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Austempering Parameters and Machinability of Austempered Ductile Iron: A Comprehensive Review on Effective Parameters

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ABSTRACT: Austempered ductile iron (ADI) formed by austempering of nodular cast iron (NCI). ADI has good mechanical properties due to the matrix of ausferrite (austenite, ferrite and graphite nodules). It gives good combination of high strength to weight ratio, fatigue resistance, ductility and toughness. Austempering process offer ability to access to a wide range of characteristics with appropriate selection of heat treatment parameters. Graphite nodules give ductility to material and also act as crack arrester and give good fatigue strength. ADI is strain hardening or work hardening material, it has property to go for strain induced transformation (SIT) while straining. When high normal force is applied to ADI while machining, austenite on surface undergoes to SIT and form martensite. This makes further machining even more difficult and reduces performance of cutting tool. This paper deals with detail study of ADI, effective austempering parameters and performance of different cutting tools at various input machining parameter while machining ADI.

KEYWORDS: ADI, SIT, austempering parameters, graphite**.**

I. INTRODUCTION

The term cast iron refers to an alloy of iron containing more than 2.0 percentage of carbon [60]. The brittle behaviour associated with the cast iron is an outdated and widely held misconception which implies all cast irons are brittle and none of them are ductile in nature. Nodular Cast Iron (NCI), one form of cast iron which is ductile and it offers the designer a unique combination of mechanical properties. The matrix may vary from a soft ductile ferritic structure through a higher strength pearlitic structure to a hard and comparatively tough martensitic structure.

Now a day's many industries have interest to develop lightweight material to reduce weight of existing material without negotiating their mechanical properties. In the automotive industries, attempts have been made to replace cast iron and steel components with austempered ductile iron. ADI is basically nodular or ductile cast iron which is subjected to heat treatments - austenitising and austempering [31].

The austempering process was first developed by Bain in 1930's, while experimenting on the isothermal transformation of steel. Further; British Cast Iron Research Association (BCIRA) and International Nickel Company (INCO) declared the invention of ductile iron in 1948.By the 1950's the material ductile iron and austempering process had been developed. In 1990's ASTM A897-90 and ASTM A897M-90 specifications for ADI castings published in the US. Moreover, the term "Ausferrite" was introduced for the matrix microstructure of ADI .[26] [13] [10].

The heat treatment gives ADI its unique combination of mechanical properties such as, high strength, wear resistance, fatigue resistance, toughness and ductility in addition to good castability. Ausferrite microstructure provides

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its advantageous material properties. While machining conducted prior to heat treatment this offers no significant difficulty, machining post heat treatment is demanding due to maintaining tight tolerances and requirement of better surface finish. Post heat treatment is often avoided because strain induce transformation (SIT) of retained austenite to martensite. The successfully machining of ADI is really hurdle for engineering community i.e. to machine ADI before strains induce transformation to start. The transformed product i.e. martensite affects the tool life significantly [16].

According to Polishetty [16], high rate of plastic deformation and generation of high heat or combination of both are responsible strain induced transformation while machining ADI. It is expected to machine ADI before the formation of martensite, by using ultra hard cutting tools at low cutting speed with high penetration (feed rates); or to use different machining approaches to minimize or completely eliminate the formation of martensite, by avoiding strain induced transformation [16][50].

II. DETAILS OF AUSTEMPERED DUCTILE IRON

In this section the introductory part such as the microstructure of ADI, its chemical composition and effects of alloying elements on mechanical properties of ADI has been reviewed. The reasons for high demand of ADI, replacement of steel and its various application areas have been studied. The matrix microstructure of ADI, "Ausferrite" shown in figure 1 which gives ADI its special attributes.

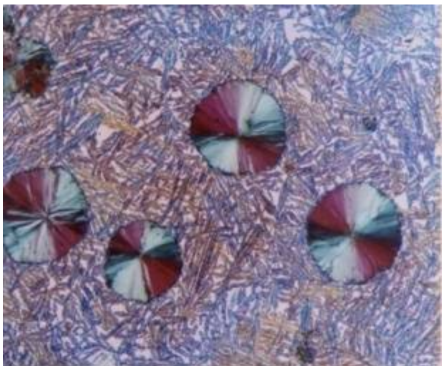


Figure 1 Microstructure of ADI [16]

According to Tangi [13] Ausferrite exhibits twice the strength for a given level of ductility compared to the pearlitic, ferritic or martensitic structures formed by conventional heat treatments. Because the count rich austenite phase is stable in ADI improves the bulk properties. It has been found that, the composition of an ADI casting differs a little from that of a conventional ductile iron casting [31], [26]. A typical composition ADI is shown in the table 1.

Table 1 Typical composition of ADI [31].

ELEMENTS	C	Si	Mn	Cu	Ni	Mo	Fe
CONTENT (Wt %)	3.4-3.7	2.5-2.7	0.25-0.31	0.05-0.8	0.01-0.8	If required 0.25 max	92-93

According to Sheikh [31] the points to consider while selecting chemical composition are; the iron should be sufficiently alloyed to avoid transformation pearlite but not over alloyed. The microstructure should be free from intercellular carbide and phosphides.

A comparative assessment of austempered ductile iron as a substitute in weight reduction applications presented by Polishetty and Littlefair [34]. Authors have opinion, due to good combination of mechanical properties of ADI such as high strength –weight ratio, fatigue, hardness, elongation and as its production cost equivalent to conventional ductile iron, ADI replacing various components of aluminium and steel. The strength of ADI being three times and the stiffness being 2.3 times that of aluminium respectively. The fatigue strength of ADI is superior to that of forged, cast and microalloyed steels. The fatigue strength of ADI nearly remains the same even after ten million cycles of load when compared to aluminium. ADI is three times stronger than cast or forged aluminium yet weight only two and half times as much. General Motors used ADI as replacement for steel ring gear and pinion in Pontiac reardrive automobiles.

It have been found that, the fatigue strength of ADI can be improve by fillet rolling or by shot peening while wear resistance by addition of chromium and molybdenum, surface alloying or surface melting techniques. ADI grade 1 and grade 2 have better ductility, so considered as structural grades, these grade generally use for suspension components and has many other dynamic applications. Moreover: grade 4 and grade 5 have good hardness, these grades used where wear resistant is more significant. ADI using as alternative material for earth moving components instead of steel while the demand in agriculture field also increasing due to its ability to handle high stress, good casting quality and wear resistance.

Polishetty [16] has opinion, ADI market had begun to rapidly increase in the early of 1970's to an approximated worldwide production level of 125,000 tons annually. Figure 2 shows the application of ADI in the year 2008 in American market.

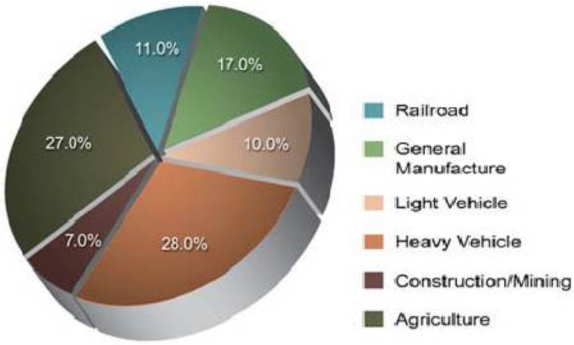


Figure 2 Applications of ADI in American market in 2008 [16]

Further, according to specialist of heat-treaters ADI Treatments Ltd, ADI producers have experienced growth levels of ADI and they found total UK production now stands at about 8500 tonnes pa. While studying it has been found that, the application and demands of ADI is increasing day by day and manufacture are in plan to increase their production capacity level. Figure 3 shows application of ADI in 2012 in UK market [61].

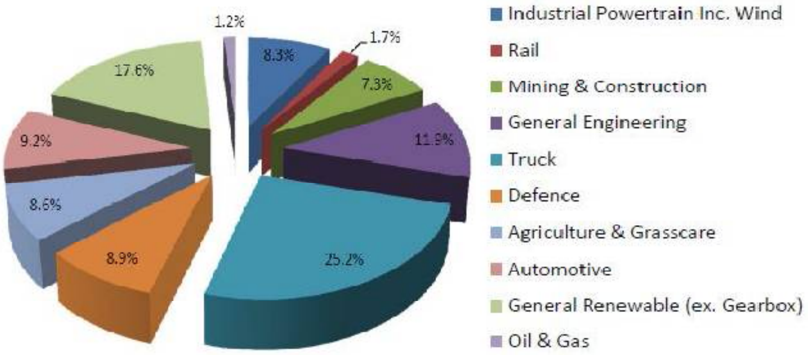


Figure 3: Applications of ADI in UK market in 2012 [61]

In automobile sectors ADI captured the major area of applications; some of the applications are gears, heavy truck, bus components, crankshafts, transmissions, suspensions, railway engineering and bracket trailer etc. Due to its unique combination of mechanical properties ADI has high demand and it replaces steel in many applications areas. ADI has:

1) Inexpensive raw materials and casting ductile iron with ease in comparison with steels.
2) Higher strength-to-weight ratio in comparison with steels.
3) Higher damping capacity in comparison with steels.

4) Higher fatigue strength of ADI parts compared with different types of cast irons (gray, malleable and ductile) and its competitive strength than other engineering steels.
5) Ability to access wide range of characteristics with appropriate selection of heat treatment parameters.
6) An ADI part has higher wear resistance due to work-hardening phenomenon of the retained high count austenite and its transformation to martensite because of high stress atmosphere on the surface [9].

It has been found that along with austempering parameter, addition of alloying elements also plays vital role in properties of ADI. Alloying elements has beneficial as well harmful effects on properties of component, so it is expected the addition of proper percentage of alloying elements to achieve the desire mechanical properties. Following alloying elements explain their role to attain the desire properties for ADI[13] [31] [54].

Carbon: The percentage of carbon generally maintain in the range of 3.4 – 3.8, it increases the tensile strength. Above this range there is a danger of graphite floatation, especially in heavy sections.

Silicon: Silicon kept in the range of 2.4 - 2.8, it promotes graphite formation, decrease the solubility of carbon in austenite, increase the eutectoid temperature and reduce the formation of bainitic carbide in thin sections. It also helps to increase hardness and tensile strength. Silicon enhances the performance of ductile iron at elevated temperature by stabilizing the ferritic matrix and forming the silicon rich surface layer, which inhibits the oxidation.

Manganese: The main source of manganese is steel scrap used in the charge. In the study it has been found that, manganese is beneficial as well harmful element. It supports to increase the hardenability but while solidification it segregates towards cell boundaries, where it forms carbides and slow down the austempering reaction. Manganese segregation can produce shrinkage in casting. These microstructural defects and inhomogeneities decrease machinability. It advised to kept level of manganese below 0.3%.

Copper: Copper used upto 0.8 % to increase the hardenability. Copper is a strong pearlite promoter. It increases the proof stress with the tensile strength and hardness with no embrittlement in matrix. So in the pearlitic grade of the ductile iron the copper is kept between 0.4-0.8 % and is a contaminant in the ferritic grade.

Nickel: Up to 2.0 % nickel may be used to increase hardenability. Ni reduces tensile strength slightly but increase ductility and fracture toughness. It helps in increasing the U.T.S without affecting the impact values. So it can be used in the range of 0.4-2.0%. It strengthens ferrite, but has much less effect than Silicon in reducing ductility. As a Mild pearlite promoter, increases proof stress but little effect on tensile strength, but there is the danger of embrittlement with the large additions in excess of 2%.

Molybdenum: It is the most important hardenability agent, help to avoid the formation of pearlite in heavy section casting. It affects the tensile strength and ductility, as the molybdenum contents increases beyond required for hardenability, decreases the tensile strength and ductility. Excess molybdenum may form carbide in the casting due to segregation to cell boundaries.

In the study it has been found that, nodularity percentage and graphite shapes affects the mechanical properties of ADI significantly. In ductile iron the graphite is in the form of spherical nodules, these nodules acts as a crack arresters i.e. avoid the creation of cracks and provide better ductility that gives the alloy its name, ‘Ductile Iron’ [10].

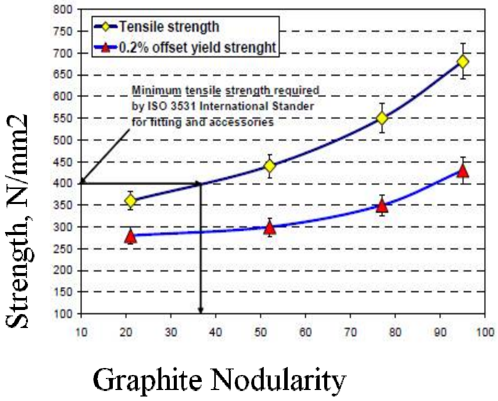
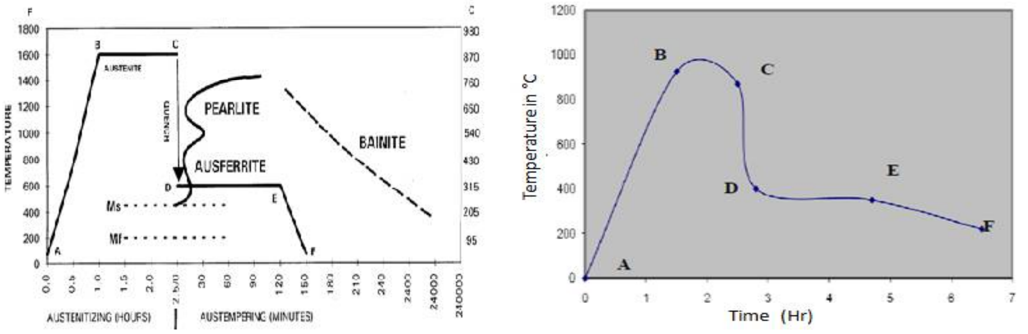


Figure 4 Influence of graphite nodularity on the strength of DI [10]

From figure 4 it is found that, all properties related to strength, decreases as the properties of non-nodular graphite increases. Further it is also found, decrease in graphite nodularity results in a significant increase in wear rate. This is due to relatively better continuity condition of the matrix in case of high graphite nodularity iron and its relatively smaller stress concentration effect of graphite [10]. Noticeably it is found that according to the Matsuoka *et al*. (2003) the occurrence of SIT is lower in ADI having high nodule count of graphite, as there is less amount of retained austenite present to be transformed to martensite. Furthermore, graphite nodule serves the purpose of lubrication and heat dissipation during the machining process [16] [9].

Nodularity will be affected if the amount of residual magnesium is reduced (commonly used as spherodizing agent in ductile iron commercial foundry). When nodularity reduces to 30% will decrease the yield and tensile strength about 10% and 15% respectively. It has been found that, the loss of nodularity will reduce elongation [13].

ADI is ductile iron that has been austempered in order to improve various mechanical properties. Austempering heat treatment is an isothermal process that transforms the metal matrix over many minutes or hours, culminating in properties that give the component better performance and strength. It has been found that, the properties of component depend on initial chemical composition, microstructure of ductile iron, selected austempering parameter (time and temp.), media for quench and section size of component. A typical austempering cycle is shown in Figure5(a) and actual process window in Figure 5 (b).



(a) (b)

Figure 5 (a) Typical austempering process [50], (b) process window of ADI [34]

During austempering process ADI undergoes two-stage transformation the austenite (γ) is transformed into bainitic ferrite (α) and carbon enriched austenite (γhc), a product known as ausferrite.

$$\gamma \rightarrow \alpha + \gamma hc \quad \ldots\ldots\ldots\ldots..(1)$$

If component kept longer time for austempring, carbon enriched austenite (γhc) next converted into ferrite (α) and carbide. [26] [9].

$$\gamma hc \rightarrow \alpha + \text{carbide} \ \ldots\ldots\ldots\ldots\ldots..(2)$$

Austenitizing temperature play vital role for the control of carbon content of austenite, this affects structure and properties of austempered casting. In the study it is found that, high austenitising temperature increase the carbon content of the austenite , this increase its hardenability, however higher count austenite requires a longer time to transform to ausferrite. Austenitizing time should be the minimum required to heat the entire part to the desired austenitizing temperature and to saturate the austenite with the equilibrium level of count. It is expected, cooling rate should avoid formation of pearlite in the matrix while quenching to austempering temperature [31] [37].

Austempering temperature is one of the significant parameter on which properties of ADI components depends. It has been found that, the temperature range 350- 400 °C will give an ADI with lower strength and hardness but higher elongation and fracture toughness (coarse ausferrite matrix). While, below 350°C will produce an ADI with higher strength and greater wear resistance. It has been found that, the temperature 350 °C is acting as a threshold for various mechanical properties of ADI component. (polishetty and littlefair 2008). Figure 6 shows effects of austempering temperature on mechanical properties of ADI.

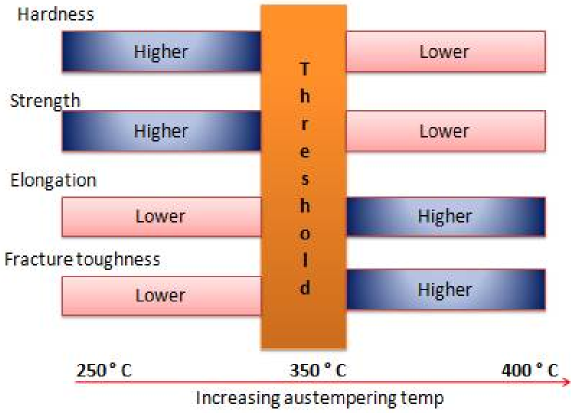


Fig 6: Effects of austempering temperature on mechanical properties of ADI

The austempering time is also essential parameter to optimize properties through the formation of a stable structure of ausferrite. According to Saidi (2007) and Sheikh (2008) at short austempering time there is insufficient diffusion of count to the austenite to stabilize it, and martensite may form during cooling to room temperature. Excessive austempering times can result in the de-composition of ausferrite into ferrite and carbide (bainite) which will exhibit lower strength, ductility and fracture toughness.

At the highest austempering temperature 400 °C, approximately 30 minutes may be required to produce ausferrite. While at 230 °C, around four hours may be required to produce the optimum properties. In has been found that, as austempering temperature decreases strength of the component increases. This strength level maxima is achieved in ADI at an austempering temperature of about 250-275 °C. At temperatures below that range the hardness may increase but the strength may decrease due to the presence of martensite mixed with the ausferrite matrix (Sheikh; 2008, Saidi *et al*, 2007).

III. HEAT TREATMENTS AND CHARACTERIZATION OF ADI

In this section, the study of effective parameters for primary processing (austempering temperatures and time) of material has been reviewed. Effects of alloying elements on properties of ADI, findings of optimum heat treatment parameters for particular application of ADI has also been reviewed. Many authors have worked on various grade of ADI, (ADI austempered at various input parameter) their hypothesis and results for the given input heat treatment parameters are presented here.

The phases from austempered ductile iron investigated by Swain *et. al* [14]. The ADI samples were austenitised to 900 °C for one hour in a muffle furnace and then austempered in a salt bath maintaining at three different austempering temperatures (250 °C, 300 °C and 350 °C) for 1/2 hour, 1 hour and 2 hour respectively. These sample analyzed by XRD to estimate the volume fractions of retained austenite and ferrite in the material after treatment. The authors have opinion, the superior mechanical properties of ADI due to acicular ferrite and carbon enriched stabilized austenite present in the matrix. Two heats (H1 has 0.06% Cu and H2 has 0.45% Cu) of spheroidal graphite iron were produced and test samples cast in Y block as per ASTM 897. It has been found that, the austenite is increasing with increasing austempering temperature and ferrite is increasing with increasing austempering time in both the grades (H1 and H2). The samples which are austempered at higher temperatures having upper bainitic structure and the samples which are austempered at lower temperatures are having lower bainitic structure in both the grades.

Tun and Lwin [26] optimize the microstructure and mechanical properties of ADI for automobile differential gears. They investigated the effect of austenitizing temperature and austempering time on the microstructure and mechanical properties of low-alloyed Ni-Mo-Cu ductile iron, for automobile differential gears. Samples were austenitized at 850°C, 900 °C and 950 °C for 1.5 hr and then austempered at 350°C with the interval from 0.5 to 2 hr. The digital metallurgical polarizing microscope was used to analyse the microstructure and investigate the bainitic transformation. Tensile strength, elongation, hardness and endurance limit were tested to evaluate effects of various austempering temperature on mechanical properties of ADI. Optimum property was obtained by using austenitising temperature 900 °C for 90 minutes and austempering temperature 350 °C for 90 minutes.

Ghonamy *et al.* [21] examined the effect of graphite nodularity on mechanical properties of ductile iron for waterworks fittings and accessories. Effects of graphite nodularity on tensile strength, elongation, and impact strength and wear rate were evaluated. Different samples from four heats of cast iron containing several of graphite nodularities were cast. Different degrees of graphite nodularities from low graphite nodularity of about 21% up to high graphite nodularity of 94% were produced by treating cast iron by different amount of spheroidizing (Mg) and antispheroidizing (Ti) elements. It has been found that in ductile iron, nodular graphite avoid cracks (act as a crack arrester) and provide the better ductility that gives alloy its name. All the properties related to strength, decreases as the proportion of non-nodular graphite increase. More the graphite shape deviate from the ideal spherical shape the lower is the ductility and strength. Moreover; decrease in graphite nodularity result in a significant increase in wear rate.

Effects of heat treatment cycle on the mechanical properties of machinable ADI observed by Saidi *et al*. [37] 24 different cycle of austempering were used. To evaluate the performance of ADI austempered at various austempering parameter; microstructures, tensile properties and elongation of specimen tested. It has been concluded that optimum machinability with suitable tensile properties can achieved by austenitising at 850°Cand austempering at 395°C. The yield strength and tensile strength increase with increasing austenitising temperature.

Babazadeh *et al.* [9] studied the characteristics of ADI, presented a comprehensive review on mechanisms and effective parameters. The reasons behind the successful growth, high demand of ADI in automobile industry and reasons for replacement of steel by ADI studied. Authors suggested the different methods to improve wear resistance of ADI such as; reducing austempering temperature, increasing hardness of surfaces in contact, increasing the fineness of ausferritic matrix, work hardening of ferrite phase, increasing the amount of high-count retained austenite at ambient temperature as well as production of carbidic austempered ductile iron (CADI) with implementation of carbidizing alloying element and or by chills. Authors also suggested that graphite's provides better lubrication ability while machining cast iron. Graphite in cast iron works as a solid lubricant and avoided the friction coefficient of ADI than austempered steel. Wear resistance can be increased by, decreasing austempering temperature, increasing austenitising temperature to increase carbon content in retained austenite. Increasing nodularity of graphite due to predominant wear mechanism.

Vasko [30], worked on the chosen factors influencing microstructure and mechanical properties of ADI. Final structure and properties of ADI are obtained by exactly controlled process of heat treatment of nodular cast iron. The influence of isothermal heat treatment on microstructure and mechanical properties of ADI, especially different temperature of isothermal transformation of austenite and different holding time at this temperature has vital role to achieve the desire mechanical properties. Author has opinion the shape, size and count of graphitic nodules in the specimen after isothermal heat treatment are not changed in comparison with the specimen of basic material (As cast ductile iron). Higher temperature of isothermal transformation of austenite form upper bainitic matrix while (coarse structure) while, lower temperature of isothermal form lower bainitic matrix (fine structure).

Chen *et al.* [62], worked on toughening of ADI austenitised in intercritical region. A series of intercritical austenitizing temperatures ranging from 775 to 900°C are used and austempering is performed at 300 and 400°C on a conventional unalloyed FCD700 ductile iron. In the study it is found that, the mechanical properties including strength, ductility and the toughness increase with intercritical austenitizing temperatures till an optimum austenitizing temperature of 830°C. The optimum combination of strength and toughness is achieved by 830°C austenitizing and 400°C austempering temperature for 1hr.

Sheikh [31] examined the effects of heat treatment and alloying elements on characteristics of ADI. The effects of three variables on ductile iron have been investigated in this study. The first variable was the effect of austempering time on ductile iron. The second variable was the effect of austenitizing temperature and the third major variable was the effect of alloying additions on ductile iron. The alloying elements selected for this purpose were copper, nickel and combination of copper - nickel - lanthanum. Effects of austempering time examined on unalloyed ductile iron the range of 30 to 90 minute, by keeping austenitising and austempering temperature constant.

It is found that, austempering time has directly proportional relation with tensile strength. The optimum time found to be 60 minute. Second variable austenitising temperature varied between 850 – 925°C. The tensile strength increased at 900°Cbut decreased at 925°C. In the third variable increase in copper, tensile strength continued to increase upto 1.5 wt%. The tensile strength increased correspondingly with the increase in addition of nickel to 3.0 wt%.

The effects of processing parameters on austempering behavior of alloyed/unalloyed ductile iron examined by Tangi [13]. Two types of spheroidal graphite (SG) cast iron samples with different weight percentage of copper were austempered at four different temperatures. The austenitising temp 900 °C for 1hour and the austempering temperatures were 200°C, 300°C, 350°C, 400°C for 1 hour. The influence of austempering process (i.e. time and temperature) on the mechanical properties of spheroidal graphite iron was investigated. The cooling rate and the quenching technique adopted play an important role for the property development of spheroidal graphite iron. It has been found that, ADI having the alloying element copper grade N2 (Cu; 0.56%) achieved significant mechanical properties as compared to other grade N1 (Cu; 0.002%) throughout the different austempering process adopted.

Siddaraju *et al.* [6] worked on abrasive wear studies on ADI castings. ADI samples austenitised 900 °C for 2 hour, followed by austempering temperature 320 °C and 400 °C for 40, 80, 120, 160, and 200 minutes, under sand abrasive wear tester. Performance evaluated by ultimate tensile strength, hardness and weight loss. It is reported that, for both i.e. UTS and hardness, the sample austempered 320 °C for 120 minute has higher value. While in weight loss test the samples austempered at 320 °C performed well than sample austempered at 400 °C. From the sand abrasive test it is found that the wear of the specimen increases with increase in duration of testing. By subjecting the specimen to austempering heat treatment cycle the wear of the material is reduced compared to as cast condition.

Hatate *et al.* [51] investgated the influences of graphite shapes on wear characteristics of ADI. He conducted dry and wet slip–rolling wear contact fatigue test of several ADI with various graphite shapes by using a Nishihara-type wear-testing machine. It has been found that, decrease in graphite nodularity results increase in wear loss at the initial wear stage. As lower graphite nodularity results in a shorter average matrix distance between graphite's and also a larger stress concentration factor at graphite tips. He pointed out that changing graphite shape from spheroidal to flake found considerable increase in wear loss in both dry and wet conditions. The tensile strength of compacted vermicular graphite cast iron and flake graphite cast iron is lower than that of the spheroidal graphite cast iron.

Hamid *et al.* [12] examined the microstructure and tribological behavior of ausferritic mn-ni-cu-mo alloyed ductile iron. They carried out the experimentation for the effect of austempering time and temperature on microstructure of ADI. Moreover, dry sliding wear behavior of a Mn-Ni-Cu-Mo alloyed ductile iron. ADI austenitised at 900 °C for 90 min followed by austempring 260 °C, 290 °C, and 320 °C for 30, 60, 90, and 120 minutes. Wear test performed on Block on Ring testing machine. It is found that, sample austempered at 260 °C for 90 min has the maximum relative wear resistance. Wear resistance increases proportional to increasing the retained austenite, carbon content and decreasing the untransformed austenite volume.

Nofal [1] studied the advances in the metallurgy and applications of ADI. According to Nofal the strengthening mechanism of ADI still under investigation. This mystery related to the precipitation hardening arising from the formation of very tiny precipitates such as M6C type carbides. Strengthening of ferrite related to strain hardening caused by very high dislocation density, accompanied by high density small dislocation loops. Austenite strengthening is caused by solution hardening mechanism supported by grain refining due to twinning. At low austempering temperature (~300°C), the austenite is plastically stable due to the higher C-content and the finer distribution of the phase in the microstructure. At higher austempering temperature (above 370°C) austenite volume is usually higher than 25% and the proof stress is controlled by the austenite, which is distributed in larger interconnected areas.

Wear behavior of austempered ductile iron with nanosized additives tested by kaleicheva [4]. He used 4 samples in upper bainite and 4 samples in lower bainite of ADI (one as without nanoadditives and three with addition of nanoadditives). ADI strengthen with i) titanium nitride + titanium carbonitride (TiN + TiCN) ii) titanium nitride TiN and iii) cubic boron nitride cBN, the particles are coated by electroless nickel coating EFTTOMNICKEL. The nickel coating improves the particles wetting into the melt and their uniformity distribution into the casting volume. Samples of ADI austenitised at 900°C for 1 hour and austempered at 280° C and 380°C for 2 hour. Wear resistance of ADI samples examined on pin - disc" using an accelerated testing method and device. Further the samples metallographically analyzed by metallographic microscope GX41 OLIMPUS and hardness measured by Vickers method. Authors have opinion the nanosized additives change the bainitic ferrite morphology and the austenitic conversion degree during the austempering. In study it has been found that, the cast iron with a upper bainitic structure the nanosized additives increase the wear resistance with 4÷32 % in comparison to the irons without nanoadditives. While, wear resistance of the irons with lower bainitic structure show the highest value, for the cast iron without nanoadditives.

IV. MACHINABILITY OF ADI

In this section, the effects of various input machining parameters (speed, feed, depth of cut and cutting environment) while machining (especially turning) of ADI are reviewed. Performance between various cutting tools while machining ADI has been studied. Selections of output parameters and machine tools used for their measurement have also been reviewed. Major finding while machining ADI and reasons behind the same have been studied.

Wear characteristics of ultra-hard cutting tools when machining ADI investigated by polishetty *et al.* [15]. Machining trials consist of turning ADI (ASTMGrade3) using (ToolA PCBN with 90% CBN content, ToolB PCBN with 50% CBN content, ToolC Al2O3+Tic,ToolD silicon carbide-whisker reinforced). In roughing condition cutting parameters are (Vc = 425 m/min cons, Doc = 2 mm, F = 0.1- 0.4 mm/rev) in finishing (Vc = 700 m/min cons, Doc = 0.5 mm, F = 0.1- 0.4 mm/rev). It is found that, in machining ADI requires cutting tool inserts having high toughness and efficient thermal conductivity, for rough machining operations. For finish machining, a relatively low thermal conductivity insert is required in order to concentrate the heat in the shear zone leading to softening of the work piece and reduction of insert wear on the cutting edge. It is found that, 1) Tool D (SiC) and Tool B (50% CBN content) are suitable for light cuts, high-speed machining operations or finishing. 2) Whilst Tool D (SiC) and Tool A (90% CBN content) are suitable for heavy cuts or rough machining. 3) The cutting tool D (SiC) is suitable for both rough and finish machining. 4) Machining ADI using Tool C (TiC) has not produced any advantage in machining results.

Klock and Arft, [5] worked on high performance turning of austempered ductile iron with carbide inserts (CNMA 120408, CNMG 120408 coated with TiCN, Al2O3). For cutting parameters (Vc = 165 m/min, F - 0.4 mm/rev cons. Doc - 2 mm cons.) For ADI 900 grade. According to them, strong tendency of strain hardening characterized by formation of discontinuous chip, which is responsible for wear mechanism. They developed 3D simulation model for longitudinal external turning process. The result obtained from simulation has been found that optimized inserts geometry increased tool life by 70 % in dry and by 100 % in wet condition.

Katuku *et al.* [22] investigated the wear, cutting forces and chip characteristics when dry turning ASTM Grade 2 austempered ductile iron with PcBN cutting tools under finishing conditions. Cutting parameters (Vc = 50-800 m/min, F - 0.05 mm/rev, Doc - 0.2 mm) used. It has been found that, rapid tool wear upto cutting speed (Vc = 200 m/min), slow tool wear between the cutting speed (Vc = 200-600 m/min) and substantial increase in flank wear over cutting speed (Vc= 600 m/min). Cutting speed greater than (Vc= 600 m/min) responsible for the oxidation wear of PcBN cutting tools. Dynamic cutting forces decreased with increasing cutting speed upto (Vc= 200 m/min). Cutting speeds between 150 and 500 m/min were found to be optimum for the production of workpiece with acceptable cutting tool life, flank wear rate and lower dynamic cutting forces.

Aslants and Ucon [24] investigated the performance of ceramic and cermet cutting tools for the machining of ADI with cutting tool (Al2O3 based ceramic tool CNGA 120404TIN22 and cermets tool coated with TiCN+TiN; 120404-NF IC530N) were used. For two samples of ductile iron austempred at 270 °C, 375 °C and one sample as cast were used. The turning cutting parameters (Vc = 100-500 m/min, F = 0.1 mm/rev, Doc = 1 mm). It is found that ceramic tool has high flank wear resistant and longer tool life than cermets tool. Ceramic tool has shown inversely proportional relation between cutting speed and cutting force. The cutting force, feed force and thrust force found higher while machining ADI-250, medium for ADI-375, and low for as cast (NCI). With increase in cutting speed help to reduce BUE and gives improve surface quality. At higher cutting speed (greater than 300 m/min) better surface quality obtained by cermets tool. Higher cutting forces, short tool life and better surface finish has been found for ADI-250, because its lower austempering temp (250°C).

Wang *et al.* studied the influence of cutting parameters on cutting forces and chip shape of ADI under finishing. The cutting tool adapted was alumina based TiC coated (SNGA 120408, square) with the multi factor method for the ductile iron austenitised at 890°Cfor 120 minute followed by salt bath NaNo3, austempered at 350 °Cfor 60 minute. Pointed out that depth of cut had the main influence on cutting force followed by the feed of cut. Recommended cutting parameters are: (Vc= 163.4 m/min, F= 0.16 mm/rev, Doc= 0.15 mm). Cutting force increased nearly linearly with growth of depth of cut and feed rate.

Brandenberg [50] provided the recommendation for machining of ADI. According to Brandenberg, addition of various alloying elements such as molybdenum and manganese may form the carbide in matrix while casting. Though the formation of carbide can be reduce by adjusting the use of alloying elements. Moreover, when a high normal force is applied to ADI, austenite on the surface undergoes to a strain induced transformation to martensite while machining ADI, this transformation right in front of the tool face makes it even more difficult to machine. The solutions suggested from author are, total machining before heat treatment, rough machine prior to heat treatment-finish machine after heat treatment or complete machine after heat treatment with different machining approaches.

Polishetty [16] worked on machinability and microstructural studies on phase transformation in ADI. Research divided in two categories: characterization of ADI and study of phase transformation. Machinability of grades 900, 1050, 1200 and 1400 was evaluated using surface texture, microhardness, chip morphology and metallographic analysis for drilling. The experimental design mainly focuses on phase transformational causes and its effects on machining. From this experimental work, the hypothesis made by polishetty is “microstructure is rapidly changed from ausferrite to martensite due to high rate of plastic deformation and heat or combination of both”. He suggest for the machinability of ADI, either to machine despite the formation of martensite or to use different machining approaches to minimize or even completely eliminate the production of martensite by avoiding strain hardening to start. According to author in dry machining of ADI, graphite nodules act as a solid lubricant as graphite has small coefficient of friction.

Influence of the cutting parameters at the tool life when turning ADI under roughing conditions investigated by Marcelo *et al.* [8]. Workpiece under experimentation were as cast DI, ADI grade 2, 3, and 4. Cutting tool carbide KR 3205 tool used, for cutting parameter (Vc = 60 m/min, F= 0.2 mm/rev, Doc = 1.5 mm). Performance evaluated by tool life and consumed power. He reported that machining of ADI in its austempered condition is highly desirable because it can yield the tight tolerances and surface finish generally required, save machining time and thus reduce costs. Higher the number of the ADI grade, most difficult this material is to be machined. Greater feed rate allows greater material removal with greater tool life. Lower cutting speeds for carbide tools when machining ADI, provide greater tool life.

The material related aspects of the machinability of austempered ductile iron examined by Klock *et al.* [7]. They discussed the austempering process, influence of alloying element on properties of ADI, metallic matrix and austempering time on machinability. Simultaneously carries the machining test, in dry longitudinal turning operation on pearlitic cast iron EN-GJS 700-2, austenitic-ferritic EN-GJS 900-8 (grade 1) and austenitic-ferritic EN-GJS 1200-2 (grade 3). Under constant cutting parameter (Vc =160 m/min, F= 0.2 mm/rev, Doc= 2 mm). Tool for turning, K-20 coated carbide inserts (Al_2O_3+ TiCN with negative geometry, CNMA120408). For GJS 700 they found abrasive flank wear (T=27 min), while machining ADI GJS 900 strong crater wear was found close to cutting edge, tool life reduced by 50% (T=13.5 min). GJS 1200 shows delamination of coating and finally in breakage of the tools. By reducing the cutting speed in machining ADI 1200 (80 m/min, and 120 m/min) delamination can be avoided and tool life improved 20 and 8 minutes respectively. Authors suggested for application of coolant as there is high thermal load on tool, in order to minimize the crater wear.

Aslantas *et al.* [32] evaluated the performance of CBN tools when turning ADI material. ADI samples austenitised at 900 °C for 60 minutes. Followed by austempering temperature 250 °C and 325 °C for 60 minutes. Performance of tool evaluated by cutting forces, surface finish and chip morphology. Workpiece has 80% perlitic and 20% ferritic structure. The cutting tool specification are CNMA120404T IB55. Cutting parameter (Vc= 100, 200, 300, 400 m/min. Doc= 1 mm, F= 0.05 mm/rev). It is found that, lower cutting speed and lower austempering temperature is responsible for higher cutting forces. Chip produced for ductile iron is tight curl shape, for ADI austempered at 250 °C are ribbon like shape and austempered at 325 °C again tight curl shape. Maximum tool wear and better surface finish observed while machining ADI austempered at 250 °C. Authors have opinion, when a high normal force is applied to ADI, a strain-induced phase transformation occurs on the surface of the part. The force exerted by the tool during turning can cause a localized phase change in the material in front of the tool. Austenite on the surface undergoes a transformation to martensite, which is harder and more brittle than the ausferrite structure.

Datta and Batra [8] examined the influence of composition and austempering temperature on machinability of ADI. Ductile irons alloyed with different contents of 0, 0.1, 0.3 and 0.6 wt. % of Ni. To evaluate the performance of different composition, above each sample austenitised at 900 °C for 120 minute followed by austempering temperature 270 °C, 320 °C 370 °C and 420 °C for 120 minutes. Milling test performed with parameter machinability index, cutting forces and surface roughness. High speed steel (HSS) milling cutter having diameter of 77.30 mm was used. (Vc= 54 m/min, F = 0.41 mm/rev, Doc= 0.5 mm, no coolant). Machinability index has the directly proportional relation with austempering temperature. The cutting forces in ADI austempered at austempering temperature 270 ° C to 420 °C increased with increasing Ni content. It is found that cutting forces decreased by increasing austempering temperature from 270 ° C to 420 °C. Samples austempered at higher temperature has better machinability. Lower values of Ra shows for the samples austempered at lower austempering temperature.

The influence of depth of cut on the machinability of an alloyed ADI examined by Avishan *et al.* [28]. According to Avishan martensite form in matrix by transformation induced plasticity (TRIP) phenomenon reduces the mechanical and physical properties of ADI while machining. Cutting parameter (Vc= 116.18 m/min, Doc= 0.1, 0.5, and 1 mm) were selected. TABA DNMG 150608 T813 CVD coated tools were selected to machine the specimen. Sample austenitised at 870 °C followed by austempering at 375, 340 and 300 °C. The parameters used, including impact energy, tensile strength, hardness and microhardness along the cross-section of samples. He reported that reducing the depth of cut not improve the machinability. It is found that cutting with depth of cut 0.5 mm had best while for 0.1 mm had the worst results were found.

The cutting tool's wear behavior, for turning machining of ADI analyzed by Valter *et al.* [38]. They carry out the comparative experimentation of cemented carbide (TiN+Al2O3+TiCN), ceramic (TiC), CBN (TiN) tools, for the input parameter (Vc= 120-200 m/min for carbide, Vc = 200-400 m/min for ceramic and CBN, F= 0.3 mm/rev cons, Doc = 1.6 mm cons). They found that, Al2O3 coating on carbide tool, acts as an effective thermal barrier to distribute heat evenly, flank and crater wear observed on carbide tools. Ceramic tool has problem of edge chipping in the cut edge when the flank wear increase. Performance of CBN showed better result when compared with ceramics. Comparing these three tools, cemented carbide tool, had higher tenacity as aluminium oxide coating presented on carbide substrate gives longest machining length for a cutting speed of 120 m/min.

Cakir and Isik [36] investigating the machinability of austempered ductile irons having different austempering temperatures and times investigated by Cakir and Isik (2007). They conducted the series of test, the ADI bars austempered at 250°C, 300°C, 350°C and 400 °C for 1 hour and 2 hour. Tool life, tool wear rate, cutting forces, and surface finish were used to evaluate the performance with coated carbide inserts, ISO SNMG 120408 (K10), in dry turning environment. Machinability tests were carried out according to ISO 3685: 1993 (*E*) standard. Authors found some unexpected result, ADI austempered at 300 °C for 1 h and 2 h, having less hardness values seemed to wear the tool faster than the harder structures.

V. CONCLUSIONS

While studying the literature of ADI, its effective austempering process parameters and machining with different cutting tools for various input parameter following conclusions can be drawn:

1) Austempering heat treatment offers access to achieve desire mechanical properties with "Ausferrite matrix."

2) Phase transformation (austenite to martensite) due to high plastic deformation and high cutting temperature while machining, making hurdle for the further growth of ADI.

3) Ideal spherical shape and better percentage nodularity gives ADI with better strength and ductility, at the same time as ADI having high nodule count has less possibility to undergo strain induce transformation.
4) Temperature of 350 °C acting as a threshold for various mechanical properties of ADI. Above 350 °C austempering gives better elongation and fracture toughness. While below 350 °C gives better strength and hardness.
5) Graphite nodule serves the purpose of lubrication and heat dissipation during the machining process, so many authors recommend dry cutting environment for machining of ADI.
6) The machining (turning) parameter ranges has been found for coated carbide tool are, Vc= 60-200m/min, F=0.1-0.3, Doc= 0.1-1.2 mm, for cermets, Vc= 150-300m/min, F=0.08-0.3, Doc= 0.2-1.5 mm, for ceramic, Vc= 150-400m/min, F=0.08-0.4, Doc= 0.2-2 mm and for PcBN are Vc= 150-500 m/min, F=0.05-0.3, Doc= 0.5-2 mm.
7) Higher depth of cut reduces the chances of SIT, as tool avoids facing newly formed hardened surface.

We hope, this study will give some direction for the selection input machining parameter while machining ADI.

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