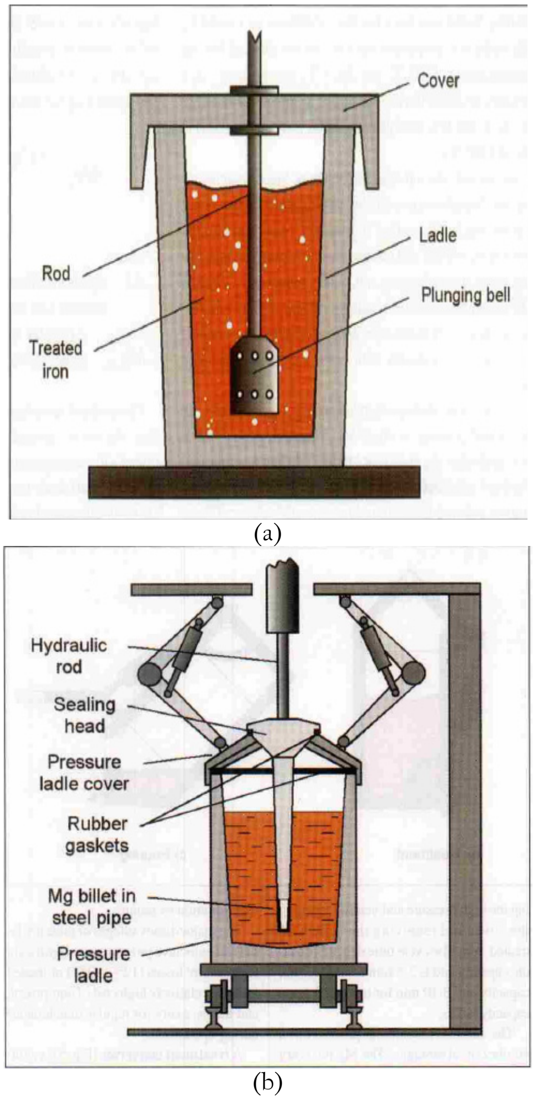


Fig. 4: Schematic of (a) Plunging and (b) sealed pressure ladle processes (Lerner and Panteleev, 2002)

The treatment converter shown in Fig. 5 (Lerner and Panteleev, 2002), is a latter development over the plunging and pressure ladle/autoclave process. It is a tilting cylindrical vessel lined with a refractory material, with a simple reaction chamber at the bottom of the vessel, above the liquid iron surface, when the converter is in a horizontal position, to avoid a premature Mg contact with the iron. This is a more efficient and safe design, compared with the plunging and pressure ladle/autoclave processes. It provides effective desulphurization and makes possible the use of cupola-melted high sulphur base iron. Although an Mg recovery of up to 50-55% is possible, the process suffers from a relatively long treatment cycle involving post-inoculation, etc. It requires a high financial investment in equipment and ancillary devices.

In modern graphite nodularizing treatments, magnesium still forms the base treatment agent, used in combination with other nodularizing elements (as masteralloys), or as Fe-Mg-Si alloys. In these cases, the modes of introduction of the nodularizer in molten iron to be treated are significantly different from the techniques reported above for pure magnesium treatment. Recent research on the use of multiple nodularizing elements as a substitute for pure magnesium has been aimed primarily at the need to reduce the smoke and flare produced by addition of magnesium or magnesium-ferrosilicon, to achieve higher magnesium recovery and minimal fading, and to reduce the susceptibility to chilling inherent in both magnesium and cerium treatments (Imasogie, 1994, 2002, 2003; Takita and Ueda 1979; Lerner and Panteleev, 2003). With this shift, came several notable melt treatment techniques using multiple-element treatment alloys (masteralloys) and Fe-Mg-Si alloys.

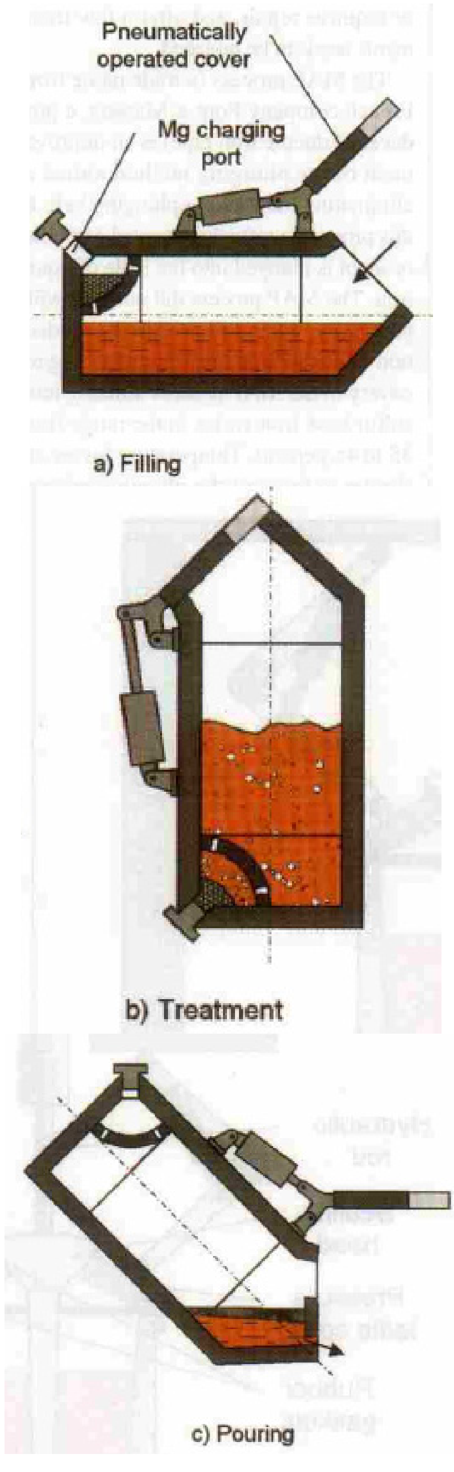
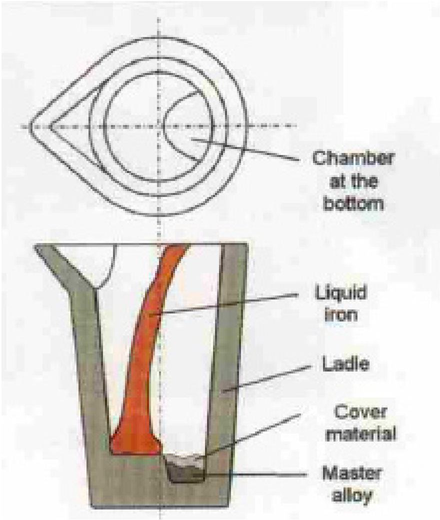


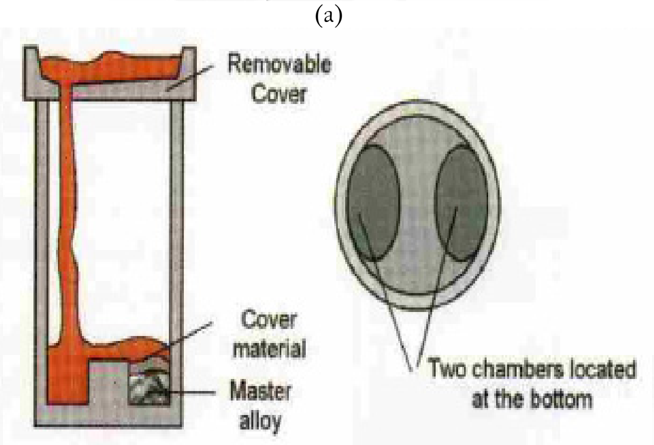
Fig. 5: Schematic of the treatment converter illustrating the treatment sequence (Lerner and Panteleev, 2002)

Generally, these techniques are classified into two main groups; namely, "In-Ladle" and "In-mold". The in-ladle techniques include the "open-ladle" process, of which the well-known "sandwich process" (Figs. 6(a)), is a special case.

It is pertinent to mention here that the OAU/EMDI DI-ADI research group has been able to adapt the sandwich method to successfully treat Rotary Furnace melted cast iron. To achieve this, a pre-heatable treatment ladle was designed and fabricated in-house, to offset any temperature loss during and after treatment. An easily removable wire-gauze sheath mechanism was used to secure the ironfilings cover material and the treatment alloy in place in the chamber at the bottom of the ladle, prior to tapping. The sheath is steadily withdrawn, while a slight toggling-stirring action is applied, when the ladle is about three-quarter filled with molten metal, an action which effectively triggers the release, dispersal and reaction of the nodularizing agent as the sheath is taken up through the melt. In this way, a higher treatment agent recovery was achieved.



(a)



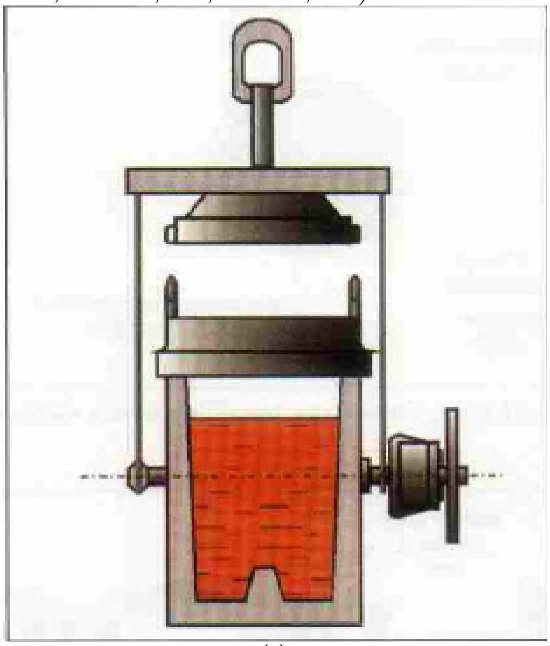
(b)

Fig. 6: Schematic of (a) Sandwich method, (b) Two-chamber tundish ladle with removable cover (Lerner and Panteleev, 2003).

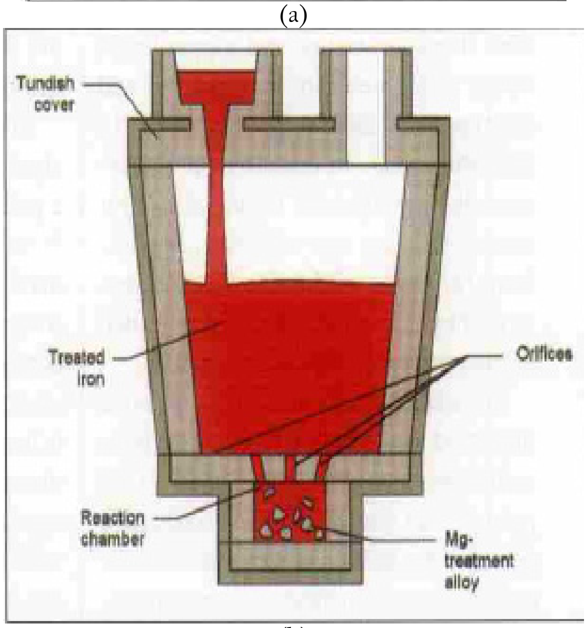
A latter modification to the open ladle sandwich process makes use of the "tundish ladle" with a lifting and/or removable cover (Fig. 6(b)). In fact, the "tundish process" is an improvement on the sandwich method aimed at reducing the oxygen level inside the ladle (Lerner and Panteleev, 2003). The tundish ladle with lifting cover (Fig. 7(a)) and the tundish "converter" (Fig. 7(b)) are the most modern Mg-Fe-Si and master-alloy treatment equipment. The latter is a further modification of the sandwich process, which is a combination of a conventional tundish ladle and Mg-Fe-Si/master-alloy treatment converter (Lerner and Panteleev, 2003). This device contains a reaction chamber attached to the bottom of the ladle to hold pure Mg or master alloys. Liquid iron is tapped through the tundish cover and then through the orifices, located at the bottom, enters the reaction chamber and reacts with the nodularizer preloaded in the chamber before tapping. A crane or monorail delivery system allows for the use of the tundish-converter also as a transfer ladle to tap ductile iron into a pouring ladle or autopour (Lerner and Panteleev, 2003). About 30% of the world's ductile iron is currently produced by this method. Mg recovery (with little or no fading) in the tundish process may reach up to 75%.

Another advantage of the tundish converter is the relatively low cost of tundish ladles, coupled with its environmental safety and low emission levels. The only disadvantage is the inherent temperature losses and the relatively long treatment cycle.

The "In-mold" treatment process and the flow-through Mg-based master alloy treatment process are the major technological revolutions in the graphite nodularizing processes for the mass production of ductile iron automotive parts, since the last quarter of the last century (Figs. 8(a) and (b), respectively) (Lerner and Panteleev, 2003; Dremann, 1983; Hummer, 1985).



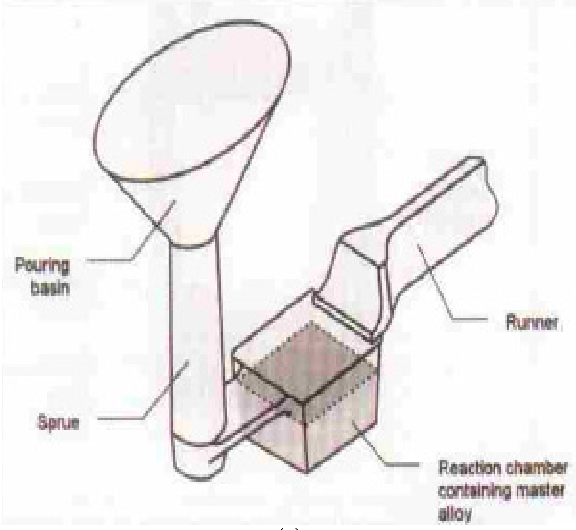
(a)



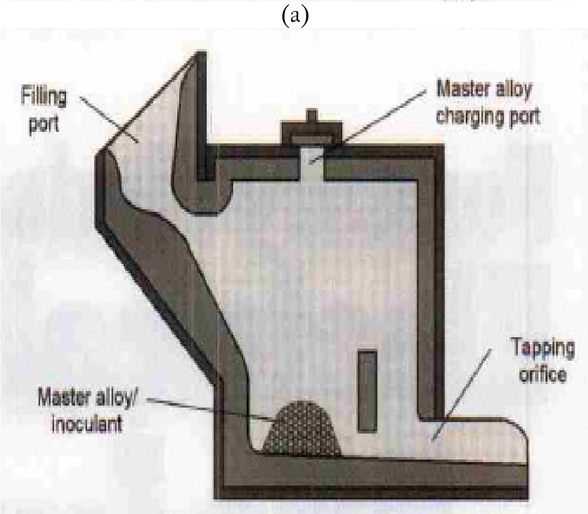
(b)

Fig. 7: Schematic of (a) the tundish ladle with lifting cover, (b) tundish converter (Lerner and Panteleev, 2003).

In the in-mold process (Fig. 8 (a)), the nodularizer; typically, the FeMgSi or Mg-based master alloy with 3-5% Mg content is placed into the reaction chamber of each mold during mold assembly (Lerner and Panteleev, 2003). The liquid iron is treated by passing it over the reaction chamber that is a part of the running system of the mold. The process allows Mg recoveries of 70-80%, while temperature losses and pyro-effects are minimized. However, its major disadvantage is the high risk of impurities and slag build-up in the casting. Nowadays, extremely low-sulphur irons are treated using this technique to avoid slag build-up and its penetration into the castings.



(a)



(b)

Fig. 8: Schematic of (a) In-mold process and (b) Flow-through Mg-based master alloy treatment process, for the mass production ductile iron (Lerner and Panteleev, 2003)

The flow-through (Fig. 8 (b)) is an improvement on the in-mold treatment process and it is made up of a device/unit located between the source of liquid iron and the target ladle. Oxygen access is prevented by the sealed charging orifice linked to the reaction chamber. The process has a high Mg recovery of 60-70%, with low temperature losses and low smoke, flare or pyro-effect levels. The entire unit is cheap and offers a cost-effective production route for high quality and quantity ductile iron.

Finally, for continuous casting of ductile iron (e.g. as in ConCast mold-lines), the cored-wire treatment process (Fig. 9) stands out. The Mg-containing wire is introduced into liquid iron by a special automated feeding device that gradually delivers wire into the closed ladle. The automation allows for precise control of residual Mg content, flexibility with respect to the required capacity, base sulphur content and temperature ranges. As a continuous casting process, the cored-wire method is suitable for making ductile iron concurrently with its production on a horizontal casting machine.

As mentioned above, previous work (Imasogie, 1994, 2002, 2003; Imasogie *et al.*, 2000, 2001; Umoru *et al.*, 2005; Adetunji *et al.*, 2008; Olusunle, 2008), pertinent to the sandwich nodularization process have been carried out by the OAU/EMDI DI-ADI research group, to enhance our local understanding of the graphite nodularization process, to establish optimum production parameters and evaluate the as-cast and heat treated properties of DI produced.

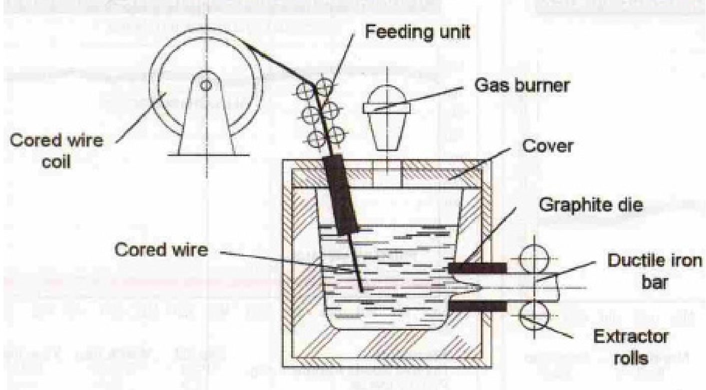


Fig. 9: A schematic of the cored-wire treatment process for horizontal continuous casting of ductile iron (Lerner and Panteleev, 2003)

3.2. Post Treatment Inoculation of Ductile Iron

Post treatment inoculation is required to promote graphitization. There are three common methods of post-treatment inoculation, which may be used individually or in combination; namely, in the ladle, in the stream while pouring and in the mold (in-mold). Most commercial inoculant grade FeSi contains elements in relatively low concentrations which are active inoculants such as Ca, Al, Zr, Ba, Sr, Ti, etc.

Research has shown that late-stream inoculation produces a dramatically higher nodule count thereby increasing the strength of the iron produced (crs-latestream.pdf, (2006)). However, late-stream inoculation also increases the potential for producing nodule populations with distinctly large and small nodule sizes. Generally, large nodules are believed to reduce fatigue strength, while nodules above a critical size have been observed to significantly reduce fatigue properties. It has been reported that an increase in fatigue strength of 10 % or greater can be achieved by improvements in the control of graphite nodule size distribution with late-stream inoculation. It is believed that fatigue life failures are often initiated at large graphite nodules, nodule clusters, non-metallic inclusions and micro-shrinkage porosity (Nicoletto *et al.*, 2002).

4. RECENT IMPROVEMENTS IN DUCTILE IRON PRODUCTION TECHNOLOGY

A number of other recent but proprietary processes are now available for producing ductile irons including the Georg Fischer converter, for which bespoke alloys have been developed to operate in conjunction with some specific techniques and in-mold processes mentioned above. In fact, “Inmold” is the trademark of Materials and Methods Limited, and “Flotret” and “Sigmat” are among their patented processes. “Imconod” is a patented process of International Meehanite Metal Co. The NovaCast PQ Inmold process (Fig. 10; Sillen, (2006)) was specifically designed to solve the problem of magnesium based nodularizers’ “fading” and low recovery in treatment. The method is used for both compacted graphite iron (CGI) and ductile iron production. The fading is due to a gradual vaporization of magnesium and to agglomeration of nucleation particles, which makes them too large to act as graphite nodule nucleation sites. This results in unwanted deterioration of graphite shape and form.

Measured in terms of magnesium level, fading in a normal sized ladle is approximately 0.0005% per minute. In the PQ Inmold method, there is little or no fading since the reaction occurs in an oxygen-free environment. The time span between the reaction and the filling of the mold cavity is very short, often less than 2 seconds. The treatment temperature is the same as the pouring temperature, usually about 100 ^{o}C lower than with conventional methods. This means that the magnesium level remains virtually the same in every casting. The magnesium recovery is equally very high compared with the conventional methods.

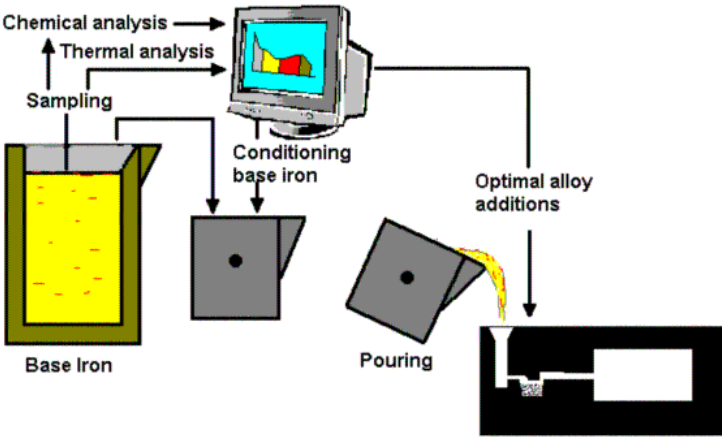


Fig. 10: A schematic of the NovaCast PQ Inmold method.

The process requires much fewer operational steps before the mold cavity is filled, since all critical steps are made fully automated. Also, the need for costly investment in specialized production equipment is very low and no extra ventilation is required. There is no need for any separate inoculant or inoculation, since there is already high magnesium recovery and no fading. Thus, low magnesium levels can be used, with the added advantage that the risk of defects such as dross, carbide, microshrinkage and variations in graphite shape and in the matrix is minimized. The process is environmentally friendly, with no white smoke and pyrotechniques from the magnesium reaction and it is energy efficient. There is also much less slag and used refractories can be recycled.

The PortCast-Intermet Porto Foundry now routinely cast several high-volume general types of automobile family castings, such as brake components, suspension arms, different cases, bearing caps, etc., for most renowned end user car producers in their ConCast unit (Palmeira *et al*., 2006). They use a very powerful and new informatics tool - DataPro® in combination with CAD and CAE softwares to model, adapt and simulate the different production layouts in order to have the Intergovernmental Panel on Climate Change (IPPC) compliant installations operate in an efficient, competitive and environmentally friendly manner.

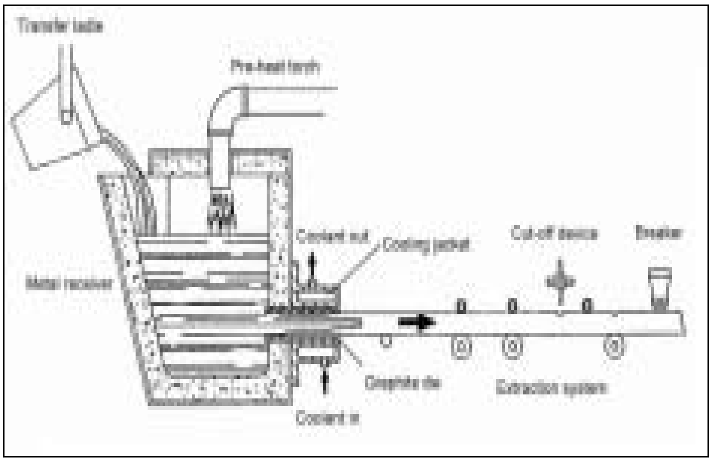


Fig. 11: A Schematic View of Horizontal Continuous Casting (HCC) Process.

The goal of high-volume production of ductile iron can be achieved by Horizontal Continuous Casting (HCC); a relatively new but promising method of producing near-net-shape high quality cast bars (Lerner, 2004). Fig. 11 presents a schematic view of HCC. Molten iron is tapped from the transfer ladle into a heatable metal receiver (as shown), to maintain the required temperature range and compensate for temperature losses during drawing process. Following a sequence of operations and upon complete solidification, a special mechanism cuts and breaks the bars to required lengths. The major advantages of HCC for ductile iron process include:

i. High casting yield of 92-95%, since it eliminates traditional feeder needs due to the fact that molten metal in the receiver plays the role of a pre-heated riser that continuously supplies liquid metal to feed the bar during solidification and also compensate for shrinkage.
ii. The absence of casting defects, usually associated with sand molding (sand inclusions, dense gas and shrinkage porosities, etc.), makes the product ideal for hydraulic and pneumatic components' applications.
iii. For the same reasons, and a very uniform grain structure, HCC bars have excellent machinability.
iv. Optimal balance between iron chemistry, melt temperature, iron level in the receiver, drawing and cooling parameters, ensures production of defect-free high quality bar stocks.

The method of informational macrodynamics (IMD) is used for a systematic informational solidification modeling and optimization of the HCC of the ductile iron process (Lerner and Lerner, 2000).

Over the last few decades, design engineers have been able to optimize casting quality, integrity and performance with increased speed and confidence by using CAD/CAM, solid modeling and finite element analysis (FEA) techniques to achieve accurate analysis of stress distributions and component deflections under simulated operating conditions (Ductile Iron Society, (2010)). In addition to enhancing functional design, the analytical capabilities of CAD/CAM have enabled foundry engineers to maximize casting integrity and reduce production costs through the optimization of solidification behavior. Furthermore, the mechanization and automation of casting processes have significantly reduced the cost of high volume castings, while new and innovative techniques such as the use of Styrofoam patterns and CAD/CAM patterns production have substantially reduced both development times and costs for prototype and short-run castings. These developments have led in many cases, to the replacement of multi-part (e.g. in planetary gear system), welded and/or fastened steel assembly by a single ductile iron casting, thus offering significant savings in production costs. In addition, inventory costs are reduced, close-tolerance machining required to fit parts together is eliminated, assembly errors are less and engineering, inspection and administrative costs related to multi-part assemblies are significantly reduced.

5. MICROSTRUCTURE AND FRACTURE CHARACTERISTICS OF DUCTILE IRONS

Ductile iron is a prime example of engineering materials where the properties achieved depend upon the characteristics of the microstructure (graphite form and distribution and matrix features). The microstructure is determined in part during solidification (graphite shape, size and distribution) and in part during solid-state transformation (matrix). The microstructures are normally characterized using the following numerical assessment indices: graphite nodule count, percentage nodularity or degree of nodularization, % ferrite, etc. The determination of the mechanical properties and failure characteristics, follow applicable ASTM, BSI or DIN specifications.

There is enough evidence to suggest that the overall fracture path is controlled by initial nodule decohesion and microcracking of the graphite/matrix interface of ductile iron. It is thus the graphite–nodule distribution that dictates the least energy propagation path. For example, in ferritic ductile iron, dimple pattern of fracture is found to be the predominant and operative mode of fracture as shown in Fig. 12a (Imasogie *et al*., 2000). But in ferritic-pearlitic matrix structures, two different fracture patterns are observed, (Fig. 12(b)). In the vicinity of the graphite nodules, the wider areas of the ferrite phase are deformed considerably and the overall fracture occurs in a ductile manner. On the other hand, brittle fracture with "river patterns" and "beach-markings", in pearlitic areas are observed. In fully pearlitic matrix ductile iron, a complex pattern of fracture is observed, reflecting the low toughness of the material. Many cleavage facets are observed on the fracture surface; (Fig. 12(c)).

Impact toughness is known to increase with ferrite % and nodule count. Increase in % ferrite is found to modify the fracture micro-mechanisms from transcrystalline cleavage to transcrystalline ductile fracture with nodule decohesion and cavitation and final dimple formation. A fracture surface roughness parameter has been introduced (Nicoletto, 2002) and found to correlate linearly with impact toughness. However, in all cases, hardness decreases with increase in nodule count and ferrite content, while impact toughness increases with ferrite percent and nodule count. Therefore, optimization of the mechanical properties and/or performance while maintaining suitable melting, treatment and casting practice can be achieved by chemical composition, treatment practice, alloy content and matrix microstructure control.

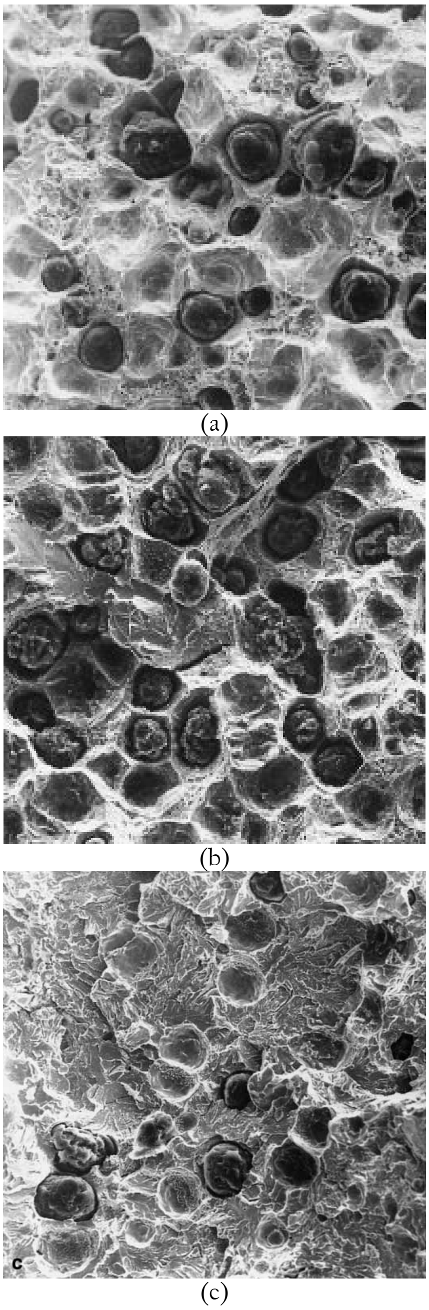


Fig. 12: Fractographs of as-cast (a) Ferritic ductile iron, showing predominantly ductile fracture; (b) Ferritic-pearlitic ductile iron, showing mixed mode fracture, with evidence of graphite as 'crack arrester'; (c) Fully pearlitic ductile iron, showing facets of intergranular brittle fracture and characteristic river markings (Imasogie, et al (2000)).

6. APPLICATIONS WHERE DUCTILE IRONS EXCEL

Many technological advances have been recorded by the Nigerian DI/ADI group and researchers globally in the last three decades, to improve production efficiency in the ductile iron founding industry, to enable it to continue to produce quality castings at costs which make their use economical compared with other materials and methods of manufacture. As products go, the ductile iron material can be tailored to fit an unusually broad diversity of needs. This is why ductile iron is termed versatile. It has in many instances been chosen over and above cast steel, steel forgings, high strength gray iron, and steel fabrications including weldments, in parts ranging from a fraction of a kilogramme (e.g. pump cylinder), to mill rolls. Designers are converting steel castings, forgings, and fabrications to ductile iron castings to gain the following benefits
(http://www.steelinc.com.au/ADI/ADIbenefits.htm):

i. Improved strength to weight ratio
ii. Better surface detail and finish
iii. Improved machinability
iv. Reduced machining allowance
v. Lower component cost
vi. More strength per dollar
vii. Reduced component weight

Fig. 13 shows a picture of some of the ductile iron castings used in a Japanese automobile. Virtually all functional component parts in Japanese cars are now made from DI and ADI castings. Other steel castings, forgings, and fabrications have been converted to Ductile Iron castings at lower cost with equal or superior performance.

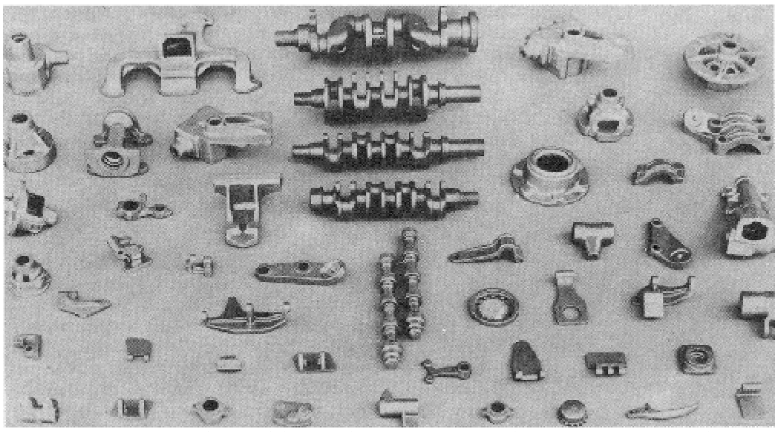


Fig.. 13: A Picture of some of the Ductile Iron Castings Used in a Japanese Automobile (http://www.steelinc.com.au/ADI/ADIbenefits.htm)

According to Chandler (1977), conversion - cost reduction is a common motive for switching to ductile iron castings. For example, manufacturing costs were slashed 69% in converting a two-piece fabrication; a steam turbine governor case, to a one-piece ductile iron casting. Formerly, steel bar stock 10.16 cm in diameter and 6.45 cm steel tubing were joined by welding and machined in eight separate operations. Remarkably, the one-piece casting exceeds maximum engineering requirements. Another notable case involved a conversion from a steel forging. Primarily, as a forging, the part, a wire rope clamp for conveyor idler and support stand, cost $2.31 per unit to manufacture. But by going to a sand-cast clamp of an 80- 55- 06 grade of ductile iron, it became possible to shave part cost by 91%. Also, the ductile iron castings had more than adequate strength and toughness; and machining was eliminated because functional surfaces had sufficient accuracy in the as-cast condition. Another special case, involves the use of the 65-4-12 grade of ductile iron casing lined with Teflon. The complex plug valve, which controls the flow of extremely corrosive liquids in chemical processing plants, was formerly made of a variety of exotic materials, including Type 316 stainless steel, Monel, Hastelloy B, titanium and tantalum. In some specific cases, unit costs ran as high as $229. The item is now down to $79. Cast recessor and machined grooves in the body and plug lock the Teflon in place. It will not collapse in a high vacuum or during thermal cycling.

In addition to cost, other considerations such as mechanical properties' requirements, corrosion resistance, weight and thermal (spalling) qualities, recommend ductile irons over and above all other materials. Specifically, the oil manifold for earth-moving equipment is presently made of ductile iron because the application called for a combination of high strength and good ductility. Ductile iron piston for diesel locomotive engines is stronger and has more wear resistance than previously used types. Reduction in weight (by 50%) also means less stress on other parts, such as bearings. Drive sleeves for automatic torque control devices were formerly steel castings or made from solid steel billets. Service conditions range up to 6.67 x 10^5 N of thrust and 5700 Nm of torque. The drive shaft for farm equipment was formerly gray iron. Full-length, heavy-duty ductile iron pipe have now replaced sand core for hub, which simplifies machining and assembly. The high – strength part weighs 32.84 kg. Ductile iron planetary carriers for earth-moving equipment combine high strength, dimensional stability, and resistance to wear, shock and sudden loading. The weights range from 3.4 to 126.3 kg. Ductile iron suspension link for railroad track scale transmits 3.1 x 10^5 N of force from platform to a lever. Bending movements in the lever system were reduced by 50% because a smaller link is possible. Final drive housing for earth-moving equipment (118 kg) was switched from gray iron to get more strength to handle unusual shock loads. Existing pattern for gray iron was used. The base for rubber impeller in centrifugal slurry pumps was a six-part steel weldment. On introducing ductile iron, the casting trimmed 12% from component weight and reduced per-part cost from $ 69.40 to $ 32.35. The front wheel casting for heavy machinery was switched from steel to ductile iron primarily to bring about a reduction in costs. This rather complex part weighs 73 kg. Door mechanism for bomber aircraft, formerly an eight-part steel weldment, was converted because it had a tendency to warp. Ductile iron casting reduced part cost from $182 to $41. Tool storage index for a numerically controlled machining center formally required 2, 115 manufacturing operations. Conversion to one-piece casting cut number to 24. Drive gear for tyre changer was formerly machined from steel. A smooth finish on ductile iron casting cut per-part machining cost from $4.55 to 23 cents. Part cost dropped from $9.00 to $3.50. The compression discharge casting was switched from a cast-weld structure that called for 200 manufacturing operations to a one-piece casting that requires only ten. Bi-directional valve bodies were made from carbon steel. Now, tapered body bore does not require machining or lapping. Per-unit cost of machining is now $2.00; from $ 14.00 (Chandler, 1977).

Other notable applications of ductile iron where cost has been reduced and properties improved, include bull rings, sinter pallets, cams, cylinders, liners, burring discs, drawing dies, drawing wheels, mining knives, asphalt mixer liners, hot-forming dies, rock jaw crushers, coal pulverizer rings, bridge bearings, impellers for outboard diesel engines, heavy section sheet metal dies, pulp press rolls, hot air valves, pump castings that carry coal- containing mud, wire straightening dies, drop balls, compressor valves, bearing cages, auto-body dies, explosive-forming dies, sprockets, bushings, piston rings, hydrospin mandrels, grinder rolls, oil – well pump beams, sheet and ball mill rolls, and grooved rolls for finishing stands (as compiled in Table 1 (Chandler, (1977), O'Rourke, (2004), Keough and Hayrynen (2000), US Pipe and Foundry Company, (2013). Guesser *et al.* (2012) discussed the potential of using ADI for gears in replacing conventional induction hardened steels. The ADI gears were produced from continuous cast iron bars and heat-treated to achieve a grade 3 of ASTM ADI Standard A897M-06 (UTS > 1200 MPa).

In particular, there have been recent developments in trenchless piping applications with ductile iron that can be used for horizontal directional drilling (HDD) and pipe bursting (US Pipe and Foundry Company, (2013). This pipe has the same great qualities of being rugged, durable and dependable in extreme trenchless conditions with conventional steel pipes, but has the added advantage of not requiring the rather expensive special piping cladding and long lead times.

The Table can be split to 2 (i.e Table 1(a), 1(b)) because of its length. The update of the Table with more recent additions, say up to 2013 is recommended.

7. CONCLUSION

In the last half century, ductile iron (DI) has earned what can be described as a unique position among engineering materials. Although it is not a cure-all material, it is generally agreed that no other ferrous material can match its combination of castability, mechanical properties and design flexibility at low cost, while allowing the manufacturer to obtain a wide range of properties in a component. There is no doubt that we have made giant strides in our understanding of the production, characterization and applications of ductile iron and austempered ductile iron (ADI). But what is required now is to harness this knowledge and to bring these special purpose engineering materials to the fore, in terms of their large scale production capacity, to meet specific needs (in transportation, construction, agricultural mechanization, oil and gas and allied industries, etc.) of the country. To do this successfully, there is an urgent need through research and development, to obtain more practical information on their dynamic properties such as fatigue strength, impact toughness, sliding-friction-wear resistance, micro-mechanism of fracture and/or failure, etc. This will require serious funding and commitment from relevant agencies and institutions, to research and development of this class of engineering materials.

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Table 1: Examples of Conversions to Ductile Iron (Caine, 1984)

COMPONENT	CONVERTED FROM	CONVERTED TO	COST SAVINGS	OTHER DESIGN IMPROVEMENTS
Off-road Truck Suspension Cylinder	Welded Steel Fabrication	BS2789 420/12	>20%	Reduced machining costs. Reduced inventory and stock control costs.
Backhoe Loader Stabilizer Foot	Steel Weldment	ASTM A-536 80-55-06	49%	Used as-cast. All machining and fabricating costs eliminated.
Rope Clamp and Eye Nut	Steel Forging	ASTM A-536 80-55-06	82%	Stronger. Improved appearance.
Crankshaft for Supercharged Engine	Steel Forging	ASTM A-897 ADI	39%	Lighter/stronger/improved wear resistance. Improved sound dampening.
Diesel Engine Timing Gears	Carburized Steel Forging	ASTM A-897 ADI	30%	Increased machine shop productivity. Reduced wt. & noise. Rapid "break-in."
Aircraft Towbar Head	Steel Weldment	ASTM A-536 80-55-06	76%	Improved mech. properties. Reduced machining. Improved appearance.
Worm Gear and Post Screw	Bronze and Steel Fabrication	ASTM A-536 60-40-18	46%	Improved performance. Simplified final assembly.
4WD ATV Wheel Hub	Aluminum Casting	ASTM A-536 65-45-12	50%	Light weight. Increased strength and safety. Improved aesthetics.
Fertilizer Injection Knife	Steel Forging and Weldment	ASTM A-897 ADI	44%	Excellent wear resistance. Eliminated all fabrication costs.
Stainless Steel Banding Jig	Tool Steel Inv. Casting	ASTM A-897 ADI	77%	Significant reduction in machining costs achieved with equal performance.
Wire Rope Clamp	Steel Forging	ASTM A-536 80-55-06	92%	Close tolerance as-cast. High strength. Marketing advantages.
Aircraft Door Fixture	Steel Weldment	ASTM A-536 65-45-10	78%	Solved warpage problem. Increased strength. Reduced number of parts.
Gas Turbine Casing	Steel Castings	BS2789 400/12	>30%	Additional savings in machining costs. 17% less wt. Better vibration damping.
Truck Drive Shaft U-Joint Slip Yoke	Steel Forging	ASTM A-536 100-70-03	47%	Reduced material and machining costs for equivalent reliability.
Tractor Brake Anchor	Steel Fabrication	ASTM A-536 80-55-06	44%	Equivalent mechanical properties with reduced machining costs.
Air Compressor Block	Steel Weldment	ASTM A-536 65-45-12	46%	Improved sound damping and product integrity. Reduced manufacturing operations.
Automobile Steering Knuckle	Eleven-part Assembly	ASTM A-536 60-40-18	large	Reduced manufacturing operations, parts inventory. Improved reliability.
Photometer Housing	Steel Fabrication	ASTM A-536 65-45-12	45%	Weight reduction. Improved appearance. Improved performance.
Truck Cab Mount	Steel Fabrication	ASTM A-536 80-55-06	31%	Improved fatigue life. Two-part casting replaced 34 parts and 25 welds.
Cam for Cotton Picker	Hardened Tool Steel	SAE J-434C D5506	68%	Reduced surface loads. Increased picking speeds. Improved efficiency.
Backhoe Loader Swing Pivot	Steel Weldment	ASTM A-536 65-45-12	31%	Reduced manufacturing time. Better machining. Improved wear properties.
Tractor Transmission Hydraulic Lift Case	Gray Iron Casting	BS2789 420/12	40% (vs Steel)	Updated design required. Stronger. Steel casting 40% more, plus pattern change
Plug Valve	SS, Monel and Titanium	ASTM A-536 &0-40-18	66%	Close dimensional tolerances. Enabled installation of plastic liner.
Air Compressor Crankcase	Steel Weldment	ASTM A-536 60-40-18	82%	Improved sound damping and shock resistance.

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