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A Review on Mechanical and Microstructural Properties of Ductile Iron Casting

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ABSTRACT

An entirely new cast iron family was born when Ductile Iron was discovered in 1948. Ductile Iron, which combines the castability of grey iron and the hardness of steel, has gained widespread recognition as an inexpensive solution for complicated ferrous components. Spheroidal-graphite cast iron (SG) was traditionally referred to as nodular cast iron or spheroidal-graphite iron, but the global word is ductile cast iron. As with grey cast iron, eutectic graphite segregates from the solidified molten iron in the solidification process of ductile iron. However, due to additives added to the molten iron before to casting, graphite develops as spheres rather than the flakes typical of grey iron. Ductile iron is a ternary Fe-C-Si alloy in which the carbon and silicon percentages are generally 3.5 - 3.9 percent and 1.8 - 2.8 percent, respectively, of the total iron content. The selection of the composition is controlled by the size of the casting piece and the mechanical qualities that are desired. The present review mainly focused on the effect of carbon equivalence on the mechanical and microstructural properties of ductile iron.

Keywords: Ductile iron, Carbon Equivalent, CO2 sand mold, Cooling Parameters, Production rate optimization.

1. Introduction

It was originally known as spheroidal-graphite (SG) cast iron or nodular iron, but it is now referred to as ductile iron, which is the worldwide nomenclature for the material. It is a kind of cast iron in which graphite is observed in the microstructure as spheres (nodules) (Choi et al. 2004). During solidification of the ductile iron, eutectic graphite segregates from the molten iron in a manner that is comparable to the method in which eutectic graphite segregates from grey cast iron. Although the graphite develops as spheres in preference to as flakes or any other form characteristic of grey iron, this is due to the addition of chemicals to the molten iron prior to casting (Xu, Ferry, and Wang 2005). Compared to grey iron or malleable iron, spheroidal graphite-containing cast iron is significantly stronger and has more elongation. It may be thought of as a natural composite in which the spheroidal graphite lends unique features to ductile iron, with the ductile iron serving as the matrix.

The invention of Ductile Iron was first documented in 1948. Due to a decade of active research and development in the 1950s, ductile iron had a tremendous surge in use as an engineering material throughout the 1960s, and the quick increase in commercial application has continued to this day. Ductile iron has been used as a technologically valuable material for a number of years and is still in use today (Pedersen and Tiedje 2008; Herfurth and Scharf 2021). However, although many researchers have evaluated its mechanical performance under a variety of settings, others have sought to understand its solidification behavior and the several variables that must be considered in order to produce a product that is acceptable. We are still at a loss to explain how a flake-like graphite form evolves into the spheroidal morphology that gives ductile iron its better qualities, even after more than a decade of research. Because the graphite in ductile iron occurs as spheroids rather than flakes, as it does in grey iron, an uncommon mix of qualities may be achieved by using it. It is possible to achieve this kind of solidification by adding a very small but specified quantity of Mg or Ce or both to molten iron with the appropriate composition. The base iron is closely regulated in the amount of certain minor components that can interfere with the production of graphite spheroid that can be present in the base iron. The magnesium that has been added interacts with the Sulphur and oxygen in the molten iron, altering the way graphite is produced. Control techniques have been created in order to improve the efficiency with which ductile iron is processed. Because of the high carbon and silicon content of ductile iron, the casting method has a number of advantages, although the graphite spheroids have only a little impact on the metal's mechanical qualities. Malleable iron has a linear stress-strain relationship and a wide range of yield strengths, making it a versatile material (Willidal, Bauer, and Schumacher 2005).

Castings are made available in a broad range of sizes, with portions that can be either extremely thin or very thick depending on the application. The varied grades are formed by tailoring the matrix structure around the graphite, which may be done either by casting or by heat treatment after the graphite has been cast. Because there are only modest compositional changes between the standard grades, it is necessary to make modifications in order to promote the ideal matrix microstructures.

Ductile iron is a ternary Fe-C-Si alloy in which the carbon and silicon percentages are generally 3.5 - 3.9 percent and 1.8 - 2.8 percent, respectively, of the total iron content (Salazar F. et al. 1999). The selection of the composition is controlled by the size of the casting piece and the mechanical qualities that are desired. However, despite the fact that nodule formation is influenced by C and Si levels, the quality of the alloy and the inclusion of spheroidizing elements are ultimately responsible for nodule formation. However, the two important parameters which are (i) the Si and C contents and (ii) the cooling parameters determine the quantity of graphite incorporated in the metallic phases.

The peculiar mechanical and physical characteristics of ductile iron can be attributed to the spheroidal graphite shape formed during solidification. With this breakthrough, the metals industry witnessed one of its most significant commercial breakthroughs in its history. Ferrous casting manufacturing predates ancient times, as is generally known, but developments in the craft have been extremely gradual throughout the many thousands of years required. Not until the beginning of the twentieth century did the science of metallurgy make substantial advancements. Compositional, melting and solidification properties, cooling speeds, processing factors and many other parameters were studied by the metallurgists at this time. It was discovered that graphite size, volume, form, and distribution might be correlated to its strength, and ways for altering these parameters were being developed. There was no mention of either (i) spheroidal graphite in the as-cast condition or (ii) ductility of any sort of high carbon cast iron in the technical literature. An abrasion-white cast iron with high hardness that arises from a martensite-carbide matrix fostered by Ni and Cr concentrations of 4.5 and 1.5 percent was one of the materials to be born in this period and promoted in the 1930s. Grinding mill balls, plates, rollers, and many more applications needing exceptional abrasion resistance continue to be made from this substance or family of materials. In light of the enormous mining potential, this is a well-known Australian commodity that is extremely likely to see significant development. When Cr became rare after World War II, white cast iron became less carbidic, softening and so losing its intended abrasion resistance. Without Cr, this would be the case. An alternative for Cr as a carbide producer in martensitic white cast iron is being sought by research institutes across the world. Naturally, the component must be conveniently accessible.

2. Modern Trends

There have been several important developments in foundry equipment, materials, and methods throughout the first two decades of SG iron production. In many cases, the development & expansion of these companies was directly tied to the improvement of the process of generating SG iron, and the manufacture of high-quality SG iron is today a routine affair. To a greater extent, everyone is aware with these developments, which include the invention of the basic cupola, the water-cooled cupola, the commercial development of shell moulding, alloys, and equipment for treating the iron, as well as their rise to new levels of renown. It has gained popularity in Europe because to the more exact control it provides over composition and temperature, as well as the fact that a broad variety of charge materials may be employed in induction furnace melting. In the early 1960s, curiosity in electric arc furnace melting began to expand to other regions of the world, particularly the United States. With enhanced precision and efficiency, Designer Engineers can now optimize casting geometry and efficiency with more speed and certainty. CAD/CAM, solid modelling and finite element analysis (FEA) techniques have advanced significantly in recent years, allowing for very accurate characterization of stress distributions and component deflections under simulated operating circumstances, among other applications. In addition to improving functional design, the analytical capabilities of CAD/CAM have enabled foundry engineers to maximize casting integrity while simultaneously reducing production costs by optimizing solidification behavior.

A broad range of production rates, component sizes, and design complexity necessitate castings, which offer a lower cost alternative to fabrications and forges. Low volume castings have seen significant savings due to mechanization and automation, whereas prototype and short run castings have seen significant savings due to new and inventive processes including Styrofoam templates and CAD/CAM pattern manufacturing. Prototypes, frequently in the form of fabrications that "compromise" the final design, will become less important as trust in FEA techniques grows, and more innovative components will proceed directly from the design stage to production castings. Ductile iron castings are now widely used in a variety of fields, including transportation, wind energy, and agricultural machinery. Approximately 55% of the world's ductile iron castings are used for automotive castings. The rapid growth of ductile iron industries and the high annual utilization of ductile iron castings are testimonials to the out standings mechanical properties, quality and economics of ductile iron castings.

Crankshafts, front wheel spindle supports, and connecting rods are just a few of the key automotive applications for which ductile iron castings are employed, and their excellent dependability and process economies are additional evidence of their superior performance in these applications.

3. Design Flexibility

Compared to any other method utilized for the manufacturing of technical components, the casting process provides far greater design flexibility. Because of this adaptability, the design engineer may tailor the design of the component to the functionality of the component. To maximize the load carrying capability of the component, metal may be inserted where it is needed, and metal can be removed from unstressed places to minimize the overall weight of the part. Streamlined cross-sectional changes can help to lower stress concentrations in a given area. Consequently, both initial and lifespan costs are decreased due to material and energy reduction as well as improved component performance as a result. According to recent research conducted by the National Center for Manufacturing Sciences (NCMS), the substitution of fabricated structures with Ductile Iron castings might result in cost reductions of 39-50 percent in certain machine tool applications. Since the surprising appearance of SG cast iron on the material science horizon more than two decades ago, a cast iron with dramatically superior qualities than grey cast iron and much greater cast ability than steel has been developed. Engineers eventually discovered that it was not a single material with a specific set of features, but rather a material that was available at any moment and capable of providing a wide range of technical equipment’s at any time. One of the more interesting applications of improved ductile iron is the possibility of property improvements of sufficient magnitude to permit a redesign that would result in a net decrease in the cost of a part, increase the life of a part to such an extent that the alloy cost would be offset, or substantially improve the operating economy of mechanical equipment by allowing it to operate under much more severe operating conditions. Since its origin, ductile iron castings have proven to be a reliable resource for the automobile sector in a variety of applications. Castings have been increasingly popular in recent years, with a wide range of companies utilizing them. One example of this development is the current V-8 engine, in which castings are now utilized for each of the primary components, as is the case with today's engines. There are two design objects in each central foundry project involving the development of a new casting application: First and foremost, functional attributes of the castings must be superior to those of the components that will be substituted. Second, make use of the casting process's ability to combine the components principle with other principles. The invention of the integrated ductile iron steering knuckle achieved both of the aims.

Because of the inherent flexibility of ductile iron and the casting process, the developer was able to combine three separate elements into a single unit for the integrated ductile iron steering knuckle. Consequently, due to the design flexibility, the product offers a major advance over traditional techniques of fabricating steering knuckles.

4. Chemical Composition of Ductile Iron

Chemically, this product is the same as grey iron and is an alloy of iron, chromium, and silicon. In fact, it has been present since 1948, making it one of the more recent advancements in cast iron technology. In order to counteract the brittle character of grey and white irons, it was invented, as the name implies. It is also extremely ductile when cast in a solid state. The principal trace elements found in ductile iron can have a significant impact on the structure of the iron and, as a result, on its mechanical characteristics. All elements, with the exception of silicon, lead to the formation of pearlite, and all elements, with the exception of silicon, nickel, and copper, promote the formation of carbides. The elements that are included into the solution tend to improve the strength qualities of ferritic ductile iron in general. The tensile strength and hardness of ductile iron, with the exception of carbon, increase with increasing concentration of the element. For the element’s silicon and nickel, amount to which ferrite is impacted by solid solution strengthening. When silicon is added to ferritic iron, the proof and tensile strength rise by around 82 N/mm2, however when nickel is added, the characteristics increase by roughly 46 N/mm2. Increases in tensile strength and proof strength are acquired at the price of ductility in ferritic irons, and the iron might become embrittled as a result of this process in some cases.

4.1 Structure

Following the application of appropriate treatments to the melt, the morphology of graphite particles takes on a nodular or almost cylindrical shape, whereas in grey iron graphite is in flake shape. The most important microstructural elements of ductile iron are carbon in its many chemical and morphological forms, as well as the continuous metal matrix in which the carbon and/or carbide are distributed.

4.2 Graphite

In cast iron, Graphite is the stable form of pure carbon that may be found. Low density, low hardness, and high thermal conductivity and lubricity are some of the most essential physical features of this substance. The form of graphite, which can range from flake to spherical, has a considerable impact on the mechanical characteristics of ductile irons, and it is important to understand this. Ductile iron is distinguished by the fact that all of its graphite is contained within tiny spheroids. The fact that this graphite contains around 10% of the total volume of ductile iron is mitigated by its compact spherical form, which has a little impact on mechanical attributes. There are few instances where the graphite in commercially available ductile iron is not in perfect spheres. When it does arise, it might take on a slightly uneven shape. Of course, the deterioration of the spheroid form might have an impact on the mechanical characteristics of the material. When the metal solidifies, the shape of the graphite is determined, and it cannot be modified in any manner other than by remelting the metal. The distinction between the various classes of ductile iron is found in the microstructure of the metal around the graphite, which is referred to as the matrix of the metal. The microstructure of the casting changes depending on the composition and cooling rate of the casting. For a minimum hardness (as-cast), the casting can be slowly cooled in the mould while still heated above the critical temperature; alternatively, if the casting has sufficiently uniform sections, the casting can be unshackled of moulding sand while still heated above the critical temperature and then normalized. Fig. 1 and Fig. 2 represents shape of graphite in ductile and grey cast iron (Bočkus, Venckunas, and Žaldarys 2008)..

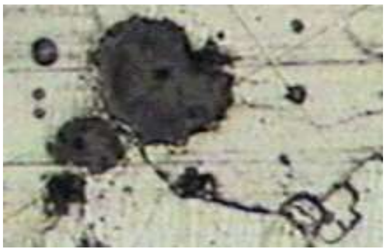

Fig.1 Micrograph of spheroid In ductile iron.

Fig. 2 Micrograph of flakes in Grey Cast iron.

4.3 Ferrite

In a cast iron, this is the purest phase of iron that can be found. The presence of Ferrite gives reduced strength and hardness in typical Ductile Iron, but higher ductility and toughness. Austempered Ductile Iron (ADI) is made up of exceptionally fine-grained acicular ferrite, which gives an outstanding combination of high strength, ductility, and toughness. The elements that are included into the solution typically improve the strength qualities of ferritic ductile iron. Except for carbon, of course.

4.4 Pearlite

The eutectoid reaction results in pearlite, which is a lamellar cementite in a ferrite matrix combination. In many technical applications, the combination of greater strength and reduced ductility provided by pearlite cast irons is exactly what is needed.

4.5 Martensite

Rapid cooling results in the formation of martensite, which is a supersaturated solid solution of carbon in iron. Untampered martensite is very hard and brittle in its natural state. In order to achieve a regulated mix of high strength wear resistance and ductility, martensite is typically "tempered"-heat treated to lower its carbon content by the precipitation of carbides-in order to reduce its carbon content.

4.6 Austenite

A high-temperature phase made up of carbon dissolved in iron, austenitic and Austempered cast iron can have this phase at normal temperature. Austenitic irons have austenite that has been stabilized by nickel to a degree ranging from 18 to 36%. Austenite is formed in Austempered irons as a result of a combination of rapid cooling, which prevents the formation of pearlite, and carbon supersaturation during the austempering process, which delays the onset of the austenite-to-martensite transformation until temperatures well below room temperature. The austenite matrix in austenitic irons gives ductility and toughness at all temperatures, as well as corrosion resistance and strong high temperature characteristics, particularly when subjected to thermal cycling. Adding stabilized austenite in lower strength grades, in fractions up to 40% in lower strength grades, enhances toughness and ductility while also improving the responsiveness to surface treatments like as fillet rolling and annealing.

4.7 Bainite

The mixture of ferrite and carbide is known as Bainite and produced through heat treatment of steel.

5. Family of Ductile Iron

In the ductile iron the nodule count present in the matrix controls the mechanical properties of the alloy. Hence, due to the importance of the matrix which in turn ascertain the mechanical properties of the resulting alloy, denotes the family of ductile iron.

5.1 Ferritic Ductile Iron

If the matrix of ductile iron is ferrite, then the resulting alloy is Ferritic ductile iron. Moreover, due the soft nature of ferrite the ferritic ductile iron possesses good ductility, impact resistance and tensile and yield strength corresponding to low carbon steel. Despite the fact that ferritic ductile iron may be manufactured as-cast, it is often subjected to an annealing heat treatment in order to achieve the greatest possible ductility and low temperature toughness.

5.2 Ferritic-Pearlitic Ductile Iron

These are the most often observed grades of ductile iron, and they are typically manufactured in the as-cast state. The graphite spheroids are embedded in a matrix that contains ferrite as well as pearlite. With high machinability and cheap production costs, these grades have properties in the middle of the spectrum between ferritic and pearlitic grades.

5.3 Pearlitic Ductile Iron

High strength, good wear resistance, mild ductility, and impact resistance are achieved by incorporating graphite spheroids into a pearlite matrix. It is also more machinability-friendly than steels with equivalent physical characteristics. The two varieties of Ductile Iron mentioned above are the most prevalent, and they are often utilized in their as-cast state, with the exception of pearlitic ductile iron. However, ductile iron may also be alloyed and/or heat treated to produce other grades that can be used in a variety of other applications in addition to those listed above.

5.4 Martensitic Ductile iron

This kind of ductile iron is produced by using adequate alloy additives to avoid pearlite production, as well as a quench-and-temper heat treatment procedure. The tempered martensite matrix that forms as a result of this process produces extremely high strength and wear resistance, but with lower degrees of ductility.

5.5 Austenitic Ductile Iron

This ductile iron, which has been alloyed to generate an austenitic matrix, has excellent corrosion and oxidation resistance, as well as exceptional strength and dimensional stability at elevated temperatures.

5.6 Austempered Ductile iron (ADI)

It is the most recent addition to the ductile iron family, and it is a sub-group of ductile iron that is generated by subjecting standard ductile iron to a particular austempering heat treatment after casting. ADI is about twice as strong as pearlitic ductile iron, yet it retains its excellent elongation and toughness despite its increased strength. This combination results in a material that has excellent wear resistance and fatigue strength properties.

6. Factors that affect Properties of Ductile Iron

Ductile iron is a unique type of material that has an excellent balance between tensile strength and malleability, making for extensive application in the construction and engineering sectors. As a result of its chemical composition, heat treatment technique, and processing factors, it has a microstructure that is consistent with the characteristics of the material. The next section contains some lists of important aspects that are responsible for the usual mechanical characteristics of the material.

6.1 Effect of Graphite Shape

Gray and ductile iron have quite different mechanical characteristics, thus it's no surprise that nodularity plays a big impact in ductile iron attributes. Nodularity has a significant impact on the ductile iron's yield and tensile strengths. It is possible to make the nodules lengthier without making them sharp or "spiky" by decreasing the quantity of residual magnesium (the most frequent spheroidizing agent used in commercial ductile iron). When nodularity is reduced by 30%, yield strength and tensile strength are both lowered by 10% and 15%, respectively. The tensile characteristics of graphite are drastically reduced when lead is added in small amounts because the spiky or plate-like graphite networks formed as a result of the addition are intergranular. It is possible to assess the influence of nodularity on pearlitic ductile iron by comparing the mechanical characteristics of irons with nodularity 90, 70 and 40 percent at constant carbide levels. Pearlitic iron, compared to ferritic iron, has a far greater sensitivity to the decrease of nodularity caused by magnesium. As the nodularity reduces to 70 percent, the strength of ductile iron decreases more rapidly, although at low carbide levels characteristic of excellent grade ductile iron, there is little loss of strength. Nodularity may be practically eliminated by stating that the nodularity exceeds 80-85% and that there should be no intercellular flake graphite in the design. A combination of regulating flake-producing components and their effects through the use of small additions of cerium may easily meet these criteria through appropriate manufacturing procedures that ensure good nodularity and avoid flake or spiky graphite.

6.2 Effect of Carbide in the Structure

When compared to flake-graphite castings of identical section and size, as well as carbon and silicon concentrations, ductile iron castings are more prone to include carbides. This phenomenon can be attributed partly because the spherodizing process generally involves the addition of magnesium and/or cerium, both of which are elements that promote the formation of eutectic carbide, and partly because the sequence of solidification produced by the growth of nodular graphite tends to promote under cooling during solidification to temperatures at which white iron structure is more likely to form. Ductile irons can include carbides in three different forms: Eutectic carbide (also known as chill) is formed primarily as a result of fast solidification and is particularly common in corners and thin sections. Reduced inoculation, and in particular reduced silicon, as well as the presence of carbide-promoting components all enhance the possibility that carbides will be found in a structure. Inverse chill, which has a fine acicular shape, occurs at or around the heat center of a casting section and is characterized by fine acicular form. It is often necessary to re-position or vary the size of the gates in order to change the pattern of solidification of the casting in order to resolve this problem. Effect of nodularity and carbide properties are represented in Fig. 3 and Fig. 4 respectively (Bočkus, Venckunas, and Žaldarys 2008)..

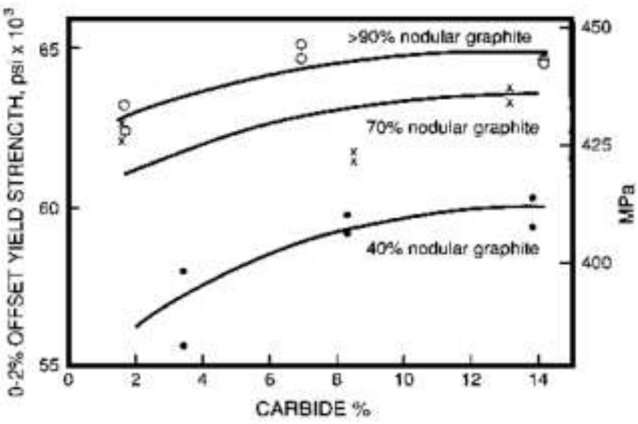

Fig.3 Effect of nodularity and carbide content on yield strength of pearlitic Ductile Iron.

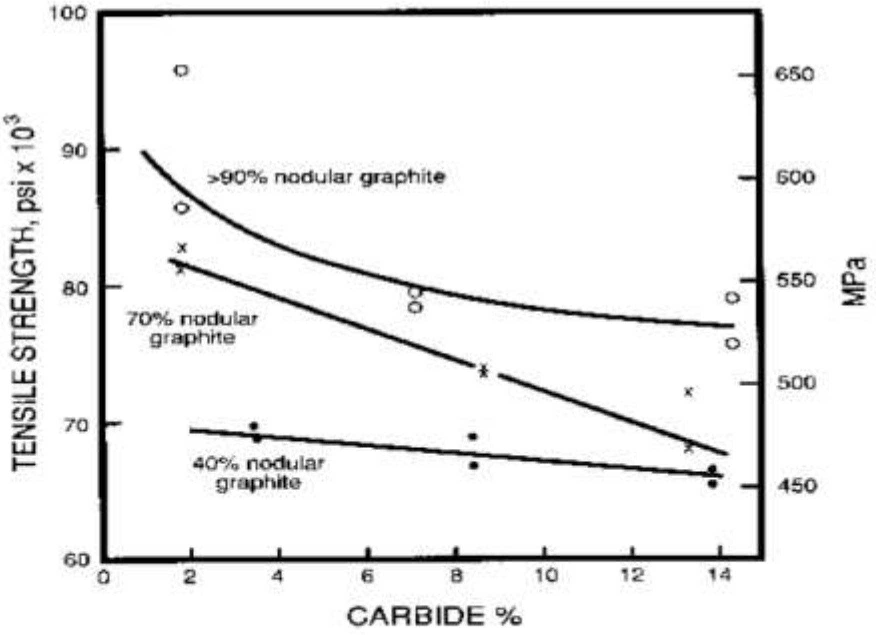

Fig.4 Effect of nodularity and carbide content on tensile strength of pearlitic Ductile

Iron.

Carbide segregation is more common in heavy parts than in light sections. Their occurrence is associated with the segregation of trace quantities of carbide-forming elements such as manganese or chromium in the eutectic cell boundary area. Heat treatment does not readily decompose these carbides because of their chemical structure. It is undesirable to have carbide present in ductile iron for a variety of reasons, including the following:

- It increases the possibility of shrinkage porosity forming and, as a result, increases the amount of feed required during the casting process.
- The probability of cracking rises throughout the shakeout and fettling process.
- It has a negative effect on the ductility of iron.
- It has a significant negative influence on impact resistance.
- It enhances hardness while also decreasing machinability.
- It must be heated to 900-920 °C in order to eliminate the carbide.

Carbide formation in all three types is avoided by effective inoculation, which results in a high nodule number, and by keeping a low concentration of carbide-promoting components in the soil. The presence of high silicon concentrations is also advantageous, although the possibility for embrittlement caused by silicon concentrations more than roughly 2.6 percent should not be neglected (Gonzaga et al. 2009).

6.3 Effect of Nodule Count

Nodule Count, measured in terms of the number of graphite nodules per square millimeter of Ductile Iron, has an effect on the mechanical characteristics of Ductile Iron as well, but not as strongly and directly as graphite form [16]. However, there is an ideal range of nodule count for each section size of castings, and nodule counts in excess of this range might result in a loss of characteristics. The number of nodules has the following implications on the microstructure, which can have a substantial impact on properties:

- The number of nodules in ductile iron as-cast has an effect on the pearlitic content of the iron. Increasing the number of nodules reduces the amount of pearlite present, resulting in decreased strength and increased elongation.

- The number of nodules has an effect on carbide content. As the number of nodules in the material increases, the volume proportion of chill carbides and carbides associated with "inverse chill" decreases, resulting in improved tensile strength, ductility, and machinability.

- The number of nodules in a matrix has an effect on its homogeneity. Increasing the number of nodules results in a microstructure that is finer and more homogenous. Due to the refinement of the matrix structure, there is less segregation of harmful elements that might result in the formation of intercellular carbides, pearlite, or degenerate graphite.

- The number of nodules has an effect on the size and form of the graphite. Increasing the number of nodules leads in a reduction in nodule size, which enhances the tensile, fatigue, and fracture characteristics of the material. Inoculation procedures that are employed to increase nodule count frequently result in the nodules becoming more spherical. As a result, increased nodule count is typically related with increased nodularity.

6.4 Effect of Graphite Volume

The volume fraction of graphite in Ductile Iron can also have an effect on certain of the tensile characteristics of the material. The size of the casting section can have an impact on both the volume percentage and the size of graphite nodules. Increasing the section size of a casting slows the cooling rate of the casting, causing more carbon to precipitate in the stable graphite phase rather than the carbide phase, which is more favored by greater cooling rates. The lower cooling rates of the bigger diameter bars also have an effect on graphite nucleating potentials, resulting in a reduction in the number of nodules while increasing the size of the nodules. In large castings, graphite flotation can cause changes in the amount of graphite, which can be detrimental to the mechanical qualities of the cast iron alloy. Graphite flotation occurs when low cooling rates combined with a high carbon equivalent result in the formation of huge nodules that float to the surface of the liquid during solidification. As a result, the bigger nodules in the lower section of the castings are depleted, while a build-up occurs on the upper surface of the castings. In these bigger bars, graphite flotation at greater carbon levels may result in a reduction of the graphite volume in the center of the bars, as indicated by an increasing curvature with increasing bar diameter. The lower rate of rise in graphite volume as a consequence of increasing carbon would be reflected in flatter curves at higher carbon levels as a result of the reduced rate of increase in graphite volume. Graphite flotation can result in a significant loss of characteristics around the upper surface of large ductile iron castings, especially when used in conjunction with other processes. This issue, on the other hand, may be easily prevented by decreasing the carbon equivalent as the size of the casting section grows.

7. Mechanical Properties of Ductile iron

The diverse and successful applications of ductile iron in crucial components across all industries demonstrate the material's adaptability and propose a plethora of new possibilities. When designing with ductile iron, the design engineer had to have exposure to engineering data detailing the mechanical characteristics of ductile iron, including elastic behavior and strength, ductility, hardness, fracture toughness, and fatigue parameters. Many applications need physical features such as thermal expansion, thermal conductivity, heat capacity, density, as well as magnetic and electrical properties.

8. Conclusions

Ductile iron is distinguished by the presence of minute spheroids of graphite in every particle. There are few instances where the graphite in commercially manufactured ductile iron is not in perfect spheres. The shape of the graphite is established when the metal solidifies. Ductile iron is a more suitable material for the automobile industry. As mentioned above, the comparatively high strength and toughness of ductile iron make it a superior construction material when compared to grey or malleable iron in many instances. Due to the fact that it does not require heat treatment to develop graphite nodules (as does malleable iron to make temper-carbon nodules), ductile iron may compete with malleable iron despite the fact that it requires a treatment and inoculation procedure.

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