Filler materials used to weld ductile cast iron – A review

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Abstract. Austempered ductile iron (ADI) is a new engineering material type which continue receiving increased attention in research and industry. Extensive research conducted so far has demonstrated that ADI has excellent property combination such as high strength-weight ratio, ductility and toughness, good fatigue strength, damping properties and wear resistance. As a result of to their exceptional mechanical property mix, fabrication simplicity, low cost and lowest weight per unit strength ratio compared to common steels, this family of ferrous cast alloys have begun replacing cast and forged steels in some engineering applications. However, a major limiting factor to widespread use of ADI in manufacturing industry remains its weldability, more especially during fabrication process. Current work presents a review of various filler materials (electrodes) used to weld ductile cast iron using two common industrial welding processes, namely, shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW). The successes as well as short-comings of these electrodes on weldability of ductile iron have been recorded and a clear need for an improved filler material is identified.

1 Introduction

Ductile iron (DI) is a class of cast iron produced by treating the molten cast iron with magnesium before casting. Due to their ease to cast, about 8% lower melting energy over steel, ease of machining, wide range of mechanical properties, and economic advantages, these family of ferrous cast alloys have begun replacing cast and forged steels in some engineering applications [1-11]. Among cast iron materials class, the austempered ductile iron (ADI) has recently received much attention from academic and

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industrial research point of view [1-11]. This is owed to the fact that ADI materials possess a unique combination of properties such as fabrication simplicity, low cost, high strength-weight ratio, ductility and toughness, good fatigue strength, damping properties, moderate wear resistance, and lowest weight per unit strength ratio compared to common steels, rendering ADI an interesting industrial engineering material [1, 8, 10]. It is this rare excellent property combination that elevates ADI materials to compete with the current industrially used lightweight alloys mostly in the automobile, rail, agriculture and mining industries to produce parts such as crankshafts, steering knuckles, brackets, valves, differential carriers, brake callipers, hubs, water pipes, etc., for use in a wide variety of applications [1, 8, 10]. These properties opened new doors of application for ADI in the manufacturing industry as design engineers, vehicle makers, foundry-men and other manufacturers who are faced with the challenge to produce lighter, stronger, stiffer and cheaper metal parts [2, 3]. In spite of these appealing properties, lack of optimal weldability remains a major limiting factor to widespread industrial use of ADIs [4, 5]. Moreover, in almost all metal manufacturing industries, in particular transportation industry, welding plays a major role in assembly of large and complicated structures. These vital industries that use welding to manufacture their products are the driving force of a modern economy. In addition, welding is also heavily involved in the repair and maintenance of components and process equipment.

Thus, welding is amongst the key challenges encountered by engineering designers seeking to assemble ADI parts during manufacturing. This situation is aggravated by lack of suitable welding consumables with compatible chemical compositions, mechanical properties and microstructure to this promising class of engineering materials. Therefore, there is industrial wide need to improve the weldability of ADIs. The current study aims to provide brief review on weld or filler materials used to weld ductile cast irons, and discusses the advantages and short-comings thereof.

2 Literature review

The term, cast iron, identifies a large family of ferrous alloys containing more than 2.0 wt. % carbon (C) and 1.0 to 3.0 wt. % silicon (Si). The different properties of castings can be achieved by varying C and Si, other alloying elements, as well as by varying melting, casting and heat treatment practice. Cast irons, as the name implies, are indeed to be cast to shape rather than formed in solid state. This class of materials is known to have low melting temperatures, high fluidity in molten state, and undergoes lows shrinkage during solidification. However, cast irons have relatively low impact resistance and ductility, which limits their use [12]. This must be taken into account when designing castings to withstand stress loads encountered during operation.

2.1 Types of Cast Irons

In the iron–carbon phase diagram shown in Figure 1, carbon is thermodynamically more stable as graphite than cementite. However, graphite is not formed in typical steels due to low carbon content, leading to sluggish reaction to graphite. But when the carbon content is increased to that of typical cast irons (2–4% C), either graphite or cementite may separate depending on the cooling rate, chemical composition and heat treatment. Cast irons can be divided into four main groups, based on composition and metallurgical structure. The composition of cast iron (CI) varies significantly depending upon the grade of pig iron used in its manufacture. The mode and concentration of carbon in the CI is controlled to produce various grades of CI, which differ significantly in their mechanical properties and weldability.

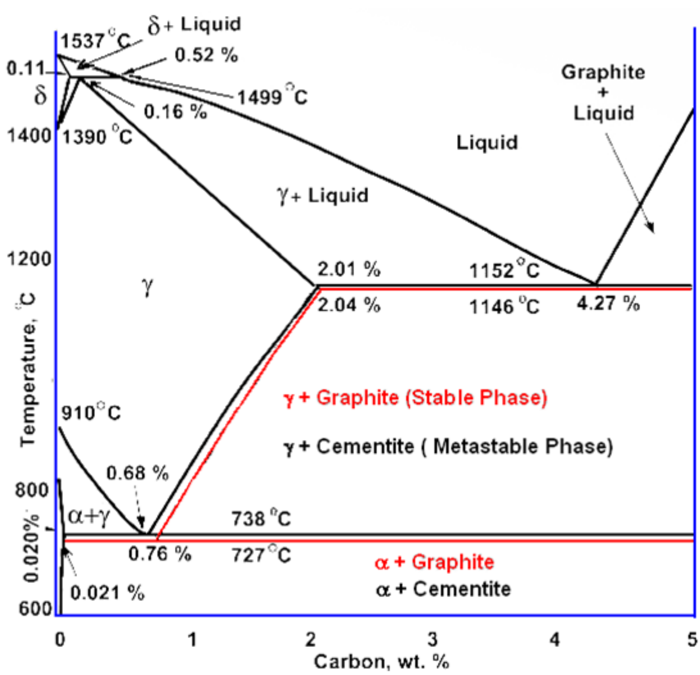

Fig. 1. Fe-C phase diagram showing stable and metastable of cast-iron [11].

2.1.1 Grey cast iron (GCI)

Grey cast irons are iron-carbon-silicon alloys having uncombined carbon in the form of graphite flakes embedded in the ferrite–pearlite matrix, as shown in Figure 2. These iron-carbon-silicon alloys are named grey cast irons due to their grey appearance of fractured surfaces as a result of presence of both cementite and graphite. Grey cast irons are used for a wide variety of applications because of their good strength/cost ratio, ease to cast into intricate shapes. The latter is owed to low density graphite flakes which compensate for the freezing contraction, thus giving good castings free from porosity. Furthermore, the graphite flakes provides damping characteristics and good machinability. The limited strength and ductility of grey cast iron may be improved by small additions of the carbide formers (Cr, Mo), which reduce the flake size and refine the pearlite. Addition of copper (Cu), chromium (Cr), molybdenum (Mo), and nickel (Ni) are to these alloys aid to control matrix microstructure, promote graphite formation and improve corrosion resistance. However, the graphite flakes also acts as stress concentrators, leading to poor toughness. In addition, these graphite flakes can dissolve during welding, thus entering the weld pool and precipitate as high carbon martensite which embrittle the heat-affected zone (HAZ) and the weld metal.

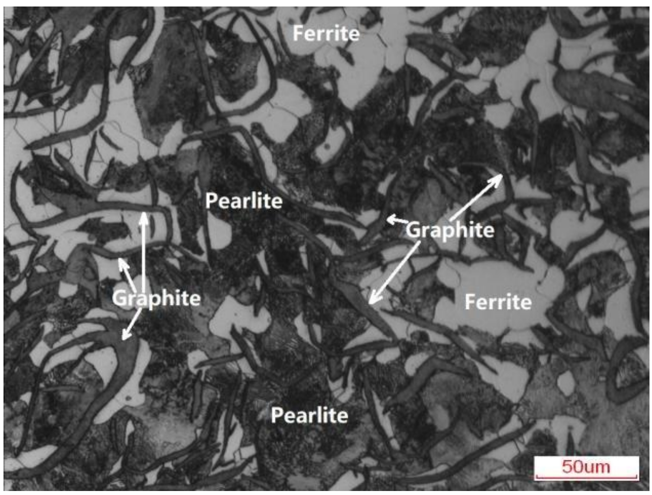

Fig. 2. Illustration of typical grey cast iron micrograph [11].

2.1.2 White cast iron (WCI)

White cast iron is formed when C combines with Fe, Cr, Mo to form carbide and does not precipitate as graphite during solidification, as depicted in Figure 3. It is called white because carbon exists as cementite characterized by bright fracture produced by this brittle constituent. High cooling rates tend to stabilize the cementite, and the presence of carbide formers give rise to formation of white irons**.** Hard and brittle microstructure of the parent material made of mainly carbides makes the structure difficult to machine. In addition, the absence of adequate ductility renders this material unweldable, since some level of ductility is required in welding to accommodate the thermal stresses in the base metal. The main use of white irons is as a starting material for malleable cast iron, in which the cementite in the casting is decomposed by annealing. Such irons contain sufficient Si (less than 1.3%) to promote the decomposition process during the heat treatment, but not enough to produce graphite flakes during casting.

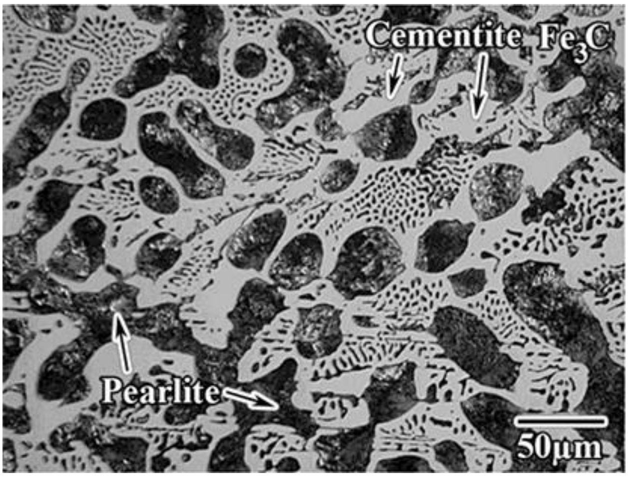

Fig. 3. Illustration of typical white cast iron micrograph [32].

2.1.3 Malleable cast iron (MCI)

Malleable cast iron is formed by heat-treating white cast irons of suitable compositions. During certain heat-treatment conditions, iron carbide decomposes into iron and carbon, as shown in Figure 4. This decomposition reaction is promoted by high temperatures, slow cooling rates and high carbon and silicon contents. At room temperature, the microstructure therefore consists of temper carbon nodules in a ferrite matrix, generally known as ferritic malleable cast iron resulting in improved ductility. However, the ductility of the heat-affected zone (HAZ) of malleable cast iron is severely reduced during welding because graphite dissolves and precipitates as iron carbide. Minimal ductility is regained through post-weld annealing which softens the hardened zone. Despite these limitations, malleable cast irons can be welded satisfactorily and economically if precautions are taken. Because most malleable iron castings are small, preheating is seldom required. If desired, small welded parts can be stress relieved at temperatures up to 550°C. For heavy sections and highly restrained joints, preheating at temperatures up to 200°C and a post weld malleabilizing heat treatment are recommended. However, this practice is costly and thus not always followed.

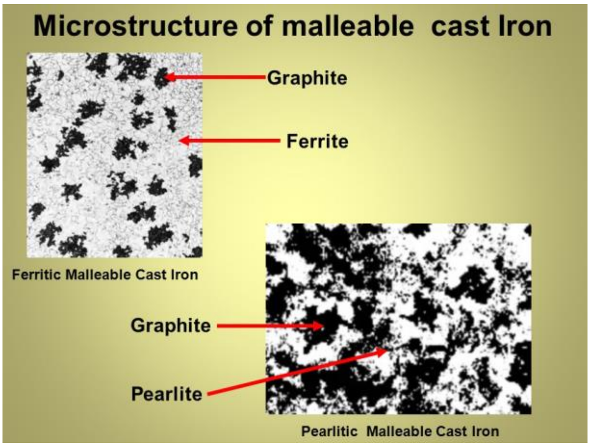

Fig. 4. Illustration of typical malleable cast iron micrograph [32].

2.1.4 Ductile cast iron (DCI)

Ductile cast iron and grey cast iron are similar in carbon and silicon content. However, in the case of ductile cast iron, the free graphite precipitates from the melt as spherical particles (nodules) as shown in Figure 5 rather than as flakes in grey cast iron which form sharp internal edges resulting in lower mechanical properties relative to that of ductile cast iron. Spheroidization or nodulization of graphite is achieved by introducing magnesium or cerium to low sulphur molten metal in the ladle, preferably lower than 0.02%. As a result, spheroidal or nodular graphite is a class of cast iron that offers better mechanical properties without destroying the excellent casting and machining properties. Due to their excellent toughness, spheroidal graphite (SG) cast irons are used in various applications such as water and sewer pipes, agricultural (tractor and implement parts); automotive and diesel (crankshafts, pistons and cylinder heads); electrical fittings, switch boxes, motor frames and circuit breaker parts; mining (hoist drums, drive pulleys, flywheels and elevator buckets); and steel mill (work rolls, furnace doors, table rolls and bearings). In addition, good strength and ductility can be obtained in castings that are too thick in section for malleabilizing. This combination of properties provides ductile cast iron a potential to compete or even replace steel castings and forgings in certain applications. Heat treating the ductile cast iron produces austempered ductile iron (ADI). ADI is ductile iron or spheroidal graphite with a microstructure comprised of ausferrite (retained austenite and ferrite). This is attained through an isothermal heat treatment process called austempering, wherein the ductile iron is heated to its austenitizing temperature (840 °C – 900 °C) and held for a certain time period until transformation to austenite phase is complete. This is then followed by quenching in salt bath or oil at temperature of about 250 °C – 400 °C and held for between 0.5 and 3 hours to allow isothermal transformation of austenite to bainitic ferrite before cooling in air. In this way, a metallurgical microstructure called bainite is formed in medium-to-high carbon ferrous metals since the transformation is usually incomplete, yielding properties that combine high hardness with toughness, resulting in a material with resistance to brittle fatigue (less distortion and cracking). An excellent combination of strength, fracture toughness and wear resistance possessed by ADI has made it appealing for a wide variety of applications in automotive, rail and heavy engineering industries.

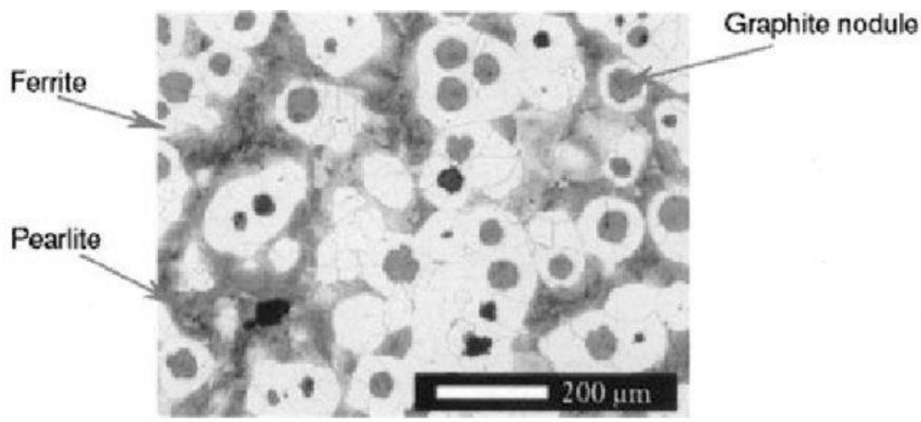

Fig.5. Illustration of typical ductile cast iron micrograph [11].

Among the above types of cast irons mentioned above, the ductile cast iron has emerged as an important cast material to an engineering designer who wish to capitalize on several manufacturing advantages offered by this material, such as low cost, lowest weight per unit strength ratio, ease of machining, low melting temperature, good fluidity, high damping capacity, good wear resistance and excellent heat resistance properties, comparable to common steels [11]. However, lack of optimal weldability remains a major limiting factor to widespread industrial use of ADIs [4,5].

2.2 Weldability of Cast Irons

Cast irons include a large family of alloys covering a wide range of chemical compositions and metallurgical microstructures. Some of these materials are weldable, while others require great care to produce sound welds. Certain cast irons are also considered not weldable. Major factors contributing to the difficulty of welding cast iron are its high carbon content and lack of ductility.

Shielded Metal Arc Welding (SMAW), Flux cored arc (FCAW), Metal Inert Gas (MIG), and Tungsten Inert Gas (TIG) welding processes are normally used with nickel-based welding consumables to produce high-quality welds. However, the most common industrial welding processes used in welding ductile cast iron are shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW). As illustrated in Figure 6, there are typically three distinct regions formed during welding of cast iron, namely, (i) weld metal or fusion zone which melts during welding and re-solidify on cooling, (ii) heat-affected zone (HAZ) which is not melted during welding process but undergoes microstructural alterations, and lastly (iii) unaffected base metal zone in which the structure is not affected by weld thermal cycle.

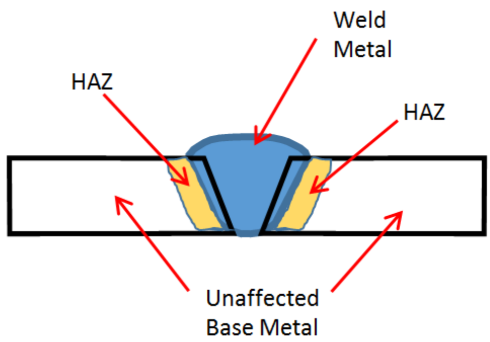

Fig. 6. Illustration of welded-joint base, HAZ and weld metal zones.

Due to the deployed thermal cycle, most commercial filler materials used to weld DI result in very high hardness in the HAZ compared to the base metal. This is attributed to the effect of temperature on the microstructure with high carbon content, promoting formation of hard brittle phases such as martensite and carbide. Besides likelihood to cause cracks at the joints, this resulting high hardness is detrimental to other properties such as toughness, weldability and machinability, which are key to the manufacturing process. Therefore, a better understanding of the origin of extreme hardness may bring out development of novel filler materials suitable to welding cast iron materials stands to benefit of local manufacturing industry, i.e. assembly in transportation industry and lower scrap rate in foundries through defect repairs. Typically, welding cast iron takes place for repair jobs of defects that arise during operation and for repairs of post-production whenever defects were discovered after casting operations and subsequent machining processes. There are several factors that influence the weldability of cast irons, namely, (i) type of cast iron, (ii) chemical composition of cast iron, (iii) chemical composition of filler material, (iv) structure of the matrix, and (v) the welding process [11]. Hence, the choice of a suitable filler material remains critical for a particular type of cast iron.

3 Analysis and discussion

In general, cast irons are considered as a difficult material to weld due to their inherent brittleness as well as how their metallurgical structure is affected by the weld thermal cycle [11, 13]. Unsatisfactory weldability of DCI in particular stems from formation of C-rich martensite, massive iron carbide in the HAZ and partial fusion zone [14]. A number of weld or filler materials have been investigated to weld ductile cast iron, namely, ferritic and austenitic stainless steels, nickel, Ni-based alloys, and Fe-Ni-Mn alloys [15]. The inherent successes and short-comings relating to mechanical properties of weld metals, heat affected zone (HAZ) are analysed and discussed in this section.

3.1 Steel and Fe-based alloys as filler material for DCI

Several types of steel has been investigated by several researchers in attempt to improve weldability of DCI [11, 13, 15-18]. The main driving force behind the desire to use steel electrodes in welding DCI is the low cost. However, this choice poses challenges such as the contraction of the steel weld metal, the carbon picked up from cast iron by the weld metal, and the hardness of the weld metal caused by rapid cooling, which must be considered. Steel shrinks more than cast iron when cooled from molten material to a solid state. Thus when mild steel electrode is used, this uneven shrinkage causes strain at the joint after welding. Consequently, if large quantity of filler material is applied to the joint, the cast iron may crack just back of the line of fusion unless preventative steps are taken. On the other hand, stainless steel filers are not a good choice either. This is so because the high amount of chromium in filler and high amount of carbon in cast iron combine together to form carbon rich chromium carbide which is brittle and lead to cracking of the welds.

The desire to use Fe-based alloys as filler materials for welding DCI began a while ago with Fe-Ni-Mn based alloys [15, 19], and was later pursued in the form of Fe-Cr-Ni alloys with chemical compositions closer to that of stainless steel [20]. The Fe-Ni-Mn filler metals have been demonstrated to be capable of welding DI without the need to preheat or postheat while attaining tensile properties that match those of base metal. However, this conclusion led to some controversy over whether the DI material is weldable or not. This emerged as end users and researchers paid more attention on achieving specific targeted properties such as yield strength, impact resistance and HAZ hardness as opposed to focusing on the actual weldability [15]. From this filler material system, it was concluded that satisfactory weldment properties do not exclusively depend on the HAZ microstructure but a combination of properties [15]. The main problem with iron filler metals lies in the brittle weld metal that results from the high carbon content that is picked up from the base metal, promoting formation of undesirable phases which are attributed to the presence of carbide forming elements such as Mn, Cr. In addition, lack of further interest is these systems could be pinned to poor oxidation and corrosion resistance.

3.2 Nickel and Ni-based alloys as filler material for DCI

The choice of Ni and its alloys as filler material for DCI has received much more attention over the years than Fe-based materials [4, 5, 11, 13-14, 17, 20-31]. Increased interest in Ni is owed to a number of the following attractive benefits: (i) Ni is an austenite stabilizer, thus widens the austenite region and contracts the ferrite region in steel; (ii) Ni ability to accommodate the high carbon content without forming carbide; (iii) Ni improves the resistance against the corrosion and oxidation at elevated temperatures; (iv) Ni improves the toughness and strength by refining the grain size;

and (v) Ni prevents scale forming on the material surface. Furthermore, when used with chromium, it improves the hardness, ductility, fatigue resistance and critical cooling rate. Since the high carbon content in DCI leads formation of martensite and brittle iron carbides during the cooling of the weld joints, precaution must be exercised on the selection of the filler material [26-28] and lower cooling rate of the weld in order to reduce martensitic transformations and carbide precipitations, to avoid cracking of the joint.

Carcel-Carrasco et al. examined the weldability of ductile cast iron when the root weld is applied with a tungsten inert gas (TIG) welding process employing an Inconel 625 source rod, and when the filler welds are applied with electrodes coated with 97.6% Ni. The test plates were preheated to improve weld fluidity and discourage the formation of brittle structures by favouring penetration and thus preventing fractures from starting [21]. They analysed microstructure of the material next to the weld in the metal-weld interface zone and on the weld itself. They obtained microstructure was correlated with the strength of the welds. Absence of formed carbides was attributed to treating an alloy with 97.6% Ni. It was further reported that upon heat treatment at 900˚C, all carbides dissolved, forming nodules in ferritic matrix graphite, as shown in Figures 7 and 8 corresponding to before and after weld, respectively.

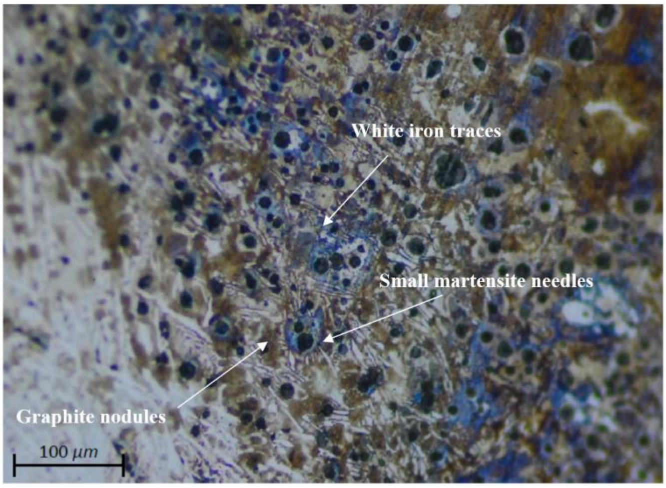

Fig. 7. Illustration of Ductile cast iron micrograph before weld [21].

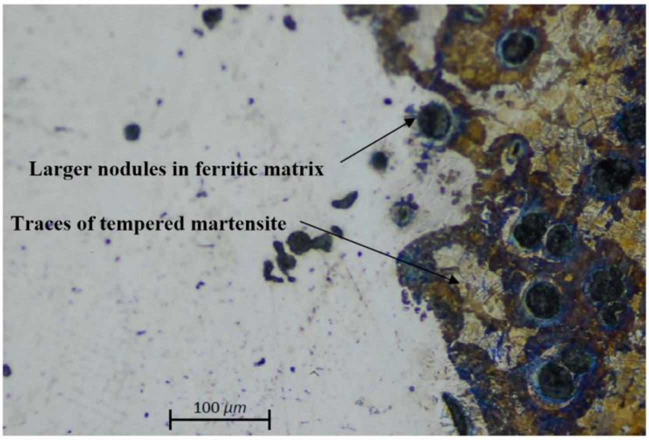

Fig. 8. Illustration of Ductile cast iron micrograph after weld [21].

Pouranvari carried out a study on welding cast iron using SMAW with Ni electrode [30]. He also applied post-weld heat treatment (PWHT) to the welded pieces. Due to possibility of increasing amount and continuity of carbides, preheating was avoided and as such formation of cracks was not reported. By annealing the material fully, a nearly uniform hardness profile was achieved. However, before PWHT, the HAZ exhibited martensitic structure and partially melted zone exhibited white cast iron structure and martensite. Applying PWHT resulted in the dissolution of martensite in HAZ, graphitization and in turn the reduction of partially melted zone hardness. This study reported the advantages of using nickel base filler material as follows: (i) formation of hard and brittle micro-constituents in the FZ is prevented; (ii) precipitation of graphite in the FZ increases its volume since a lot of carbon from the base metal mixes with the nickel filler metal, which further reduces the weld metal shrinkage during solidification, which in turn, leads to the minimization of the residual stress in FZ and HAZ causing the reduction of the cracking susceptibility of the cast iron joint; and lastly (iii) high ductility of the nickel based FZ plays an important role in the absorption of tensile stress created during welding. This contributes to the minimization of the crack susceptibility of joint. A similar investigation was conducted by El-Banna et al., in which the restoration properties of pearlitic cast iron using SMAW with various filler materials, namely, Ni, Fe-Ni alloy, Ni-Cu alloy, stainless and ferritic steel were studied [17]. It was found that higher heat input allows smaller melting region (MR) and pearlitic HAZ. In addition, it was reported that PWHT slightly reduces the maximum hardness of the HAZ.

Voigt and Loper studied the general HAZ structures of ductile cast irons using SMAW process, ENi-CI filler material, and preheating of about 300°C [14]. Sub-critical annealing and full annealing were applied to the specimens. In as weld specimens carbides were formed surrounding the graphite nodules and at intercellular regions between nodules. It is concluded that this formation cannot be effectively prevented in partially melted zone (PMZ). Martensite observed in HAZ can be avoided if the preheating temperature, interpass temperature, and postweld temperatures are maintained for sufficient times above the martensite start temperature of DCI after welding. In fact, preheating is very important to avoid the formation of martensite when welding cast iron. By application of subcritical annealing martensite was decomposed to ferrite and secondary graphite [17].

Due to ferromagnetic nature of Fe and Ni and most of their alloys, it is likely that their inherent magnetism could cause a defect called residual magnetism in welds. Moreover, it is reported elsewhere that use of pure Ni as a filler material results in weld metal porosity [33], which might arise as a result of coexistence of both FCC ferromagnetic and paramagnetic Ni phases. Although seldomly explored, it is also possible that magnetism could be contributing to high carbon being depleted from the base metal. Extreme residual magnetism, which will cause the magnet to collect ferrous particles and debris even after it has been turned off. Debris will likely cause an air gap on subsequent lifts and may permanently score the magnet causing porosity. Porosity is also an issue, particularly when oxygen or hydrogen creates surface contamination in the form of air entrapment in the weld pool.

4 Conclusions

The most common and serious issue that occurs when welding with nickel alloys is hot cracking. This occurs in the fusion line, in the heat-affected zone (HAZ) or in the weld metal, although the fusion line is the most commonly affected area. In addition to poor corrosion resistance, Fe-based filler materials containing Cr and Mn are prone to formation of hard brittle carbide in the weld due to high carbon content and fast cooling. As a result, hardened weld is susceptible to cracking, rendering this type of filler material unsuitable.

It is evident from this review that Ni, Ni-Fe and Inconel-type Ni alloys are the most popular used filler materials to weld DCI, and subsequently, with potential to be considered as weld metals for ADI which is an engineering material receiving much interest. Common setback in these filler materials is the much higher hardness at HAZ compared to weld metal and base metal. Besides its negative impact on weldability of DCI, this high hardness directly compromises other engineering properties such to ductility, toughness and machinability.

Iron based filler materials has chrome which forms carbides in the weld, in so hardening the weld. Ultimately a crack will occur in the weld. Current commercially available coated electrodes such as pure Ni, stainless steels and Fe-Ni-based alloys investigated as potential filler materials achieved limited success for full industrial use [14] due to short-comings ranging from high material cost to poor austemperability (inability to convert weld DI to ADI state) after welding. However, alloys containing in high concentration in the filler material hold much promise since its presence is beneficial in accommodating the high carbon content of cast irons, thus suppressing formation of carbides. It is widely known that to produce successful welding properties for ADI parts during and after manufacturing requires modifications in welding techniques, heat treatment (preheating and post welding), filler materials, and surface alloying. Improving the weldability of ADI materials will not only benefit the assembly of components but also the repairs of defected DI castings, thus boosting the profit margins of foundries. Therefore, there is industrial wide need to improve the weldability of ADIs by developing better performing filler materials.

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