The current status of the metallurgy and processing of austempered ductile iron (ADI)

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In the last three decades, the revolutionary material; the austempered ductile iron (ADI) with its unique combination of mechanical properties, has been offering the design engineer alternatives to conventional material process combinations,
This review is an attempt to compile the results of the worldwide explosion of research and development that followed the announcement of the first production of this material, meanwhile, reference is made to the work that has been carried out at CMRDI over the past decade. This paper is not designed to provide an in-depth investigation of any specific technology, but is rather a macro-analysis of the current state of metallurgy and processing of ADI.
Better understanding of the strengthening mechanisms of ADI led to the development of new techniques such as ausforming, squeeze casting as well as two-step austempering, which contributed to enhanced strength of the alloy. Abrasion resistance could be markedly increased through the development of carbidic ADI (CADI), bainitic/Martinsitic (B/M) ADI, locally austempered ductile iron using induction hardening techniques, as well as laser surface hardening.
Machinability problems of ADI, which have limited its mass production for long, have been solved through the development of new machinable types of ADI as IADI with mixed ferrite/ausferrite structures.
Production of thin wall ADI components may offer potentials for applications, and this could be achieved through casting or cold rolling, where strain hardening phenomena seems to be of special interest. Thin wall ADI castings are capable to build complex thin wall parts of high strength.

Keywords: ADI, strengthening mechanism, ausforming, dual-phase, machinable ADI, CADI, abrasion resistance, squeeze casting, laser treatment.

Introduction

The as-cast mechanical properties of ductile iron can be significantly improved through an austempering heat treatment. This has led to the birth of a new member of the cast iron family; the austempered ductile iron (ADI), with its unique microstructure; spheroidal graphite in an ausferritic matrix[1].

The austempering transformation in ADI can be described as two-stage reaction:

Stage I Reaction: $\gamma_c \rightarrow \alpha + \gamma_{HC}$ (toughening)

Stage II Reaction: $\gamma_{HC} \rightarrow \alpha + \varepsilon$ - carbides (embrittlement)

The morphology of the final two-phase matrix microstructure is determined by the number, shape and size of the initially formed ferrite platelets in the first stage austempering reactions. The control of this stage of transformation will, therefore, ultimately control the final microstructure and mechanical properties. The rate of ferrite formation during stage I austempering may be controlled by chemical, thermal or mechanical processing variables.

The mechanical properties of ADI depend on a number of interlinked factors, including primarily the austenitizing and austempering temperatures and times together with the as-cast microstructure, the composition and the section size. Of these, the austempering temperature is the most important. These variations in properties can be related to the changes in microstructure. At low austempering temperatures, an acicular (needle-like) ferritic phase is formed with only a small amount of retained austenite. At the very lowest austempering temperatures, the structure may also contain some martensite. This type of microstructure can provide high tensile strength and hardness but only limited ductility and poor machinability. With increased austempering temperatures, the ferrite becomes coarser with increased amounts of retained austenite (up to ~ 40%); with a typical "ausferrite" structure. This results in a substantial increase in ductility and machinability with a reduction in strength and hardness.

Since the announcement of the first production of ADI in the last decades of the last century, a worldwide explosion in research started, which provided a sound foundation for expanding the production and applications of this prospective material[2-5]. However, the practice of ADI production seems to be ahead of the theory; the strengthening mechanisms of ADI are still not very clear. The main constituents of ADI matrix are acicular ferrite and carbon enriched austenite (with the possibility of some martensite formations at low austempering temperatures), both main constituents are of low or

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medium strength. The "mystery" of the high strength of ADI, and how it may result from these constituents have been earlier related to the precipitation hardening arising from the formation of very tiny precipitates such as M_6C type carbides and others[6]. The density of these precipitates, however, seems to be too low to result in such superior strength properties. Recently, extensive use of TEM has shed more light on the strengthening mechanisms of the main structural constituents of ADI.

The following mechanisms have been proposed:

- The strengthening mechanism of ferrite was related to strain hardening caused by very high dislocation density, accompanied by high density very small dislocation loops.
- In the same time austenite strengthening is caused by solution hardening mechanism supported by grain refining due to twinning, which results in some extra coherent grain boundaries. Moreover, stacking faults representing obstacles for dislocation movement may play some strengthening role.
- Moreover, the austenite to martensite transformation at low austempering temperature is accompanied with high lattice distortion and consequently high strain energy. The martensite grains would be divided into a very large number of ultra thin microtwins. The resulting huge amount of coherent grain boundaries will impede the dislocation movement

Thanks to the extensive efforts made over the past few years, new processing techniques have opened even more opportunities for this excellent engineering material to acquire better combinations of strength, ductility, toughness, wear resistance and machinability. It is the objective of this paper to review the advances in the metallurgy of ADI that led to such properties improvement. Moreover, the novel techniques of surface engineering and welding of ADI will be shortly mentioned. Whenever possible, a reference will be made to the previous work conducted at CMRDI, where the first ADI pilot production line in Egypt has been established few years ago.

ADI with Enhanced Wear Resistance

In any material, improved tribological properties are usually enhanced by ensuring high hardness values. Higher grades of ADI austempered at low temperatures (230-260°) usually have high hardness of ~480-550 BHN and, therefore are selected when good wear resistance is the main requirement. With the increase of austempering temperature, the hardness decreases typically (290-320 BHN) leading to more wear. The increased retained austenite contents in these soft grades can work harden and/or transform to martensite when subjected to mechanical strain at the surface, resulting in significantly better wear resistance than would be expected. This effect is a disadvantage when machining, but can be very beneficial for ADI components as the worn away surfaces would be continuously replaced by a freshly formed hardened layer. The strain-hardening characteristics of ADI influence the total life cycle of components subjected to substantial plastic strains during service (e.g. fatigue, wear, machining) and, therefore, has recently attracted more attention[8-15].

Carbidic ADI (CADI)

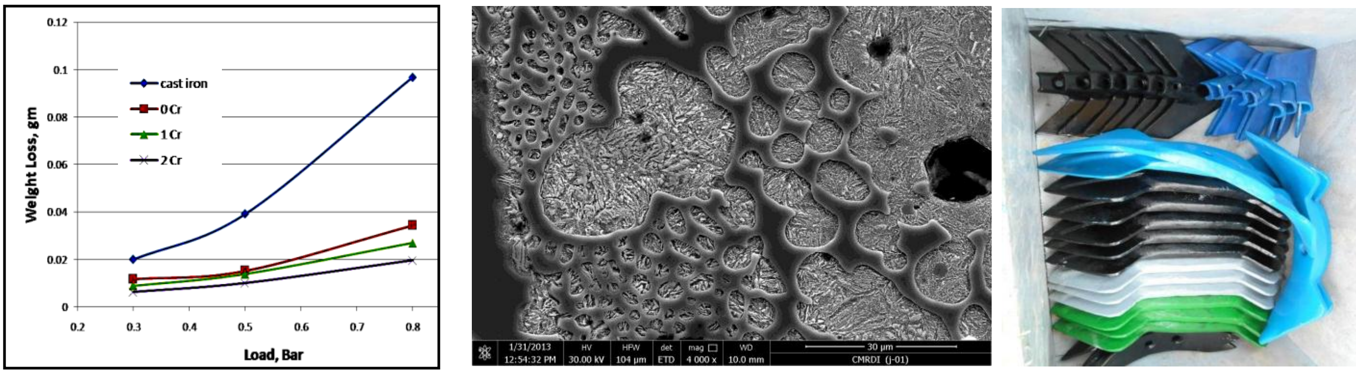
CADI is ductile iron containing carbides that is subsequently austempered to produce an ausferritic matrix with an engineered amount of carbides. Volume fraction of carbides may be controlled by partial dissolution during the subsequent austenitization process and hence the proper abrasion resistance/toughness combination may be reached. CADI exhibits excellent wear resistance and adequate toughness. The abrasion resistance of this new material is superior to that of the ADI and increases with increased carbide content. In a number of wear applications, it can compete favorably with high Cr-abrasion resistant irons with improved toughness[17-24].

Several methods have been suggested to introduce carbides to the structure of ADI.

(a) As cast carbides can be introduced to the structure of ADI through alloying with carbide promoting elements such as Cr, Mo, Ti, etc., controlling the cooling rate during solidification, adjusting the carbon equivalent to produce hypoteutectic composition or through surface chilling.
Recently, it has been reported that good balance between wear resistance and impact toughness could be achieved through the selection of Cr-content/austempering temperature combination. The wear resistance as a function of Cr-content in CADI are illustrated in Fig.1-a[25]. It should be noted that both primary as well as eutectic austenite in CADI is transformed to very fine ausferritic structure[25] (Fig.1-b). Some examples of plow points produced at CMRDI pilot foundry are illustrated in Fig.1-c.

(b) Carbides precipitated during austempering: extending the second stage austempering will result in the precipitation of fine carbides from the high carbon austenite: $\gamma_{HC} \rightarrow \alpha + \varepsilon$.

(c) Mechanically introduced carbides; crushed M_x C_y carbides are strategically placed in the mold cavity at the desired location. The metal then fills in around the carbides resulting in a continuous iron matrix with discrete carbides mechanically trapped. This method allows the engineer the option of placing carbides only where needed resulting in conventional ductile iron matrix throughout the rest of the casting. These particular carbides are essentially affected by subsequent austempering process. This technique is currently only practiced by license to Sadvik corporation and the specific method used to contain the carbides "in place" during mold filling needs further investigation.



(a) (b) (c)

Fig.1[25]: (a) effect of Cr% on the wear resistance of CADI
(b) primary and eutectic austenite transformed to fine ausferrite
(c) plow points produced at CMRDI

Other surface treatment techniques adopted to enhance the wear resistance of ADI are introduced under section (Surface Hardened ADI) of this report.

Recent research work indicates increasing interest in developing CADI microstructure and properties by adding boron[26], studying the multi-response optimisation of production parameters using Taguchi Method[27], investigation of the influence of cooling rate from the austenitization temperature[28], enhancement of mechanical properties and abrasive wear resistance by modification with nano ceria particles[29,30].

Current applications of CADI include automotive, agricultural, railroad, construction and mining as well as other engineering application, e.g. pump components, wear housing, and plates, rollers and blast parts, etc.

Bainitic/Martensite (B/M) Dual-phase ADI

A new grade of wear resistant ductile iron, with properties similar to those of ADI was recently developed by combining less expensive alloying with a controlled heat treatment to produce a bainitic-martensitic dual-phase structure[31-33]. Alloying elements such as Si and Mn that promote bainitic transformation were added in the range of 2.5-3.0% each. Moreover, such alloying facilitates the separation of bainitic transformation from martensitic one. Manganese significantly reduces the Ms temperature, dissolves unlimitedly into austenite and improves hardenability. At Mn-contents higher than 3.0%, austenite increases on the account of bainite and carbides start to precipitate. Manganese carbides formation is restrained effectively by silicon, which promotes the formation of bainitic ferrite and the enrichment of asutenite with carbon. The resulting increase in austenite stability will reduce the possibility of manganese carbides formation and manganese dissolves in austenite and ferrite. The pearlite formation is avoided by controlled cooling heat treatment; consisting of three stages:

(1) Water spraying quenching is applied for rapid cooling from austenitization temperature to about 300°C in a few minutes which suppress any pearlite transformation.
(2) Soaking in a heat preservation setting for bainitic transformation over a range of temperature form the spraying end temperature to 200°C for 2 hrs.
(3) Air cooling to room temperature for martensitic transformation.

The resulting microstructure containing bainite, martensite and 8-10 vol. % retained austenite along with the graphite spheroids will give an excellent combination of hardness and toughness which reach 51.5 HRC and 21.7 $J.cm^{-2}$ respectively and this could be attributed to the following factors[31-33]:

i) The bainite needles split the undecompensed austenite and effectively decrease the size of martensite leading to improved strength and toughness.
ii) High toughness of bainite restricts the propagation of cracks originating mainly at the graphite/matrix interface and hence toughens the iron.
iii) The presence of retained austenite (8-10 vol. %) contributes to the toughening effect.

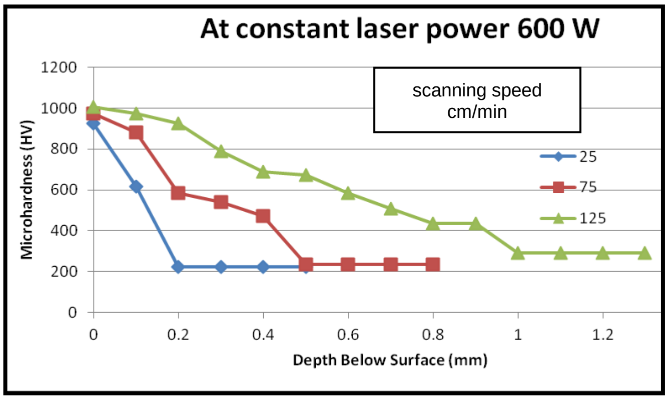
The impact wear resistance of the B/M ductile iron was found to be comparable with that of the high chromium cast iron and twice that of manganese steel. Under conditions of low impact load, such as that in the case of grinding balls and liners in the small and medium diameter ball mills, the B/M ductile iron can replace the manganese steel as a wear resistant material. In such application, the B/M ductile iron shows good work-hardening effect due to the presence of the retained austenite. The surface work-hardening effect can considerably improve the wear resistance of the hardened surfaces, while the core of the balls remains tough.

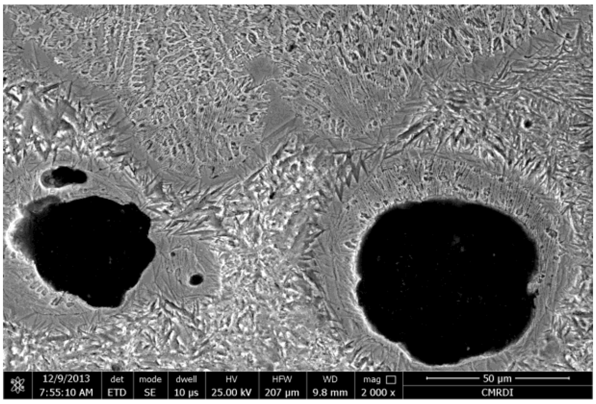
Surface Hardened ADI

Fully or mostly ferritic matrix may be hard face welded in the area of greatest wear, which results in a carbidic weld and heat affected zone at the weld/casting interface. Subsequent austemper heat treatment was found to have little or no effect on the weld structure, depending on the chemical composition of the weld material chosen, whereas the heat affected zone is eliminated and a fully ausferritic matrix results in all areas except the weld area itself. In some weld applications, powdered metal carbides can be purged into the molten weld to provide additional wear resistance[17].

Limited number of publications may be cited in the literature, where the ADI surfaces were processed by laser to enhance the wear resistance properties[34-38]. Laser processing may lead to surface hardening (LSH) or surface melting (LSM) depending on the incident laser power and scanning speed; with the depth of the processed layer directly propotentional to the power and inversely related to the linear scanning speed. LSM produces a predominantly austenitic[35] or ledeburitic microstructures with almost complete dissolution of graphite. The LSM ADI surface layer revealed a near gaussian distribution of microhardness as a function of depth, so that the microhardness is lower near the surface and higher at the central part of the laser irradiated zone[35]. LSH resulted in a primarily martensitic microstructure with almost constant microhardness values across the irradiated layer higher than that in the LSM samplers.

Laser surface treatments, especially LSH significantly increase the wear resistance of ADI which was related to the fine microstructures of austenite, ledeburite or martensite obtained after LSM or LSH, giving hardness values up to 800 H_v, work hardening of the structure as well as stress induced phase transformation of retained austenite to martensite[30-38]. Moreover, such increase in wear resistance was correlated with the lower probability of micro-cracks initiation caused by sub-surface fatigue or deformation constraints at the interface between austenite and martensite produced by the stress induced austenite transformation to martensite[37]. It should be noted that the same transformation may produce compressive stresses if the ADI are subjected to surface treatments involving cold working operations such as controlled shot peening or fillet rolling which can improve the fatigue properties rather than the tribological ones[39,42].





(a) (b)

Fig. 2: microhardness profile (a) and microstructure at the HAZ of an ADI sample irradiated with 600 W cw laser at different scanning speeds

In a current research at CMRDI, the hardness and the depth of the hardened layer were shown to increase with the laser scanning speed at constant power level. Fig. 2-a shows the microhardness profile across the transverse section of ADI laser surface processed with 600 W cw laser as a function of the laser scanning speed. Fig.2-b illustrates the microstructure of the irradiated sample at scanning speed of 75 cm/min. The upper part of the microstructure indicates that the hardened zone consists of retained austenite and martensite with all the graphite spheroids completely dissolved during laser melting of that area. The lower part of the microstructure shows the original graphite spheroids surrounded with a halo of retained austenitic dendrites as the C-content in this layer is relatively increased due to diffusion of carbon from the graphite spheroid at higher temperature. Graphite spheroids are contained in the original ausferritic matrix of ADI.

Locally Austempered Ductile Iron (LADI)

The currently available methods for "surface austempering" of ductile iron are often expensive and not as well controlled. Some components could benefit from austempering only a certain location of the component and leaving the remaining part as as-cast ductile iron with its excellent machinability. The LADI could improve the component's abrasive wear resistance, bending or contact fatigue strength in a localized area. When selecting the proper material for an engine camshaft, one must balance the needs of a hard, strong and wear resistant material for the camshaft lobes with the better machinability of the component. LADI has been found to replace the use of assembled camshaft, which is usually an expensive solution[41]. LADI is obtained by a two step proprietary process:

- The surface of the camshaft is heated using computer controlled induction technology to the austenitization temperature and held for a time sufficient to ensure uniform C-content.
- The surface is then, cooled to a temperature range of 205-230°C by spraying with a liquid polymer quench. The camshaft is then held at this quench temperature until a surface layer of 3-5 mm of ausferrite is formed.

Enhancement of Strength Properties of ADI

Ausformed Austempered Ductile Iron (AADI)

It has been shown[42,43] that the rate of ferrite formation during stage I austempering may be controlled by the following processing variables:

- ***Chemical*** **-** including alloy content selection for hardenability purposes together with the austenitization temperature selection which controls the matrix carbon content
- ***Thermal*** **-** including austempering temperature and time
- ***Mechanical*** **-** including mechanical deformation introduced into the austempering schedule just after quenching, but before any asubstantial transformation of austenite (ausforming), Fig. 3.

Naturally, an optimum final microstructure could be produced by including elements of all three processing variables. It has been shown[44-46] that mechanical processing of ADI can act as a control valve for the stage I austempering reaction. In ausformed austempered ductile iron (AADI), mechanical deformation is utilized to affect the microstructure and, consequently, the mechanical properties of ductile iron due to acceleration of ausferrite reaction, refining the microstructure and increase of the structural homogeneity.

It has been shown[47] that ausforming up to 25% reduction in height during a rolling operation contributed to add a mechanical processing component to the conventional ADI heat treatment, thus increasing the rate of ausferrite formation and leading to a much finer and more homogeneous ausferrite product (Fig. 4). The effect of ausforming on the strength values was quite dramatic (Fig. 5) (up to 70 and 50% increase in the yield and ultimate strength respectively). A mechanism involving both a refined microstructural scale as a result of enhanced ferrite nucleation together with an elevated dislocation density was suggested[48]. Hardenability elements such as Ni and Mo are usually added to increase hardenability of thick section castings, and ausforming to higher degrees of deformation was found necessary to alleviate the deleterious effects of alloy segregation on ductility[49].

It is more practical that the advantage of ausforming would be taken by forging rather than by rolling. The forging process may be performed on cast preforms, austenitized and quenched to the austempering temperature, inserted into a die, pressed or forged to the final shape and then returned back into the austempering bath to complete the accelerated transformation. Minimal deformation degrees by conventional forging standards, i.e. an average strain of 25% would be sufficient for the forming part of the processing sequence. It has been reported[49] that in situations where very severe deformation occurs, the work-piece may not need to be returned to the austempering bath to complete the transformation to ausferrite, as the latter will have been completed by the time the work-piece is extracted from the die.

The idea of creating preforms in ductile iron and then ausforming them to final shape could be quite effective for relatively simple shaped castings that must meet high demanding strength and ductility requirements, e.g. connecting rods for automotive applications. It is understood that certain deviations in design elements of both preform as well as the die set should be involved compared to the design of conventional ADI process. The abovementioned concept has been utilized to produce tank track center guides[50] using a finite element simulation technique to match both the preform design and the die design so that a uniform equivalent stain throughout the casting averaged ~20%. No inclination - to fracture or cracking has been reported.

Squeeze Casting of ADI

ADI was produced without an austenitizing step based on a patent published in 1985 by P.B. Magalhaes[51]. In this process, casting in a permanent mold allowed the ejection of the part at a temperature level above 850°C where a completely austenitic range could be guaranteed. Subsequent quenching in a salt bath would lead to the ADI ausferritic microstructure.

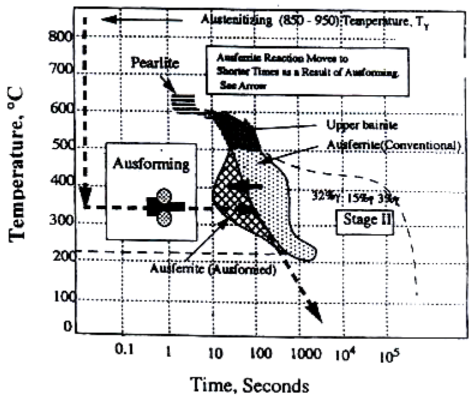


Fig. 3: Schematic representation of the ausforming process[42]

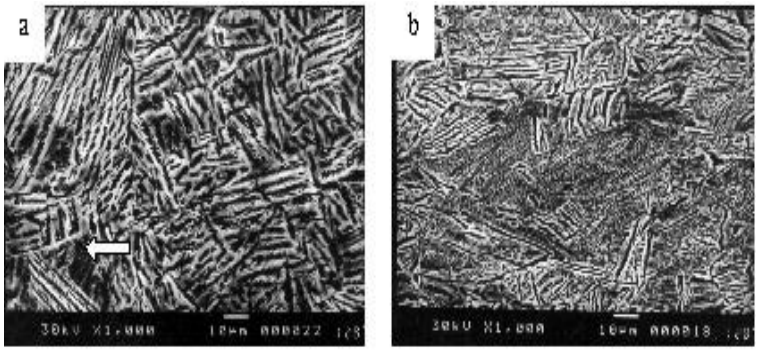


Fig. 4: SEM micrographs of ADI alloyed with 2% Ni austempered at 375°C for 1 minute. (a) Conventionally processed; (b) Ausformed to 25% reduction arrows indicate the brittle martensite formed in many zones in the conventionally processed ADI[47]

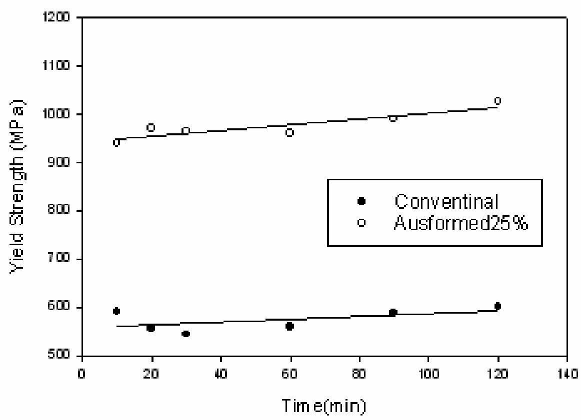


Fig. 5: Yield strength vs austempering time and ausforming reduction for adis alloyed with 2% Ni[47]

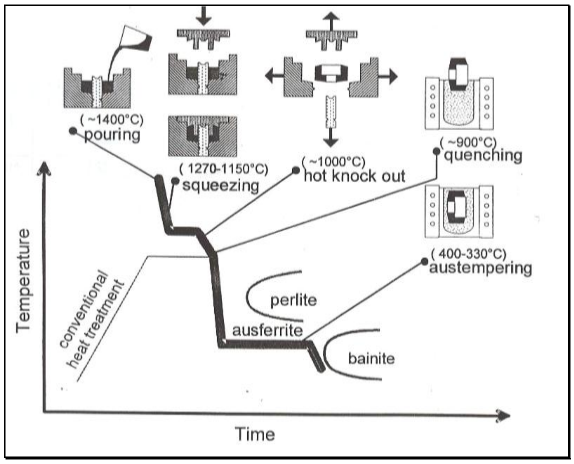


Fig. 6: Process steps and temperature regime of the SQ process and the in-situ heat treatment[52]

Based on this process, a novel technique has been simultaneously developed at TU-Aachen Foundry Institute [52] and component CPC - Finland[53] to produce superior quality ADI castings, using squeeze casting of molten metal in permanent mold, followed by in-situ heat treatment of the hot knock-out casting in the austenite range, followed by normal austempering in a salt bath. Figure 6 shows a schematic representation of the process[52].

This technique seems to have some unique advantages, such as:

- Sound castings can be produced without feeders or gating system as the solidification expansion was used to counteract solidification shrinkage.
- Increased heat transfer avoids formation of macro- and micro-segregation, which decreases the mechanical properties of ADI.
- Chemical composition of ductile iron can be selected to avoid any metastable solidification in spite of the extremely fast solidification.
- The production process is shorter and less energy consuming as the elimination of sand from the process would allow the hot castings coming out from the permanent mold to be directly introduced to the heat treatment furnace.
- The structure of the SQ ADI is much finer (the graphite as well as the ausferrite), which means better mechanical properties (ultimate tensile strength, elongation and fatigue strength).
- The casting surface is entirely free from any surface defects, which again means higher fatigue strength.
- The machinability is better.
- More environmentally friendly.

Table 1[52] shows some tensile test results of a squeeze casted ring gear test samples compared to EN standard. Fiat suspension fork was tested for fatigue strength and amazing results were achieved. This component had to pass the test without cracks loaded with 2500 KN after lifetime of 300,000 cycles. The squeeze cast forks could pass the test with 5000 KN without failure up to 3-10 million cycles. The tensile properties were much higher than pearlitic ductile iron or even better than microalloyed steels as shown in Table 2[53], yield strength was much higher than steel and elongation about the same.

Table 1: Some tensile test results of squeeze cast test samples compared to EN standard[52]

	Test 1	EN	Test 2	EN
Tensile strength, MPa	1238	1200	1115	1000
Yield strength, MPa	968	850	839	700
Elongation, %	13.4	2	15.3	5
Hardness, HB	388	340/440	363	300/360

Table 2: Comparison of different suspension fork materials[53]

	GJS-600-5	SQ ADI (Tested)	Microalloyed Steel
Tensile strength, MPa	600	950	1000
Yield strength, MPa	370	750	550
Elongation, %	10	11	12

Two-step Austempering of ADI

The mechanical properties of ADI are mainly dependent on:

- The fineness of ferrite and austenite in ausferrite
- The austenite carbon (X_γ,C_γ) where:

  X_γ is the volume fraction of austenite

  C_γ is the austenite C-content

Both these factors depend on the austempering temperature. Higher undercoolings enhance the nucleation of ferrite from the parent austenite and hence promotes finer ausferrite structure with higher yield and tensile strength but lower ductility. On the other side, higher austempering temperatures result in coarser feathery ferrite and austenite with lower strength but higher ductility properties. Moreover, higher austempering temperatures lead to higher (X_γ,C_γ) parameter which, in turn, increases fracture toughness and fatigue strength of ADI.

It is possible, therefore, to optimize the mechanical properties of ADI by ausferrite refinement as well as increasing the austenite carbon. Hence, the novel concept of two-step austempering was conceived[54], which involves first quenching the alloy to a lower temperature (250-270°C) after austenitization, thus increasing the undercooling, and then, once the nucleation of ferrite is complete, immediately raising the temperature of the quenching media to a higher temperature to enhance faster diffusion of carbon and increase austenite carbon (X_γ,C_γ) in the matrix.

The two-step austempering process has resulted in higher wear resistance in ADI compared to the conventional single-step austempering process. An analytical model for the abrasion wear behavior of ADI revealed the dependence of wear behavior of ADI on the microstructural parameters, especially the parameter $X_\gamma C_\gamma /\sqrt{d}$ where d is the ferritic cell size as well as the strain hardening exponent (n-value). The major wear resistant mechanism in ADI was shown to be the microstructural refinement in ausferrite and solution strengthening effect (high C-content in austenite) along with strain hardening effect of the austenite phase[55,56].

Meanwhile, the two-step austempering process resulted in higher crack growth rate and lower fatigue threshold than the single step ADI proces. The crack growth rate increment due to the two-step austempering process increases with the austempering temperature[57]. Moreover, it has been shown in a recent publication carried out at (CMRDI) that the two-step austempering process increases the fracture toughness of ADI, where the increment in the fracture toughness by the two-step process is more pronounced in unalloyed irons[58].

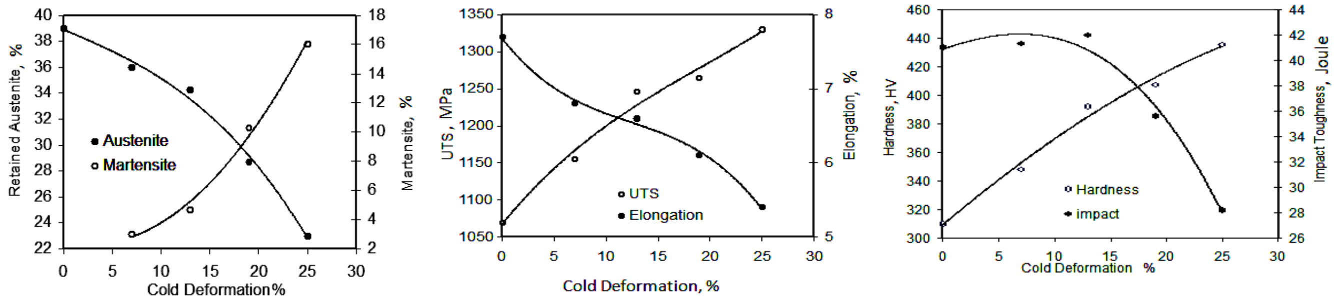
The improved toughness was correlated to reduced ferrite grain size, increased carbon content of the retained austenite as well as its stability.

Cold Rolling of ADI

ADI was subjected to cold rolling (CR) at different reduction percentages to produce as thin as 3 mm sheets without showing any evidence of cracking[59].

Increasing the cold rolling (CR) reductions, the amount of retained austenite (γ_r) was decreased due to partial transformation of retained austenite (γ_r) to martensite, (Fig. 7-a) indicate that the amount of mechanically generated martensite increases with increasing the CR reduction[59].

As can be seen from Fig. 7-b&c, the elongation and impact toughness decrease, while the ultimate tensile strength and hardness increase with increasing CR reduction. This is attributed to increase of the hardening of the investigated ADI with cold deformation processes (deformation bands and twins) and deformation - induced martensite. It must be mentioned that the observed changes in the mechanical properties at light cold deformation (7% reduction) are mainly attributed to the hardening of this alloy by plastic deformation concentrated in γ_r. At this light deformation the amount of mechanically formed martensite is very small (Fig. 7-a)[60].



(a) (b) (c)

Fig.7[59]: Effect of cold reduction pct on:
(a) volume fraction of retained austenite and mechanically formed martensite
(b) elongation and ultimate tensile strength
(c) Vickers hardness and impact toughness

Two types of martensite induced by deformation have been reported[61], the first is of the lath type, which nucleates at twin boundaries or twin intersections, the second has a plate morphology and seems to form in regions affected by the homogeneous precipitation during the austempering treatment of quasi-coherent epsilon carbides in austenite. This latter martensite is of tempered type, containing epsilon carbides of sizes larger than those found in the parent austenite before deformation.

Improved toughness of ADI results from:

- reduced ferrite particle size
- increased carbon content in the retained austenite, which increases the strain hardening ability and strain hardening coefficient
- stability of the retained austenite

Formation of strain induced martensite is known to enhance the toughness in TRIP steels. In ADI, due to the high C-content, the martensite formed is brittle and it is debatable if the formation of strain induced martensite can improve the toughness. The contribution of strain induced martensite to the toughness of ADI has been recently discussed[62]. The martensite containing ADI can be visualized as fiber reinforced ductile material. Even if the fiber is brittle, it will not make the composite brittle, as long as the fiber is shorter than a critical length, as it will not be loaded to its maximum strength and will not, therefore, fracture. According to this argument, if the retained austenite regions are not massive, then only very short-length of thin martensite will form and will improve the toughness of ADI.

Thus, ADI austempered at lower temperature and having finer ausferritic structure should benefit from the martensite formation, while that treated at higher temperatures and consisting of massive retained austenite together with coarse ferrite will not. The retained austenite in upper bainite can easily transform to strain induced martensite[62].

Thin-Wall ADI Castings

To achieve fuel economy in automotive industry, reducing the vehicle weight has been a major research area of interest over the last few decades. Although the general trend has been to use low density materials (aluminum, magnesium and composites) instead of cast iron and steel in the automotive industry, numerous examples have been recently noted in the literature where iron castings started again to replace aluminum in the industry. This is encouraged by the increased strength, ductility, stiffness, vibration damping capacity, as well as reduced cost[63-65]. If the yield stress/cost ratio of the various materials is compared, the new member of the ductile iron family, the ADI, is most of the time the winner. When mechanical properties, density and cost are included in material evaluation, ductile iron may offer more advantages than aluminum, particularly if thin wall ductile iron parts could be produced without further heat treatment processes. The potentials for ductile iron applications for lightweight automotive components have been limited by the capability to produce as-cast free carbide thin wall parts (2-3 mm)[66,67]. Production of thin-wall ductile iron castings still represents a daily challenge in modern foundries. Review of the recent literature shows that thin-wall ductile iron has been successfully produced for many years, thanks to the optimization of some critical production parameters: pouring temperature, chemical composition, thermal conductivity of the molding materials, type and amount of inoculating material in combination with the spheroidizing method adopted, casting design and other foundry basic practices[68,69].

When the commercial introduction of ADI in 1972, consistent efforts have been made to identify new applications of this new emerging material, however, difficulties have been encountered in producing ADI thicker than 100 mm due to the segregation of hardenability elements added to prevent pearlite formation. Such difficulty in obtaining the required austemperability and the heterogeneous microstructures do not represent a real problem when producing thin wall ADI castings due to the insignificant segregation tendency associated with rapid solidification of those thin wall castings. The use of ADI in thin-wall and high strength parts has, however, been mentioned in a very limited number of reference[70,71]. Successful case was recently reported[69], where a hollow connecting rod for a two-cylinder car engine and a front upright for a racing car were successfully made of thin wall ADI, which confirms the capability of ADI to build complex thin walled parts of high strength. With recent development in inoculation theory and practice, it became possible to cast thin-wall ductile iron parts completely free from carbides. Consequently, further improvements in the properties of thin wall ADI castings could be achieved with the austempering process. The results of a R&D program on the effect of wall thickness (3-10 mm) and silicon content (2.4-2.7%) on the properties of ADI has been reported[71]. It has been shown that thin-wall ADI castings austempered at 360°C and containing low silicon can exhibit ultimate strength exceeding 1100 MPa with more than 10% elongation. This is an indication that austempered thin-wall ductile iron is becoming a logical choice for the production of small, light weight and cost effective automotive components. However, more data about the metallurgy of thin-wall ADI castings seems to be of practical interest.

ADI 2 mm plates with a homogeneous ausferritic and nodule count of 300 nodules/mm^2 were produced at CMRDI[72]. It was found that decreasing the wall thickness leads to reduced amounts of retained austenite and structure refinement, which in turn increase the hardness. Increasing the austempering temperature from 350°C to 400°C resulted in reduced tensile strength values (950 and 1000 MPa for 8 and 2 mm wall thickness, respectively) to (775 and 875 MPa for the same wall thickness), increased impact strength from 40 to 80 and from 100 to 125 J at wall thicknesses of 2 and 8 mm, respectively, apparently due to increased amounts of retained austenite at higher austempering temperatures.

Machinable ADI

When ADI first started to be used for engineering applications, there were many difficulties experienced in trying to machine it, and some of these doubtlessly persist to this day. The hardest grades of ADI reach a hardness of ~50 HRC which would pose a challenge for any high volume machining operation. Although the softer grades of ADI have a typical hardness of 300-350 BHN, their matrix structure contains up to 40% retained austenite. When subjected to strains in service, as was mentioned in section (Cold Rolling of ADI) of this survey, this phase rapidly work hardens and can transform to martensite, this can thereby reduce the machinability compared with a steel of equivalent hardness. The volume fraction of high carbon austenite present in the microstructure of austempered ductile iron (ADI) is one of the important factors that influence the mechanical and physical properties of the alloy. Formation of martensite by TRIP (transformation induced plasticity) mechanism during the machining operation, in which a large amount of stress is applied to the microstructure, results in decrease in machinability of ADI. It is considered that the limited use of ADI for high volume applications is partly due to machining difficulties. This was one of the motivations in the recent developments of a machinable ADI[73-79].

A lack of experience of the high volume machining of ADI adds uncertainty to the costs and production rates and the early experiences of ADI exposed some inconsistencies in the machinability. These problems, however, can be minimized by collaboration between a knowledgeable foundryman, heat treater and machining expert.

The influence of austenitizing and austempering temperatures on the machinability of ADI was reported[80,81]. The production of machinable ADI has attracted the attention of many researchers in the last few years by optimizing the composition and heat treatment cycles of cast iron. Muhlberger developed[73] and patented[74] a machinable grade ADI by careful selection of the composition (low Mn) and heat treatment variables and this development was exploited in at least one European foundry[75,76]. More recently, two other grades of machinable ADI have been developed in the US[77,78], specifically aiming at increasing the use of ADI for automotive applications such as chassis components and crankshafts.

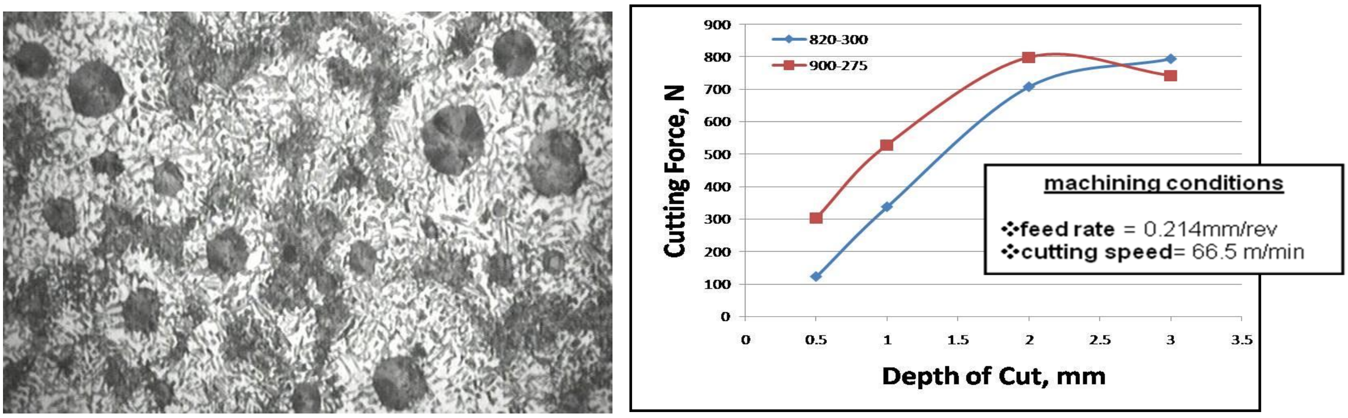
There are some differences between the two approaches, but the common feature is that the matrix structure contains a considerable amount of ferrite in both cases. The new grade, referred to as MADI™ is claimed to have unique machining characteristics and lower machining costs than as-cast ductile iron or regular ADI under appropriate conditions of speed and feed. In-plant machining trials have shown that MADI at 243 BHN could be machined on existing machine lines designed for ductile iron grade 65-45-12.

In a continuing effort to address the deficiencies of regular ADI, extensive efforts have been recently made to develop the dual-phase (ferritic-ausferritic) grades of ADI with enhanced machinability properties to compete with forged steel for power train applications[82-89]. The properties of dual phase matrix (DPM) ADI have been the subject of extensive studies.[16,55,90-99]

ADI offers an excellent compromise between the values of proof stress and elongation; both are very highly appreciated in the field of suspension parts in the automotive industry[100]. Many potential uses of ADI in competition with forged steel and aluminum alloys can be opened due to strong possibilities of weight and volume reductions.

The automotive industry has been showing a significant interest in the dual-phase intercritically austenitized ADI, several interesting publications can be cited recently in the literature.[101-109]

The optimum parameters of maching practice have been recently drawing increasing attention.[110-113]



(a) (b)

Fig. 8: (a) The microstructure of IADI austenitized at 820°C and austempered at 375°C.
(b) The cutting force reduction of IADI compared to the conventional ADI[25]

Fig. 8-a shows the microstructure of intercritically austenitized ADI sample (IADI) and the resulting decrease in machining force of this material compared to the conventional ADI (Fig. 8-b)[25].

Conclusions

1. Extensive research work over the past decade has helped to develop the property combination of ADI in three directions:
   - increased strength, ductility and toughness
   - enhanced wear resistance/toughness combination
   - improved machinability
2. Carbidic, bainitic/martensitic locally austempered as well as laser surface processed ADI offer opportunities for superior wear resistance, combined with reasonable toughness, which may open new applications for ADI.
3. ADI offers high levels of mechanical properties at a competitive cost. When the high strength of ADI is taken into account, it could successfully compete with lightweight alloys, as the additive weight required to give unit strength is lower. Moreover, when the relative cost of ADI required to give unit strength is considered, ADI seems to be one of the cheapest alloys. These points have yet to be fully appreciated by many design engineers. Currently, novel processing techniques adopted to achieve better strength and toughness properties include ausforming, cold-rolling, two-step austempering, as well as squeeze casting.
4. The current research work aiming at improving machinability of ADI looks rather vital for the future of this material. The available machining techniques required for forging steel are not always suitable for ADI components, particularly on a high volume machining line dedicated to the production of one specific product. This problem can be minimized with the development of ferritic + ausferritic ADI structures.

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