Machinability and related properties of austempered ductile iron: A review

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ABSTRACT

When the ductile iron which is also known as Spheroidal Graphite (SG) iron, is subjected to austempering heat treatment, the material is known as austempered ductile iron (ADI). This material has good mechanical properties and has various applications in different fields. This revolutionary material with its excellent combination of strength, ductility, toughness and wear resistance has the potential to replace some of the commonly used conventional materials such as steel, aluminium and other light weight alloys as it offers production advantage as well. One of the problems encountered during manufacturing is machining of ADI parts owing to its high hardness and wear resistance. Many researchers over a period of time have reported the machinability aspects of the ADI. This paper presents a review on the developments made on the machinability aspects of ADI along with other mechanical properties.

Keywords: Machinability; Austempered ductile iron; Austenitization; Austempering.

INTRODUCTION

Ductile cast iron which is also known as Spheroidal Graphite (SG) iron is a type of cast iron with better ductility compared to the other types of cast iron. When the austempering heat treatment is carried out on the ductile iron, the material is known as austempered ductile iron (ADI). Austempered ductile iron has good mechanical properties because of its unique microstructure "ausferrite" which is shown in the Figure 1. This microstructure consists of ferrite, austenite and graphite nodules. Ferrite is in acicular shape whereas austenite is rich in carbon. ADI has great strength, high hardness with good ductility and toughness [1-6]. ADI has good strength to weight ratio. It is nearly 10 % less dense than steel [7-9]. The cost associated with this material is also less because of the simple casting method. This engineering material offers the design engineers the economical benefit as it is available at lesser cost. Other mechanical properties of this material, such as wear resistance and fatigue strength are also higher [9]. Because of this superior combination of mechanical properties and lesser cost, ADI has wide range applications such as structural application, automotive industry and farm machinery [10-13].
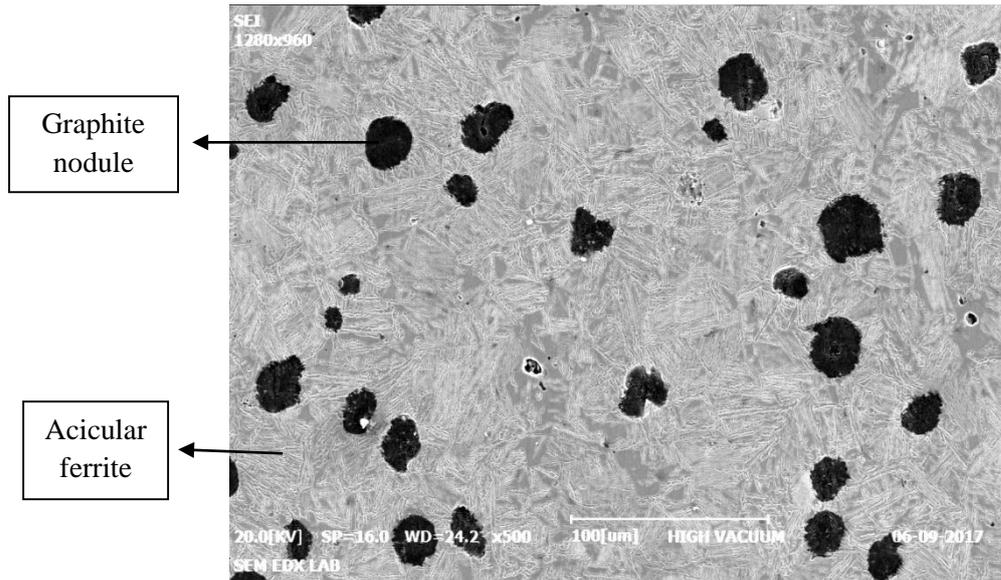
Figure 1. Microstructure of ADI.

By controlling and varying the heat treatment process parameters, chemical composition, casting size and shape, mechanical properties of the material can be altered. Table 1 shows the mechanical properties of different grades of ADI.

Table 1. Mechanical properties of different grades of ADI [14].

Grade	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Hardness (BHN)
1	900	550	9	302
2	1050	700	7	340
3	1200	850	4	387
4	1400	1100	2	418
5	1600	1300	1	460

Classification of ADI into various grades is based on the mechanical properties of the material. Grade 5 ADI offers the maximum tensile strength and hardness. However, ductility of this grade is lower compared to other grades. Grade 1 offers excellent ductility with minimum strength and hardness. Based on the requirement for the application, suitable grade ADI has to be selected.ADI is produced by the austempering heat treatment which consists of two steps. A typical heat treatment cycle for the production of ADI is shown in the Figure 2.

Process A – B represents the initial heating of the specimen to the austenitization temperature. This process is known as austenitization. The exact temperature to which the specimen is heated depends on many factors such as chemical composition, size and shape of the specimen. Specimen is held at this temperature for certain time so as to get the fully austenitic matrix (process B – C). After holding the specimen at the austenitization temperature for the fixed time, it is rapidly transferred to a salt bath which is maintained at the austempering temperature (process C- D). This process is known as austempering and the temperature is in the range 250 - 420°C. Specimen is held at that temperature for predetermined time (process D – E). It is finally air cooled to the room

temperature (process E -F). This ensures the unique microstructure to the ductile iron which is known as "ausferrite". Holding time at the austempering temperature is very important as it decides the final microstructure of the material. The first reaction which takes place during the austempering is the decomposition of austenite into acicular ferrite and carbon rich austenite. If the sample is held at the same temperature for more time, then the second reaction occurs in which carbon rich austenite decomposes into ferrite and carbide. This is not desirable as it degrades the mechanical properties of the material as it embrittles the material [15-17]. The austempering time should be such that it should be sufficient to complete the first reaction, but it should not initiate the second reaction. This time range is called as "process window".
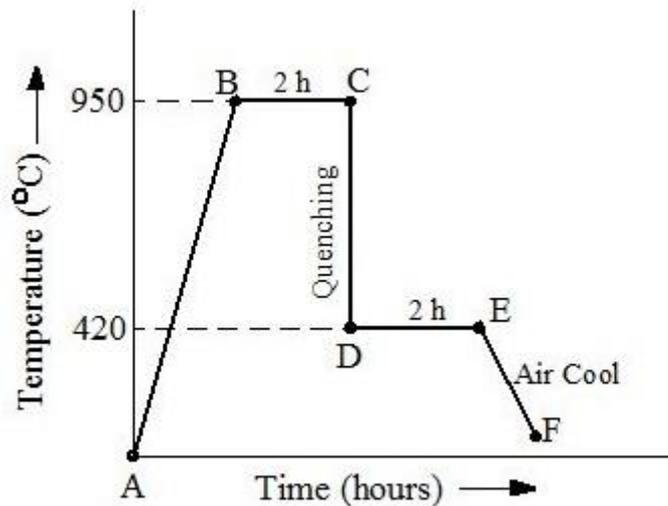

Figure 2. Typical heat treatment cycle for ADI .

The only concern associated with the ADI is the machining of this material, especially post heat treatment. Because of the high hardness and strength, there is a possibility of phase transformation from austenite to martensite because of the induced strain during machining [18-20]. This is usually determined by calculating the amount of each phase present in the material using the X- ray diffraction method [21]. This transformation severely reduces the tool life and in turn machinability. Even though it is suggested to machine the ADI prior to the heat treatment [28-31], there are several instances in which it is necessary to machine it post heat treatment. Various alloying elements present, heat treatment parameters and the selection of machining parameters greatly affect the machinability of ADI. This review article discusses the recent work carried out on the machinability and the developments happened over the recent past years.

EFFECT OF ALLOYING ELEMENTS ON ADI

Various alloying elements are added to the ductile iron in order to increase the hardnenability of the material. Commonly added alloying elements are Mo, Mn, Cu and Ni which help to increase the austemperability by avoiding the pearlite formation while cooling the material from austenitization temperature to austempering temperature [22]. Some of the alloying elements like copper and nickel help in increasing the width of the processing window for austempering reaction [23]. It is very important to carefully select the optimum level of alloying elements so that any adverse effect of these elements on the mechanical properties can be prevented. This mainly depends on casting section thickness, composition of the material and characteristics of the selected heat treatment process. The details regarding the effect of various alloying elements are discussed below.

Manganese
Hardenability of the material and the stability of austenite improves by the addition of manganese to the ADI. However, there is a concern regarding the addition of higher amount manganese to the ADI as it segregates to the intercellular regions and precipitates the carbides. This adversely affects the mechanical properties of the ADI especially leading to the reduction of ductility. Bayati et al. [24] studied the austempering kinetics in the ADI alloyed with 0.67 wt % manganese. It was found that austempering reaction gets delayed because of the high amount of manganese in the material. It is also reported that high strength can be achieved by austenitizing at a lesser temperature of 920˚C. But, at this condition, high ductility grades cannot be achieved. Murthy et al. [25] reported about the abrasion and erosion behaviour of manganese alloyed ADI. Manganese was added in three different proportions of 1 %, 2 % and 3 wt % and superior wear (abrasion and erosion) result was obtained for 2 wt % manganese alloyed ADI. This was attributed the high nodule count obtained for this condition. It is reported by Hamid and Elliott [26] that a processing window which is closed at the high austempering temperature of 375˚C to 400 ˚C can be opened by austenitizing it at low temperature of 870˚C to 920˚C.

Molybdenum
Molybdenum is the alloying element which is used mainly to improve the hardenability. However, similar to manganese, this element adversely affects the mechanical properties of ADI if used in excess. Molybdenum segregates to the intercellular regions to form carbides if excess amount of it used in the ADI [27]. Klocke et al. [28] reported that use of more than 0.3 wt % Mo, adversely affect the tool life and there is a risk of breakout of the cutting edge as the crater wear increases.

Copper
Copper is the less effective hardenability improvement alloying element. Eric et al. [32] reported that copper does not have significant effect on the tensile properties while it increases the ductility at lower austempering temperature of 350˚C [33].

Nickel
Nickel is used to improve the hardenability of the ADI. Up to 2 wt % nickel may be used to improve the hardenability [34]. Jagmohan and Batra [35] reported that cutting force of ADI increases as the nickel content increases at a particular austempering temperature.

MACHINABILITY ASPECTS OF ADI

Even though ADI offers good mechanical properties, researchers have concern regarding its machinability as the hardness and tensile strength of this material are very high. Relative machinability of ADI in comparison to other materials is shown in Figure 3. It is seen that ADI cannot be easily machined as other material such as ferritic or pearlitic ductile iron.
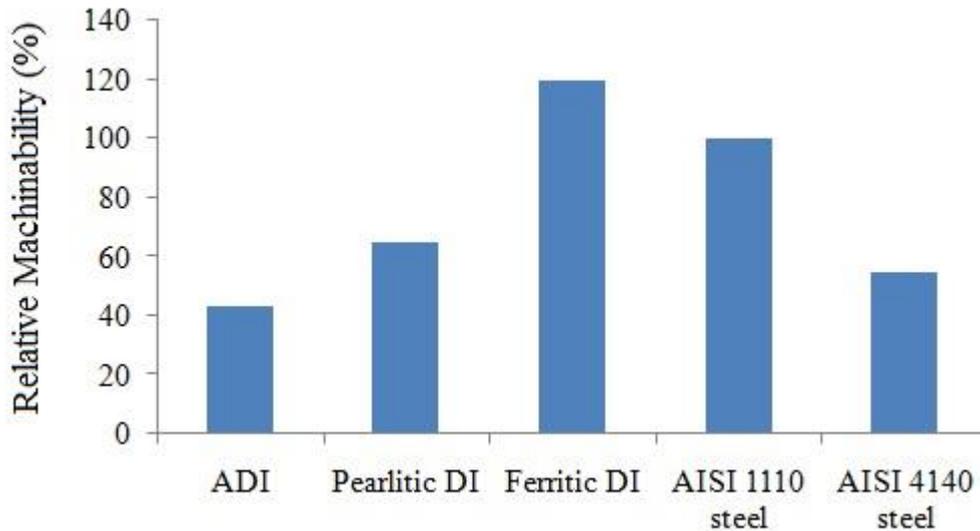
Figure 3. Relative machinability of various materials.

It is suggested to machine the ADI prior to heat treatment whenever possible. In the case of post heat treatment machining, these is a possibility of strain induced transformation of austenite to martensite. The carbon rich austenite is metastable and when ADI is subjected to plastic deformation, high carbon austenite may transform into martensite which is a hard and brittle phase. This transformation severely affects the tool life [36-38]. Therefore, selection of appropriate heat treatment parameters and the machining parameters are of paramount importance to obtain the optimum machinability.

Cakir and Isik [39] reported the machinability results for the samples which have been austempered at various temperature and time. Experiments were conducted according to the machining standard ISO 3685 [40] in order to assess the tool life. Carbide inserts of specification ISO SNMG 120408 were used to machine the samples. No coolant was used during the machining. It is reported that the higher machinability in terms of tool life, was obtained for the samples austempered at 400°C for 1 h. Lower austempering temperature of 300°C has produced some uncommon results. Samples with lesser hardness caused the greater tool wear. This was attributed to the formation of built up edge because of the inappropriate selection of cutting speed.

Manivel and Gandhinathan [41] have carried out the machinability tests on grade 3 austempered ductile iron. Cutting parameters are optimized for better tool life and surface finish. Turning operations were carried out at dry condition. CVD coated carbide cutting inserts were used to carry out the machining. Cutting speed, feed, depth of cut and nose radius are selected as the factors at different levels. Machinability test results have shown that cutting speed is the major contributing factor on tool life as well as on surface

roughness. Tool wear obtained with the nose radius of 0.4 mm was minimum. However, surface finish obtained with the nose radius of 0.4 mm was not good compared to the surface finish obtained with the nose radius of 0.8 mm. Cutting speed of 100 m/min, feed rate of 0.12 mm/rev and depth of cut 0.3 mm produced the optimum tool life.

Seker and Hasirci [42] reported the machinability results for copper and nickel alloyed ADI. Different proportion of copper and nickel were added to the ADI. Austenitization was carried out at 900°C for 90 min. Austempering was carried out at 370°C for different time duration of 60, 90, 180 and 200 min. Machining tests were conducted using cemented carbide tool of SCMT 12M508E. Machinability was assessed in terms of surface roughness and cutting force. Results have shown that increasing the austempering time from 60 min, did not have any significant effect on machinability. It is also reported that better surface roughness and cutting force were obtained for the as cast specimen alloyed with 0.7 wt % copper and 0.7 wt % nickel.

Carvalho et al. [43] reported about the machining characteristics of grade 2 and grade 3 austempered ductile iron. Heat treatment was carried out choosing the parameters carefully in order to obtain Grade 2 and Grade 3 ADI. Machining tests were carried out using carbide inserts WNMA 080408-KR 3215. Machining was carried out with the use of cutting fluid to reduce the cutting temperature. Cutting speed was set at 120 m/min and feed rate at 0.1 mm/rev. The results have shown that a lower tool life was obtained for grade 2 ADI compared to the tool life obtained for grade 3 ADI at the same cutting parameters. This result was attributed to the fact that different wear mechanism in grade 2 and grade 3 ADI. Minimum surface roughness value of Ra, 0.3 μm was obtained for grade 3 ADI while using the tool with a nose radius of 1.6 mm.

Klocke et al. [28] reported the machinability aspects of molybdenum alloyed ADI. The results have shown that tool life is not affected by the austempering time from 60 min to 180 min. ADI which was alloyed with molybdenum content of more than 0.3 wt %, has resulted in the reduction of average tool life.

Seah and Sharma [44] reported about the machining characteristics of austempered ductile iron alloyed with nickel. Machinability was assessed in terms of machinability index. It is reported that, as the austempering temperature increased, machinability index was also increased because of the severe drop in the hardness. Nickel content had only marginal effect on the hardness.

Meena and Mansori [45] investigated the dry drilling of ADI. Grade 1 austempered ductile iron was subjected to dry drilling operation using PVD coated carbide tools. Machining was carried out at various speed and feed rates. The results have shown that combination of low feed rate and high cutting speed resulted in higher cutting force. The influence of cutting speed on the surface finish was more compared to that of feed rate. Lower cutting speed produced high value of surface roughness because of the formation of built up edges.

Polishetty et al. [46] reported about the machining characteristics of austempered ductile iron when the feed rate was varied in different levels. Drilling operation was carried out to assess the effect of feed rate on cutting force while keeping speed and depth of cut at the constant values. Grade 1200 and grade 1400 ADI were used for the experiments. Depth of cut was kept constant at 25 mm and speed at 45 m/min. No coolant was used during drilling. Two different feed rate values of 0.2 and 0.35 mm/rev were used. The results have shown that increase in the cutting force as the feed rate increased. Also, there was no indication of strain induced transformation at the lower feed rate of 0.2 mm/rev. However, at the higher feed rate of 0.35mm/rev, there was strain induced transformation of austenite to martensite along certain locations at the hole boundary.

Kataku et al. [47] studied about the machining of grade 2 austempered ductile iron with various cutting seed. Dry turning operation was carried out using polycrystalline cubic boron nitride (PCBN) tool. Depth of cut of 0.2 mm and feed rate of 0.05 mm/rev were used for machining. Speed was varied from 50 to 800 m/min. The results have shown that abrasion wear was the main wear mechanism for cutting speeds less than 150 m/min. At higher cutting speed, shear localization was the major factor controlling the wear rate. Cutting speed range of 150 - 500 m/min was found to be optimum range for machining. Aslantas and Ucun [48] studied about machining of austempered ductile iron using different cutting tools. Ductile irons were austempered at various temperatures. Turning operations were carried out on CNC machine using ceramic and cermet cutting tools with geometry of CNGA 120404TIN22 and CNMG 120404- NF IC530N respectively. Constant feed rate of 0.1 mm/rev and depth of cut 1 mm were used for turning operation. Speed was varied from 100 – 500 m/min. No cutting fluid was used while carrying out the machining. The results have shown that lower cutting force was obtained at the higher austempering temperature. While using the cermet cutting tool, it was reported that cutting force decreases as the cutting speed increased. There was no significant variation of cutting force while using the ceramic tool. At the higher cutting speed better surface finish was obtained with cermet tool. It is reported that wear on tool occurs faster in cermet cutting tool compared to ceramic tool for a cutting speed of 340m/min. It was recommended to use cermet tool for machining ADI with low cutting speed.

Brandenberg [49] reported about the successful machining of ADI. It is recommended to use the deeper depth of cut value to overcome the problems caused because of the strain induced transformation of austenite to martensite during machining. This allows the cutting surface to cut below the martensite region. Whenever possible, rough machines should be carried out prior to heat treatment. It is reported that K grade carbide tools may be used while machining the ADI with the use of cutting fluid. For continuous cut processes, Al_2O_3 ceramic tool may be used. P grade tools are suggested for dry machining.

Datt and Batra [35] reported about the machinability aspects of nickel alloyed ADI. Nickel content was varied at different levels of 0, 0.1, 0.3 and 0.6 wt %. Austempering treatment was carried out at different temperatures from 270˚C to 420˚C. Milling tests were carried out to assess the machinability in terms of cutting force, machinability index and surface quality. The results have shown that least cutting force was obtained for ADI without nickel content. It was reported that cutting force decreases as the austempering temperature was increased for all the nickel alloyed ADI. The ADI alloyed with 0.6 wt % nickel, austempered at 420˚C for 120 min has shown the best machinability among all samples.

Carvalho et al. [50] reported about the machining of austempered ductile iron by varying the cutting parameters in different levels. Three different grades of ADI were subjected to machining operation using the carbide tool designed for roughing turning process. The results have shown that higher feed rates resulted in greater material removal rate with acceptable tool life which is helpful for increasing the productivity. Better machinability in terms of tool life was obtained for grade 3 ADI with higher feed rate compared to grade 2 ADI with lower feed rate. It is reported that lower cutting speed of 60 m/min resulted in better tool life.

Avishan et al. [51] studied the machining of austempered ductile iron with varying the depth of cut values. Ductile iron alloyed with copper, nickel and molybdenum was austempered at different temperatures of 300˚C, 340˚C and 375˚C. Machining tests were conducted at three different levels of depth of cut at 0.1, 0.5 and 1 mm. Cutting speed was

kept constant at 116 m/min. Machining was carried out using CVD coated tools. Tool life obtained with the lower depth of cut was not minimum. 0.5 and 1 mm depth of cut produced better machiability compared to machiability at 0.1 mm of depth of cut. It is recommended to use deeper depth of cuts for machining low alloyed ADI.

Isik [52] reported about the machinability of austempered ductile iron when it was machined using ceramic and carbide cutting. Ductile iron was austenitized at 927°C and austempered at 400°C for 1 h duration. Machining tests were carried out according to ISO 3685 standard. Two different types of cutting inserts were used to machine ADI. TiN (PVD) coated KY4400 ceramic and CVD coated carbide ISO P25 inserts were used. Turning operation was carried out with feed rate of 0.12mm/rev, depth of cut 1 mm. Different speed values were used. At the higher cutting speed, PVD coated ceramic cutting tool resulted in longer tool life compared to the CVD coated carbide tool. Better surface finish was obtained with the use of carbide tool.

SUMMARY

ADI has good mechanical properties, but its machinability is a great concern for the researchers. The main problem faced during the machining of ADI is the strain induced transformation of austenite to martensite phase which reduces the tool life significantly. It is very important to restrict the amount of alloying elements added especially manganese and molybdenum in order to prevent strain induced transformation during machining. High nodule count is always preferred as it prevents the strain induced transformation. Higher depth of cut is preferred as it helps to machine efficiently in the case of strain induced transformation. Even though there is a great concern regarding the machinability of ADI, by selecting the appropriate tool with appropriate machining parameters, ADI can be machined successfully.

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