A REVIEW ON TESTS OF AUSTEMPERED DUCTILE IRON WELDING

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Abstract: *Austempered Ductile Iron (ADI) is a new engineering material with an exceptional combination of mechanical properties and important applications in different fields. This revolutionary material with a unique combination of strength, abrasion resistance, hardness, noise and vibration capability, along with good machinability of the material has opened up new applications in various sectors of industry as a replacement of conventional materials such as steel. One of the most problems encountered by designers is the welding of ADI parts during manufacturing and the need for developing new welding consumable. This paper presents a review on ADI welding.*

Key words: *austempered ductile iron, welding, mechanical properties.*

1. Introduction

Ductile Iron is a type of cast iron invented in 1943 by Keith Millis. Austempered Ductile Iron (ADI), a relatively new metal material, was invented in the 1950s but was success commercialized and achieved only some years later, which is used for the first time in 1970 by the Finnish company Kymmene Metall Kyki that began to replace forged steel with ADI, for a wide range of industrial applications with satisfactory results.

ADI offers this superior combination of properties because it can be cast like any other member of the ductile iron family, thus offering all the production advantages of a conventional ductile iron casting. Subsequently it is subjected to the austempering process to produce mechanical properties that are superior to conventional ductile iron, cast and forged aluminium and many cast and forged steels [18].

One of the most problems encountered by designers is the welding of ADI parts during manufacturing and the need for developing new welding consumables. There are two problems during welding of ADI; first the formation of massive cementite in the as-welded ductile iron because of fast cooling rate; second the properties of ADI weld should match those of ADI base material [6].

When the ADI castings need to be produced and repaired, sometimes the welding procedure is necessary. By controlling the composition and cooling rate of the weld metal, an austenitic-bainitic microstructure can be directly obtained under as-welded conditions [8].

2. Tests of ADI Welding

Pascual et al. [10], have studied two technologies of welding the ADI, namely: SMAW (Shielded Metal Arc Welding) and

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OAW (Oxyacetylene welding), with and without preheating, on casting samples of 300×90×5 mm without groove using two types of electrodes: Fe-Cr-Ni, Ni-98% and two types of grey iron rods. The suitability of each welding technique and consumable was evaluated through the study of the mechanical characteristics of the joints. These characteristics were obtained from tensile tests and were correlated with the microstructure of the joints. Ductile iron can be welded with and without preheating but the mechanical resistance of the joint is expected to be worse than that of the ductile iron. If OAW grey iron rods are used, the mechanical properties of the joint are poorer than those of the parent metal, while if SMAW Ni or stainless electrodes are employed, an improvement in ductility is obtained, assuring a non-fragile behaviour of the weld. The better properties are obtained with Ni electrodes and preheat because of the absence of carbides and the ductility of the joint. Moreover, the process presents few difficulties. The use of stainless electrodes can be a good alternative due to their lower price.

El Kashif and Morsy [6] have studied two processes of welding the ADI, namely: SMAW and GTAW (Gas Tungsten Arc Welding), using standard electrodes as filler material: AWS-ENiFeCl and AWS-E11018-G. The results obtained from SMAW were compared with that produced from GTAW using filler metal as stripes machined from base metal material. It was found that welding with GTAW process using filler with the same material followed by austempering heat treatment has superior metallurgical and mechanical properties compared with SMAW using different electrodes for cast iron welding. The tensile test properties of the joints are lower than that of ADI using AWS-EniFeCI electrode; preheating temperature of 400 ºC resulted in the disappearance of the martensite in heat affected zone (HAZ) and the coarsening of carbides.

3. Review on Mechanical Properties

Acka et al. [2] have studied unalloyed ferritic-pearlitic ductile iron specimens which contain 3.69% C, 2.47% Si and 0.2% Mn were austempered at 375 °C to obtain upper bainitic microstructure for 20 and 100 min and then welded using GTAW without filler. The results have shown that upper bainitic ADI could be welded successfully without any crack formation in HAZ. It was also observed that HAZ of specimen which is austempered for 20 min has greater hardness than those of 100 min due to low austenite content (Figure 1).
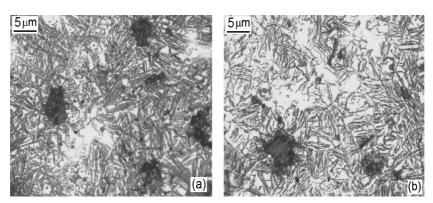

Fig. 1. *Microstructures of austempered specimens at 375 °C for 20 min* (*a*) *and 100 min* (*b*)*. Light regions are austenite* [2]

Sun et al. [15], have studied Cu, Ni, Mn and Mo all have favourable effect on austemperability of the weld, and the most pronounced increasing in the austemperability is brought by Mo. The welds were deposited on the test plates by the manual SMAW process. The microstructure of ADI weld metal mainly consists of bainitic ferrite, retained austenite and graphite nodules Cu and Ni have little effect on the tensile strength, but they can improve the ductility of ADI weld due to increased retained austenite volume fraction. Increasing weld Mn or Mo content results in impairing the ductility of ADI weld, which is mainly attributed to the formation of martensite or carbide enriched with Mo in eutectic cell boundary region. The weld alloyed with 0.54% Cu, 0.71% Ni, 0.32% Mn and 0.19% Mo has not only high austemperability but also exceptional combination of the mechanical properties, the critical bar diameter (Dc), tensile strength and elongation being 42 mm, 1142 MPa and 9.5%, respectively. They can match those of low-alloy ADI.

Microstructure and mechanical properties of ADI are dependent on isothermal austenite transformation temperature and holding time at this temperature as reported by Vasko [16].

El-Banna [4], have studied the effect of preheat temperature on the microstructure obtained in the HAZ and the carbide zone in the weld metal adjacent to HAZ has been studied in multipass welds for the as-cast and ferritic ductile cast irons. The welding was carried out with SMAW using ENiFe-CI filler metal. Preheating temperature depends on the hardness of iron (chemical composition or carbon equivalent), size and complexity of weld and type of filler material, preheating effect is to reduce residual stresses and deformation to prevent cold cracks and reduce hardness in the heat affected zone. Ductile cast iron can be welded without

and with preheat and is free from cracking; the ultimate tensile strength expected from as-cast ductile iron cannot be met on welded components while for the ferritic grade be met. Preheat temperature of 300 °C or 200 °C were adequate for the as-cast and ferritic ductile cast iron because prevent martensite formation in the heat affected zone, reduce the size of the fusion and achieve optimum mechanical properties.

One of the most important problems faced by designers is the welding parts made from ADI and the need to develop new welding consumables. Using a filler material based on nickel prevents the formation of a brittle area (carbides and martensite) in the fusion zone, during the welding process the carbon of the base material is diluted with filler material in the fusion zone and the excess carbon is precipitated as graphite during the solidification fusion zone as reported by Pouranvari [12]. Before Post Weld Heat Treatment (PWHT), heat affected zone exhibited martensitic structure and partially melted zone exhibited white cast iron structure plus martensite. Applied PWHT resulted in the dissolution of martensite in HAZ and graphitization also the reduction of partially melted zone hardness.

Jeshvaghani et al. [7] have studied effect of surface alloying on the microstructure and wear behaviour of ductile iron. Ductile iron samples were coated by single and double pass weld of a nickel-based (ENiCrFe$_3$) using SMAW. The effects of number of passes on microstructure, hardness and wear resistance of cladded layers were investigated. Optical microscopy and X-ray diffractometry were used to identify the microstructure and phase composition of cladded layers and interfaces. The hardness of the cladded layers was higher than of substrate. In samples processed

with a single and double passes, hardness reached up to 500 and 450 HV, respectively. Pin-on-plate wear tests showed that wear mechanism is predominantly de lamination in the cladded layers and substrate.

In [5] El-Banna et al. have studied the restoration and/or hardfacing by welding of worn-out parts manufactured from pearlitic ductile cast iron. The work may be divided into two sections. The first deals with studying the weldability of pearlitic ductile cast iron by means of five different types of filler material, namely, pure Ni, Fe-Ni alloy, Ni-Cu alloy, stainless steel and ferritic steel. Particular attention was directed towards the parameters affecting welding by ferritic steel filler metal. This material is attractive because of its low cost. In addition, weldments produced are characterized by excellent colour match, satisfactory hardness and the variety of austenitic transformation products which occur on cooling. Process variables such as preheating, heat input, PWHT, multipass, multilayer techniques and hardfacing process were studied in detail. The problems associated with welds with pure Ni, Ni-Fe alloy, Ni-Cu alloy and stainless steel are also present to various extent in welds made with ferritic steel filler metal. Preheating to 300 °C appears as the best option when welding by ferritic steel filler metal. This is reflected in narrow melt region, discontinuous carbide areas and bainitic HAZ. Multilayer welding allows the third layer to reach the carbon content of filler metal. This leads to the formation of a useful "buffer layer" which allows further hardfacing to be carried out

Amirsadeghi et al. [3] have studied microhardness and wear resistance of different microstructures formed by TIG (tungsten inert gas) surface melting and chromium surface alloying (using ferrochromium) of ADI. Surface melting resulted in the formation of a ledeburitic

structure in the melted zone. This structure has hardness up to 896 HV as compared to 360 HV in ADI. Chromium surface alloying yielded superior wear behaviour and reduced the wear rate of the treated specimens by about 38% and 70%, depending on the structures formed (Figure 2).
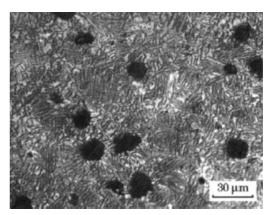

Fig. 2. *Microstructure of base material (ADI) consisting of acicular ferrite, retained austenite and nodular graphite* [3]

Surface melting reduced the wear rate of ADI by 32% and 37% for specimens with a surface hardness of 766 and 896 HV, Chromium surface alloying reduced the wear rate of AD1 by 70%, 42%, and 38% for the specimens with surface hardness of 1 078, 755 and 896 HV.

Kelly et al. [9] have studied the weldability of ductile iron using four process of welding, namely GMAW (Gas Metal Arc Welding); GTAW, SMAW and SAW (Submerged Arc Welding), using Ni-Fe-Mn as filler metal, and without preheat. Ductile iron can be welded without preheat or postheat using the Ni-Fe-Mn filler metal. The Ni-Fe-Mn system has been found to be useful with a variety of welding processes, offering the potential for increased utility and economy in welding of ductile iron.

The Ni-Fe-Mn filler metal system has been demonstrated to be capable of welding DI

without preheat or postheat and retaining 100% of the base metal tensile properties. It has also been demonstrated that DI weldments containing iron carbide, secondary graphite, and/or martensite in the HAZ can have useful tensile properties. Therefore, HAZ microstructure alone cannot be used to predict weldment performance. Additionally the Ni-Fe-Mn filler metal system has been shown to be suitable for use with all of the fusion welding processes normally applied to cast irons.

Voigt et al. [17] have studied the importance of weld preheating and postheating to prevent martensite formation in the heat affected zone and thereby provide improved toughness and ductility. Preheating must be sustained for a time sufficient to avoid martensite formation. This is especially important when welding alloyed ductile cast iron, where the hardenability is substantially increased compared to the already high hardenability of unalloyed ductile iron. Ductile cast iron is a material which presents unique weldability problems because of its strongly heterogeneous microstructure consisting of spheroidal graphite in a matrix of alloyed ferrite and/or pearlite. One should apply welding procedures that prevent the development of a continuous carbide network which is detrimental from a mechanical property standpoint.

Pascual et al. [11] have studied the weldability of spheroidal graphite ductile cast iron using a cheap Ni-Fe and a high purity Ni electrode. Manual metal arc welding was employed to join the ductile cast iron plates. Two electrodes having compositions of 57.2% Ni + 41% Fe (other elements were 0.66% C, 0.16% Si, 0.85% Mn) and 97.6% Ni (0.30% C, 0.20%Si, 0.005% P, 0.005% S, 0.2% Mn and 1% Fe) were used. High purity Ni electrodes showed a better weldability than Ni-Fe electrodes resulting from enhanced ductility due to lower acicular structures formed and better uniform distribution of graphite in the bead. In order to establish the effects of preheating and annealing treatments, three types of welding were performed. In the first case the plates to be joined were preheated at 350 °C and joined. In the second case, the plates were joined without preheating and postheating. In the third case, the plates joined without preheating were annealed at 850 °C for one hour. Samples were prepared from all as-welded and treated plates by cutting it at its centres and polished. The preheating treatment increases the ductility of the welded piece through minimizing hard and fragile microstructures.

Abboud [1] studied melting and rapid solidification of ductile iron surfaces nodular using TIG (Tungsten Inert Gas) welding process to obtain a cooled structure of high hardness and better resistance to erosion. Microhardness was between 600-800 HV; increasing welding intensity affects the microstructure and hardness. A ductile behaviour mode was found in both the as-received and TIG melted layer with a maximum erosion rate at 30° impinging angle.

In [13] Sun et al. have studied the effect of Ca, Ba, Bi and Al on the amount of carbide in ductile iron weld metal, the microstructural charac-teristics of ADI weld metal and the effect of heat treatment process on the microstructure and mechanical properties of ADI weld metal (Figure 3). On this basis the optimum composition of weld and the optimum heat treatment process of ADI weld metal were determinated and a new electrode for arc cold-welding (without preheat) of ADI was developed. The strength of ADI weld metal increases slightly from 1024 to 1040 MPa, while the elongation decreases slightly from 8.8 to 8.3% with increasing of the austenitizing temperature from 860 °C to 900 °C. When austenitizing tempe-rature exceeds 900 °C,

both the strength and elongation decrease and lower respectively to 950 MPa and 6.1% at 980 °C the retained austenite volume fraction (f_γ) in ADI weld metals increases almost linearly from 0.272 to 0.441 with increasing austenitizing temperature from 860 to 960 °C.
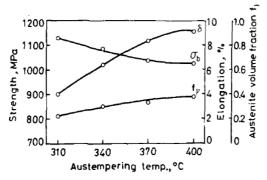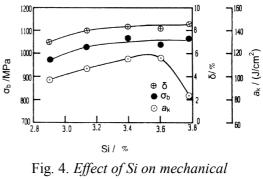

Fig. 3. *Effect of austempering temperature on microstructure and mechanical properties* [13]

The mechanical properties of welded joints can match the requirement of ADI. During arc cold-welding of ADI, the carbide formed from weld pool under extremely rapid cooling is one of the main problems, wich will seriously incrise the tendency of cracking of weld metal before austempering. The authors obtained the following conclusions:

1. Ca, Ba, Bi and Al which are properly added in combination possess strong graphitizing effect, free carbide can be fully eliminated not only in weld but also in partial fusion zone.

2. In ADI weld metal the bainitic ferrite is accompanied by the retained austenite rather than carbide because of high Si content.

3. The heat treatment process has obvious effects on the microstructure and mechanical properties of ADI weld metals. The optimum composition of weld and the proper heat treatment process are identified. The mechanical properties of weld and welded joint can match those of ADI.

In [14] Sun et al. have studied the effect of Si, Mn and Al on the microstructure and mechanical properties of ADI weld. The microstructure of ADI weld metal mainly consists of bainitic ferrite and retained austenite. Mechanical properties of ADI weld increase with increasing Si content, but an excess of Si (3.79%) results in decreasing the austemperability owing to decreasing the carbon content of the matrix austenite (Figure 4).

Fig. 4. *Effect of Si on mechanical properties of ADI weld* [14]

Mn increases the retained austenite volume fraction, but the ductility and impact toughness of weld obviously decrease with increasing Mn content because of increased amount of martensite. In the range of 0.13%-0.64% Al, increasing Al content favours improving the mechanical properties of ADI weld. It is very important to select suitable Si, Mn and Al contents to improve mechanical properties of ADI weld. A low carbon steel wire (5 mm in diameter) was chosen as the core of test electrode and the coating of test electrode was made from spheroidizing agent, graphitizing agent, fluxing agent and alloying agent.

4. Conclusions

The study of the previous work reviews the improvement of weldability ADI. Ductile iron can be welded with or without preheating, but the mechanical strength of

the welded joint is lower compared to the mechanical strength of cast iron.

If for the OAW welding process are used as filler gray cast iron rods, the mechanical properties of the welded joint will be weaker than the mechanical properties of the base material. For the SMAW welding process there were used as filler Ni or stainless steel electrodes, and were obtained the improvement of the ductility and a non-brittle behaviour of the weld. The better properties are obtained with Ni electrodes and preheating because of the carbides absence.

Using nickel base filler material, the formation of brittle martensite and carbide in fusion zone is prevented.

For GTAW was used as filler metal stripes machined from base metal material. It was found that GTAW followed by austempering heat treatment gives superior metallurgical and mechanical properties compared with SMAW using different electrodes for cast iron welding.

Acknowledgements

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