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Mini Review
Carbidic Austempered Ductile Iron an Off-spring of Cast Iron for Production of Agricultural Implement: A Review

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Abstract
This study reported the researches done so far on cast irons and that of its wear resistant candidate (cast iron) and the need to improve on the impact toughness of this wear resistant candidate. Carbidic Austempered Ductile Iron (CADI) has gained tremendous recognition in Agricultural sector because of its good wear resistance, which makes it a useful material for wear application. It has been used for ploughshare part production, cultivator, bucket conveyor, crusher plates since its production some few years ago. A review on the researches on carbidic austempered ductile iron (CADI) as an offspring of austempered ductile iron (ADI) of cast iron family showed its relevance in the production of soil opener (tiller, cultivator, ploughshare, crusher plates) is principally due to its good wear resistance properties with relatively fair impact toughness. The CADI is a novel type of austempered ductile iron consisting carbides in the ausferritic matrix. This is produced by austempering carbidic ductile iron at different temperatures and times. The CADI is a viable replacement for forged steel and has been used vastly in mining, automobile and agricultural machinery sectors. Meanwhile, its relatively low toughness, caused by coarse carbides in the matrix of the cast iron, has a destructive influence on the abrasion resistance of CADI and so limits its applications. Producing cast iron with a good balance of abrasion resistance and toughness through micro-structure modification is a welcome idea for the development of ploughshare parts for agricultural application.

Key words: Carbidic austempered ductile iron, wear, machineries, cast iron, mechanical properties

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INTRODUCTION

The rapid progress of technology requires improvement in mechanical and operational properties of the main casting alloy-cast iron[1]. The word cast irons simply stands for family of ferrous alloys with a large range of mechanical properties[2,3]. Cast iron is mainly an alloy of iron, carbon and silicon with other trace elements included. Most cast irons have chemical composition ranging from 2.0 -4.0 wt.% carbon, 1-3 wt.% silicon and the remainder being iron and other trace elements[4]. Depending on the morphology of the graphite structure obtained in cast iron, different types of cast iron are produced, these are grey cast iron, white cast iron, ductile cast iron, malleable cast iron and carbidic ductile iron. Grey cast iron is a type of cast iron which has its graphite in the form of large flakes embedded in the austenite matrix, its fracture mostly occurs along the graphite flakes and renders the fracture surface grey, hence it is called grey cast iron[5]. This large, faceted flakes reduce its ductility dramatically but gives the material some qualities such as high damping ability and impact resistance. Shrinkage and porosity in this material are minimized, sometimes avoided during solidification by the expansion of graphite when austenite shrinks[6]. The big graphite flakes assist in dampen noise and they also increase thermal conductivity. Grey cast iron do display low tensile strength and shock resistance compare to steel, Meanwhile, its compressive strength is highly comparable to low and medium carbon steel[7]. White cast iron does have its equilibrium reaction suppressed, so encouraging formation of meta stable carbides instead of graphite. This meta stable eutectic structure is called ledeburite. This micro-structure is very hard and brittle and has good strength[8]. White irons are known for excellent wear resistance properties but difficult to machine. As a result of the fact that graphite is the stable form of carbon in cast iron, the white irons can be subjected to heat treatment operation for several days during which the carbides dissolve and transformed to malleable cast iron[9]. Typical micro-structure of ductile cast iron has its graphite formed in the shape of nodules or spheroids, this is why it is known as nodular iron or spheroidal graphite iron. This ductile iron was developed from grey cast iron by addition of magnesium into liquid cast iron to convert the graphite into nodules. The nodules give the cast iron improved properties in terms of ductility, strength and toughness over other cast irons[10-12]. Carbidic Austempered Ductile Iron is a recent, special type of austempered ductile iron (ADI) containing carbides in its ausferritic matrix. The CADI is a type of cast iron that can be produced by subjecting carbidic ductile iron to austempering mode of heat treatment processes at different temperatures and time. It is an economical substitute for forged steel and has been used mostly in automobile, mining, railway and agricultural machinery sectors. This is due to its superior properties over other materials. It can also be used in applications like piston rings in internal combustion (IC) engines, dies, gears, navy ship boards and rollers[13]. The CADI has some quantities of carbides that are distributed in its ausferrite matrix, which gives good hardness and enhanced abrasion resistance compared to ADI. The CADI has been termed as a novel wear-resistant material and has attracted intensive attention in recent years[14]. Its potential areas of applications are agricultural, construction, mining components, railroad and defense industries, which requires some properties of which abrasive wear resistance is the prominent[15]. The relatively low toughness of this wear resistant candidate material is caused by its coarse carbides in its matrix, which has an adverse effect on impact toughness of CADI and thus limits its applications. Getting an optimum balance between abrasion resistance and impact toughness through micro-structure modification is highly demanded for the development of this CADI for wider industrial application[16].

Previous studies[17] revealed that addition of appropriate amount of antimony into austempered ductile iron is of advantage to its graphite morphology and its mechanical properties. This is because antimony can react with rare earth elements (REE) to form high melting point compounds which act as nucleus of globular graphite. Also, the concentration of antimony around graphite can inhibit the graphite deterioration. At present, antimony addition is usually used to improve graphite morphology in heavy section ductile iron but the appropriate amount of antimony addition to ductile cast iron is still controversial and a clear understanding on chunky graphite appearance and a safe metal preparation method to avoid chunky graphite are not yet available judging from available reports[18-20]. The current work reinforced the importance of carbidic austempered ductile iron as a viable economic substitute for had field steel in the production of agricultural implements.

AUSTEMPERED DUCTILE IRON PRODUCTION

Austempering is an isothermal heat treatment operation usually used on ferrous materials to improve their strength and toughness. Austempering of ductile cast iron consists of subjecting the cast iron to austenitization in the temperature range of 840-950°C for sufficient time in order to enrich the parent austenite with carbon, followed by rapid quenching of the cast iron to a temperature range of 230-400°C where the austenite transforms isothermally into ausferrite[21]. The typical micro-structure in ADI is known as ausferrite, which is a mixture of high carbon austenite and ferrite plates that enhances the mechanical properties of the alloy.

Austempering heat treatment of ductile irons is a 2-stage reactions[22].

First stage is represented in this equation:

$$\gamma \text{ ----------- } \alpha+\gamma hc$$

Second stage is represented in this equation:

$$\gamma hc \ \ldots\ldots\ldots \ \alpha+\text{carbide}$$

where, α is ferrite, γ is parent austenite and γhc is high carbon austenite.

In the first stage of the austempering reaction, the parent austenite breaks into high carbon austenite and ferrite. So, strength and toughness of the alloy increase to maximum values. The high carbon austenite does not transform into martensite during the final quenching and is stable at ambient temperature due to its low martensite (Ms) start temperature, long holding at this austempering temperature can trigger second stage of austempering reaction to begin and high carbon austenite will get decomposed into ferrite and carbide. This reaction is undesirable since it causes embrittlement of structure and greatly decrease the obtained toughness without considerable change in strength. The period between the end of the first stage and the beginning of the second stage is known as "process window" over which the mechanical properties of ADI is optimum[22]. Addition of alloying elements to ADI is so important because they helped in increasing austemperability and harden ability of ductile irons[23] but they can change the first and second stages of austempering reaction kinetics and process window. These alloying elements segregate during solidification in different ways and affect the speed of austempering reactions in different regions of the micro-structure. Their effects on carbon solution in parent austenite are different. They can change the first stage reaction driving force greatly or gently. As carbides form during the second stage reaction, carbide forming elements cause the rapid start of the second stage reaction. Second effect of alloying element is in their segregation tendency, this segregation takes place during eutectic solidification of initial ductile iron and leads to uneven distribution of the elements. Carbide forming elements are found on the left side of iron in the elements periodic table, examples are molybdenum, manganese and chromium. These elements segregate far away from graphite nodules in eutectic cells boundaries or intercellular regions (positive segregation) during solidification. Right hand side of iron is nickel, copper and silicon which segregate near graphite nodules in eutectic cells (reverse segregation) during solidification. Space between graphite nodules is normally divided into three regions[24]. First to freeze region 1 is eutectic cells near graphite nodules. Nickel, copper and silicon cause reverse segregation in this region. Region II is nearly constant in composition. Last to freeze region III is eutectic cells boundaries far from graphite nodules. Molybdenum, manganese and chromium with positive segregation segregate in this region. Additions of some elements affect the segregation of others. For example, silicon and nickel offsets the segregation of manganese, molybdenum and so improves the mechanical properties. Increasing manganese increases the chromium segregation intensity[25]. Segregation profile of alloying elements decreases with increasing austenitising time and temperature. Addition of nickel to cast iron leads to increase in impact energy without any major change in their strength. While antimony promotes formation of pearlite phase in ductile irons, thereby increases its hardness and strength, it can increase graphite nodule count and improve graphite nodularity[17].

Production of carbidic austempered ductile iron: One of the techniques commonly used to obtain a micro-structure with as- cast carbides in ductile iron is to reduce the quantity of its graphitizing elements, in particular silicon, to assist in promoting the precipitation of ledeburitic carbides during solidification as a result of the closer interval between the stable and meta stable diagrams[26].

The second option is achieved through high undercooling, which is promoted by the use of a chill in the mould. A third option is to alloy the melt with carbide stabilizing elements, such as chromium, molybdenum or titanium[26], these elements can strongly reduce the interval between stable and meta stable eutectic temperatures, hence promoting total or partial solidification according to the meta stable diagram[27]. It should be taken into account that an undercooling also affects the size and count of the solidification units and therefore, the micro-segregation. The lower the cooling rate, the greater the micro-segregation effect, increasing the probability for carbide precipitation at the last to freeze zones and therefore, the formation of alloyed carbides. The size and composition of carbides may vary, from typical unalloyed ledeburitic to thin plate shaped high-alloyed carbides, depending on the chemical composition and cooling rate[28]. It has been reported that ledeburitic carbides produced by controlling the cooling rate or the silicon level (non-alloyed carbides) have a high tendency to dissolve during the austenitizing stage and are less stable than alloyed carbides[29].

New cast iron of unique wear resistance: The CADI is a category of austempered ductile iron that has carbides in a typical ausferritic matrix.

The presence of carbides promotes an increase in the abrasion wear resistance, at the expense of the impact toughness. Hence, the task related to the development of this material is to be able to control the micro-structure in order to obtain the optimum balance between abrasion resistance and toughness.

Carbidic austempered ductile iron a substitute for manganese steel: The compelling need to develop a ferrous material that has good wear resistance, good strength, good impact toughness and good corrosion resistance which can be produced at a low cost and be a good substitute for high chromium steel and manganese steel that can be used in the production of agricultural implements (rippers, teeth, plow point wear plates and harvester) and mining equipment (digger teeth, cutters, mill hammers) has provoked tremendous researches on ductile cast irons. One of such is the discovering of superior mechanical properties exhibited by ductile irons with pearlite-martensite matrices as reported by Rashidi and Moshrefi-Torbati[30]. The influence of alloying elements Ni, Mo and Cu on the properties of austempered ductile iron produced by inter-critical annealing with 1% nickel, 0.25% molybdenum was reported to have good ductility[31]. Wear resistance of austempered ductile iron with dual matrix structures was found to decrease with the increase in pro-eutectoid ferrite and decrease in ausferrite content this study was investigated by Sahin *et al.*[32]. The micro-structure and abrasive wear resistance of CADI and its applications in automobile and agricultural sectors was reported[33,26]. The effect of high cooling rate, using copper chill and the addition of carbide stabilizing elements were reported[34], it was discovered that the carbides were stable during the austenitising stage of the austempering and the amount of dissolved carbide was very low. It has been shown that mechanical processing of austempered ductile iron can act as a control value for the stage 1 of austempering reaction[35]. Development of martempered ductile iron by step-quenching method using warm water as quenchant was carried out[36], in their study, various structures of martensite, bainite and fine pearlite at transformation temperatures below 250, 275 and 375°C and above 375-425°C, respectively were obtained in the ductile iron. Development and wear analysis of carbidic austempered ductile iron was investigated[37], they came out with a relationship between chromium content in the alloy, austempering parameters and the mechanical properties of CADI. Development of wear resistant carbidic austempered ductile iron that has wear resistance of about 100% over that of ADI as a result of the presence of carbides in the micro-structure was reported[34]. Ploughing conditions is said to be the cause of excessive wear of agricultural machine parts, the principal cause of this high degree of wear in plough share is the hard particles in the soil, in particular SiO_2 in quartz sand, whose hardness can be as high as 900 to 1,280 HV[38]. Austempered ductile iron is a type of cast iron that has attracted increasing attention from academic and industrial sectors owing to its good combination of tensile strength and ductility. Ductile iron components are said to display a great problem during manufacturing[39]. Many researchers have attempted to analyze and optimize single and multi-performance responses of foundry process using Taguchi methodology and came up with an optimum mechanical property. Among them is multiple progressive tools[40] and utility concept[41]. Effect of boron on the micro-structure and mechanical properties of carbidic austempered ductile iron was carried out by Peng *et al.*[42], it was reported that microscopic amounts of boron improved the harden ability of CADI but higher boron content reduced the harden ability and toughness of CADI. The effects of vanadium and austempering temperature on micro-structure and properties of carbidic austempered ductile was reported by Han *et al.*[43]. From their work, they reported that the as-cast micro-structure gave an enhanced carbides with a well distributed nodular graphite, pearlite and carbides phases. The hardness profile and wear resistance value was observed to have increased within the limit of vanadium concentration. The influence of molybdenum on micro-structure, wear resistance and corrosion resistance of carbidic austempered ductile iron were studied[43], it was discovered that as molybdenum content increased, the quantity of retained austenite and carbides increases, the acicular ferrite becomes finer and the wear resistance and corrosion resistance increased. Similarly, Zhe *et al.*[17] reported on the effects of cooling rate and antimony addition on graphite micro-structure and mechanical properties of ductile iron. They concluded that the graphite morphology and the tensile strength were improved by antimony addition.

LIMITATION IN THE USAGE OF CARBIDIC AUSTEMPERED DUCTILE IRON (CADI) FOR INDUSTRIAL APPLICATIONS

The seemly low impact toughness occasioned by coarse carbides in carbidic austempered ductile iron (CADI) has a destructive effect on the abrasion resistance of CADI, this causes limitation on the are as of applications CADI. In order to encourage industrial production and widen the application range of CADI, efforts are being made to improve its performance. How to control the morphology and size of the carbides in carbidic austempered ductile iron is yet to be fully resolved by researchers. A study conducted by Zhou *et al.*[44] on the carbide refinement mechanisms of carbidic austempered ductile iron with ceria additive in Fe-24 wt.% Cr, 4.1 wt.% C hard-facing alloys. From their findings, they opined that Ce_2O_2S precipitated prior to M_7C_3 carbides, which acts as a heterogeneous nucleus for the formation of M_7C_3 carbides. It refined the M_7C_3 carbide and improved the alloys' wear resistance. Previous studies showed that the morphology of primary carbides in high chromium cast irons changed from long lath to a granular shape with the addition of ceria nano-particles[45]. This has contributed to enhancement of impact toughness of the materials. In a bid to reduce the formation of chunky graphite, chills and anti-spheroidizing elements such as antimony or bismuth is usually used as alloying element in ductile cast iron production, which sometimes lowers the degenerating level of graphite. Previous studies[15] revealed that appropriate addition of antimony to austempered ductile iron is helpful to the graphite morphology and mechanical properties of ductile iron because antimony reacts with rare earth elements (REE) to form high melting point compounds which can act as nucleus for globular graphite formation. Moreover, the concentration of antimony around graphite can impede the graphite deterioration. At present, appropriate content of antimony addition in ductile iron is still controversial[18]. The CADI has been considered to bean economical substitute forged steel and has been used vastly in automobile, mining, railway and agricultural machinery sectors[34,16]. As a result of the characteristic low impact toughness of CADI, caused by coarse carbides in its matrix, this has limited its applications. An optimum balance between abrasion resistance and toughness through micro-structure modification of CADI is being demanded for the development of ploughshare parts for agricultural purpose.

CONCLUSION

In this study, a carbidic austempered ductile iron an off-spring of cast iron and its targeted application was reported. Also, the limitation of this material in terms of low impact toughness, though with good wear resistance was also addressed. Researchers have explore the use of alloy additions to improve the impact toughness of this material. However, incremental research work on the improvement of the impact toughness without compromising its wear resistance is a novel outcome for future consideration.

SIGNIFICANCE STATEMENT

This study discovered the importance of carbidic austempered ductile iron as a cost-effective replacement for had field steel in the production of agricultural implement. Hence, the study will help researchers to uncover the critical areas of improvement of CADI and relevant future work that can be explore on CADI.

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