A Review on the Prospect for the Development of Nanostructured and Nanocomposite Aluminium-Alloyed Austempered Ductile Iron


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Abstract: This review paper has established austempered ductile iron (ADI) as a classical material that has spectra of properties achieved by altering some processing parameters through heat treatment procedures. Concerted efforts have been made to equally explore the use of additives as additional materials to this all-important alloy. The use of modifiers at ultra-fine and nano-scale level as additive to the melt prior casting has also been reviewed. However, the continuous quest for innovative approaches of upgrading the structural and mechanical characteristics of ductile irons has open up interest in the development of nanostructured and nanocomposite components in bulky iron bearing materials. This paper cross-examines few available literatures on the nanostructured ADI with the aim of adopting similar methodology in the development of nanostructured aluminium-alloyed DI and nanostructured aluminium-alloyed ADI. Emphasis is laid on reviewing the production techniques and treatment parameters on the processing of the developed nanostructured aluminium-alloyed DI and/or aluminium-alloyed DI nanocomposites and with respect to their usage at low, moderate and extremely high and low temperatures.

Keywords — aluminium-alloyed, austempered ductile iron, development, nano-structure, nanocomposite, processing, modifiers

1 INTRODUCTION

Austempered ductile irons nowadays have progressively become a classic choice for automobile and structural applications (Omole et al., 2018; Tong et al., 2018; Agostinoa et al., 2017). This is as a result of its exceptional microstructural and mechanical properties (Alves et al., 2016; Kang et al., 2009). In quest for the development of new materials to meet up with the continuous high demand for advanced engineering materials in automobile industries,—researchers have continued to carry out investigations on various possible ways of improving the potentials of the alloys (Cocco et al., 2015). The introduction of alloying element is one of the potent ways of improving the microstructure and mechanical properties of materials (Cocco et al., 2015).

Among others, aluminium is a basic, low cost and readily available alloying addition that can be introduced to ductile iron (Soinski et al., 2016). Addition of Al to ductile irons as alloying element results in the production of Al-alloyed ductile iron which can be up to 30%. Al being a potential graphitisating agent brings about alteration in the phase and microstructural features of the alloy (Soinski, 2012). Its presence influences the nucleation process of graphite nucleation and solidification mechanism. Al increases the number of nucleation sites for graphite growth. It will initially form stable AlO2-XO nuclei which subsequently acts as nuclei for the (Mn,X)S phase to grow.

The sulphide particle will then act as the substrate for the growth of graphite flakes which are modified into spheroids or nodules in the presence of magnesium during solidification. The amount of aluminium in cast iron influence significantly both the form which can be taken by graphite in the alloy, and the microstructure of metal matrix (Soinski et al., 2015). It also improves its oxidation and corrosion resistance; and is the most effective ways of increasing the fire resistance of the material.

The Fe/AlCx (k) phase formed through a peritectic reaction at 1630°K (1357°C) between liquid and graphite. Other common compounds include FeAl and Fe2Al3C3 as shown in Fe-C-Al ternary phase diagram (Raghavan, 2007).

However, Al presence as alloying element hinders perfect spheroidization of the nodular graphite precipitates in ductile iron (Haghdadi et al., 2012; Shayestey et al., 2010). And this can adversely affect the overall properties of the ductile iron, most especially, through sand mould casting. The counteracting effect of aluminium on nodularity is because Al presence disrupts uniformity in carbon diffusion at the surface layer of austenite leading to reduction in its sphericity. As a de-oxidizing agent, it possibly might have absorbed oxygen and interfered with the graphite surface, which could eventually affect its growth into perfect spheroids. Also, due to its affinity for oxygen, more of oxygen could be absorbed such that the added Mg cannot absorb all the oxygen which eventually precipitate on the graphite surface layer and consequently, counteracted the growth into sphericity (Soinski et al., 2016; Soinski and Jakubus, 2013; Shayestey et al., 2010; and Soinski and Goraj, 2009). Notwithstanding the negative effect of its addition on spheroidisation of nodular graphite, the most desirable graphite forms are possible (Soinski et al., 2016; Soinski et al., 2015; Shayestey et al., 2010).

In addition, Al also impacts on widening the eutectic temperature of cast irons, lower cooling rate, giving sufficient time for some growing nodules to come in contact with/impinge on adjacent nodules, which eventually distorts their morphology, leading to loss in sphericity (Haghdadi et al., 2012). However, despite the seeming undesirable effect of Al on crystallization of absolutely perfect spheroids, proper process control has since been identified as key to harnessing the most desirable graphite morphologies possible. Process control in this context, applies to factors, such as melting furnace, selected melt practices, modes of inoculation, among others (Ceschini et al., 2017; Gonzaga, 2013; Haghdadi et al., 2012). The spontaneity of the graphitisation process assisted by the cooling rate favourably influences the
formation of nодular graphite. Depending on the Al wt.%, precipitates of nодular or vermicular forms of graphite are formed in the structure which may be smaller in sizes (Soinski et al., 2016; Soinski et al., 2015).

Nowadays, concerted efforts are being made to equally explore the use of additives as additional materials to this all important alloy. This was borne out of the fact that fundamentally, chemical composition, cast quality and subsequently, microstructure determine the properties and performances of the alloy. It has now been realised that in order to achieve additional outstanding quality of cast in terms of structural characteristics, further approach has to be employed. One of the most efficient method is to modify using modifiers at ultra-fine or nano-scale level as additive to the melt prior casting. There is continuous quest for innovative approaches of upgrading the structural and mechanical characteristics of ductile irons, including the process of introducing the modifiers (Zykova et al., 2018; Ferro et al., 2013; Cho et al., 2007; Slozoy et al., 2015; Shen et al., 1995). The technological advancement in nanocomposite development has equally provided further advantages in its realisation.

In recent times, research has open up interest in the development of nanostructured and nanocomposite components in bulky iron bearing materials (Myszka et al., 2014). However, there are limitations to researches carried out in this area (Panneerselvam and Putatunda, 2018) and thus scarcely reported in the literatures. Composite are materials that consist of two or more discrete materials combine together physically and chemically to form another distinct material possessing different exceptional characteristics from the constituent materials. The two constituent materials are the matrix phase which is continuous and the reinforcement phase which is discontinuous. The matrix phase could be either metals, polymers, ceramics or carbon, while the reinforcement phase which could also be either of the materials or their oxides, carbides and nitrides (Garg et al., 2019; Rosso, 2006; Kaczmars et al., 2000) in form of short, fibres, whiskers particulates and continuous fibre. When the matrix is a metal or metal alloy which are refer to as metal matrix composite (MMC), which embedded the percolating network, while other constituents are called reinforcement which are usually non-metallic materials and are commonly ceramic such as Al2O3, C and SiC. Among the prominent MMC are the Aluminium matrix composites (AMCs), Magnesium based composites (MgMCs) and Iron based metal matrix composites (FeMCs) (Garg et al., 2019; Rosso, 2006; Kaczmars et al., 2000). According to Muley et al. 2015, MMNCs are new material design concept where in second phase nano particles dispersed in matrix to enhance various properties of composite materials.

This paper is an attempt to appraise some of the various works that have been carried out in the area of nanostructured austempered ductile iron and present further alternative. Sparse reports are available on the development of nanostructured austempered ductile irons (Panneerselvam and Putatunda, 2018; Bhadreshia, 2013), but there appears to be little or no report on nanostructured aluminium-alloyed ductile irons or aluminium-alloyed ductile irons nano-composite. The area seems not to have been exploited and hence, represent research area that can be assessed which would be of immense benefit to materials applications.

2. PROCESSING TECHNIQUES OF NANOSTRUCTURED AND NANOCOMPOSITE AUSTEMPERED DUCTILE IRONS

Most of the few available reports on cast iron, particularly, ductile irons are based on the use of modifiers and plastic deformation at elevated temperature combined with heat treatment.

Myszka et al. (2014) has reported a research on nanoausferritic ductile iron. The work proposed a new appropriate heat treatment process to be carried out on gear elements made of ductile iron to obtain nanoausferritic matrix structure. The new material offers good performance characteristics and nearly no need for the application of other technological processes commonly used in the manufacture of gears. It established that for ADI to possess excellent resistance to dynamic loading, the toughness and bending strength have to be further improved. The work suggests a way of improving these ADI properties by increasing the fatigue strength through the strain hardening of product surface, for instance, by shot peening or refining the grain size within the entire product volume (Valiev and Langdon, 2006; Hurley et al., 1999). It also expresses the results of studies carried out on four types of ADI (containing 0.24% Mo) from which the gear components have been cast for the mining industry.

A heat treatment cycle was used to produce submicron-sized or nanometric grains in a mixture of ferrite and austenite present in such structures. It showed that the austempering treatment and special thermal processes are responsible for the size of ferrite grains, significant refinement of the ausferritic obtained in the austempered ductile iron matrix microstructure, even to the size of nano-scale; and these contribute to the improvement of its properties. Particularly important is the fracture toughness, which so far has been identified with the presence of stable austenite in the cast iron structure. The authors proved that the presence of austenite in ultrafine grain cast iron matrix structure is a critical factor in obtaining the satisfactory properties, corresponding to EU Standard, enabling the use of this cast iron for very responsible parts of machinery. Tests carried out on gear components for the mining industry have indicated that the material has potentially good abilities to carry loads under harsh operating conditions.

Panneerselvam and Putatunda (2018) also established that application of phase transformation technique can lead to produce nano-structured ADI despite its microstructural features. This was achieved by modifying the structure of ADI to a nanostructure size via simultaneous combination of plastic deformation at austenitic temperature and austempering process to achieve a nanostructure containing ausferrite. The process led to extra-refinement of the ADI to a nano-scale
level. With this, a more improved nanostructured ADI with enhanced mechanical properties was produced. This increases the possibility of ADI as additional materials in critical structural use. The processes have been reportedly used to produce nanostructured components made of other metals through techniques such as multiple forging, torsion straining and equal channel angular pressing among others. However, these processes have their limitations as they lead to some material defects such as micro-porosity, contamination and brittleness in the material.

Similar report was provided by Myszka, et al. (2015) and Myszka, et al. (2014) which tried to produce nanostructured ADI by austempering at lower bainitic transformation temperature range for a prolonged period and achieved a significant refinement of ferrite plates in less than 100 nm range. Putatunda et al. (2015) in its investigation likewise developed ADI possessing microstructure at nano scale with the aid of high temperature deformation and subsequently, austempering of the ductile iron. This nanostructure was achieved by subjecting material to inter-critical austenisation at diverse temperatures, followed by plastic deformed at that temperature and subsequently austempered by isothermal transformation in the molten salt bath at varied austempering temperature range for 1-2 hours. The deformation carried out in the inter-critical region and subsequent austempering process lead to exceptionally fine ferritic cell size in the nano scale range.

However, in the case of Padmanabhan and Sirisha (2014) research, it was reported that they formed nano carbon cast iron using stir casting technique. The composite was produced by adding the nano carbon into the grey cast iron melt. In order to prevent the nano carbon reinforcements from agglomeration and oxidation, sonication and copper coating of the carbon was carried out prior to addition into the melt. Aside solving the agglomeration challenge of the filler, the sonication of the reinforcement dissolution in the iron melt and preserve its form and structure so as to achieve reinforced cast iron of good toughness and strength. It also ensures good chances of even distribution in the cast iron matrix. The cast iron reinforced with multi-walled nano-sized carbon (MWCNTs) tubes, a nanocomposite material with superior strength and stiffness are innovative materials, which can widely be used for high impact applications such as automotive, military, aerospace and machining.

The studies carried out by Zykova et al. (2018) assessed the impact of TiO2 + ZrO2 + NaAlF6 mixture in an ultrafine form on the structural mechanism and features; strengthening effect and mechanical properties of ductile iron. In the research, the impact of the modifying mixtures of TiO2, ZrO2 and NaAlF6 used in ultrafine particles of 0.07 μm to 14 μm with average of -0.93 μm on the microstructure and mechanical properties of ductile iron was analysed. The modifier mixture (MM) introduced is able to promote significant change in the crystallization development of the alloy in a way that ensured refinement of the structural constituents. This subsequently resulted to an increase it the wear resistance but with a compromise in its tensile strength, while the properties such as hardness, plasticity and density of the alloy remain unaffected. Furthermore, Kaleicheva and Mishev (2018) studied the influence of nanosized additives of cubic boron nitride cBN used in making MMC with ductile iron as matrix. The additive was used to modify the structural feature of the alloy. This was achieved by prior coating of the cBNnano-sized particles with electroless nickel method before the addition into the melt. The coating assist to enhance the particles wetting in the melt and also ensure even distribution in the casting volume.

3 Influence of the Nanostructural Processing on the Mechanical Properties of Austempered Ductile Irons

From the foregoing, it could be established that the common processing of nanostructure austempered ductile iron are majorly two, which are through the use of combined austempering and deformation at elevated temperature to achieve an ultra-fine nanostructured ADI as well as the treatment with modifier mixtures or additives.

The combination of austempering treatment and plastic deformation influenced the mechanical properties of the austempered ductile iron. The yield and tensile strength improved by 39% and 22% respectively for the single step austempering process after plastically deformed at 5 mm/min. the two step austempered samples had higher strength (1304 MPa) than the single step austempered samples (1244 MPa). This was due to the finer nanostructured bainitic ferrite and austenitic structure in the samples after austempering (Panneerselvam and Putatunda, 2018).

This indicate that the special thermal processes result in significant refinement of the ausferritic ductile iron matrix microstructure to nano-scale size which eventually contributed to the improvement of its properties. Also, the presence of austenite in ultrafine grain cast iron matrix structure can be a critical factor in obtaining the satisfactory properties (Myszka et al., 2014). In the same vein, the modification of the microstructure due to the addition of nanosized additives of cBN and austempering at lower bainite temperature was equally proven to improve the hardness (HV10) and impact strength MJ/m2 by 14% in austempered ductile irons with nanosizedcBN additives and it also possess higher wear resistance (5-34%) when compared with the sample without nanoadditive. (Kaleicheva and Mishev, 2018)

4 Research Areas for Future Works

Successes on the development and applications of varieties of nanostructured ferrous alloys have been largely circulated in the literatures but that of nanostructured ADI remain sparse. More importantly, various researches available or reported so far have been on the ductile iron and austempered ductile irons. There seems to be little or no report on nanostructured ductile iron especially alloyed with some vital element such as Al, Cr and Mo which are capable of impacting differently on the material leading to diverse improvement on the
properties of the alloy. In addition, application of various heat treatment processes would as well improve the microstructure and chemical and mechanical properties thereby expanding the areas of application of the alloy. The nanocomposites with ceramic as reinforcement of the ductile iron alloyed with Al, Cr or Mo along with heat treatment processes constitute research areas that are yet to be accessed.

5 CONCLUSION
Related researches on nanostructured ductile and austempered ductile iron have been reviewed and research gaps identified. It could therefore be concluded that there is need to exploit the versatile advantages in various alloying element to produced nanostructured alloyed-ductile iron, characterise the nanostructure and determine the mechanical properties of the alloy, hence, increase in the database of materials for engineering applications

REFERENCES