The production, properties and automotive applications of austempered ductile iron

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Abstract

Ductile iron is an important material which is produced throughout the world and used for a wide range of applications. It is now well established that its as-cast mechanical properties can be significantly improved by using an austempering heat treatment to produce a new family of materials known as Austempered Ductile Irons (ADI). The improved properties enable ADI to replace steel castings and forgings in many engineering applications with significant cost benefits.

This paper describes the key features of the production of ADI in the foundry and the options for carrying out the austempering heat treatment. The integration of machining operations and surface hardening treatments into the overall production route are also discussed. An overview is given of the effect of the process variables on the mechanical properties of ADI. Previous and current applications of ADI in the automobile sector are summarised and some of the challenges in developing the high volume production of ADI are considered.

Key words: Austempered Ductile Iron, ADI, automotive components

1. Introduction

The austempering heat treatment process was first developed [1] and applied to steels in the 1930's. This consists of heating a material into the austenite phase field and then quenching it to a lower temperature (the austempering temperature) and holding at this temperature to allow the austenite to transform isothermally to an acicular ferrite phase containing carbides known as bainite. Early trials to austemper ductile iron were undertaken [2] in the 1950's, soon after the development of ductile iron. Although further development continued during the 1960's by various companies, it was not until the mid-1970's that any significant commercial production started. There were almost simultaneous announcements in the USA [3], Finland [4] and China [5] that ductile iron castings could be austempered to produce mechanical properties which enabled them to replace surface hardened steel forgings for gears and other components with significant cost benefits. This new material was initially given various names including austempered bainitic nodular iron and austempered SG iron, and various patented versions emerged [4, 6, 7], but the world gradually adopted the term Austempered Ductile Iron or ADI. The announcements of commercial production resulted in a worldwide explosion in research which provided a sound foundation for expanding the production of this material in many industrialised countries during the 1990's and beyond. This paper summarises the main features of the production of these materials and their mechanical properties, and then discusses some of the previous and current applications of ADI in the automobile sector.

2. The production of ADI

The production of ADI components must start with the production of high quality ductile iron castings of an appropriate composition in the foundry, followed by austempering under carefully controlled conditions. Any machining requirements must be integrated into the overall production route, and some

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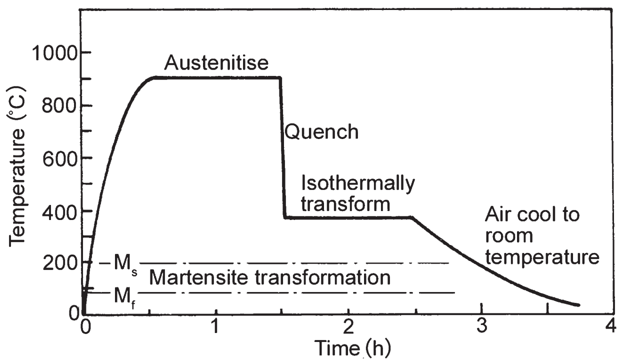

Fig. 1. Typical austempering cycle used for ductile irons.

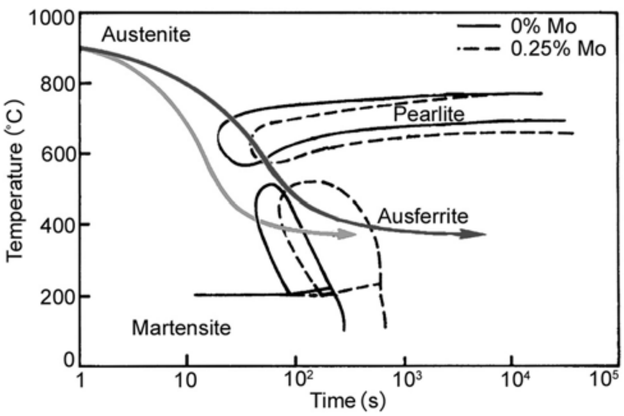

Fig. 2. CCT diagrams for 3.3% C, 2.6% Si, 0.3% Mn ductile iron with superimposed cooling curves.

components may benefit from a final surface treatment. Each stage will be considered in turn.

2.1. Foundry production

The main change in foundry practice when producing castings for austempering is to ensure that the ductile iron is correctly alloyed to allow the required microstructure to be developed during the austempering heat treatment. Figure 1 shows a schematic view of the austempering heat treatment cycle. The critical stage is the quench from the austenitising temperature to the isothermal transformation (austempering) temperature. Typical CCT (continuous cooling transformation) diagrams for ductile irons with two Mo contents are shown in Fig. 2 with superimposed schematic cooling curves for two section thicknesses. In order to produce the desired 'ausferrite' phase (described later), the ductile iron often needs to be alloyed to delay the start of the pearlite transformation. As shown in Fig. 3, for a given austempering temperature, the required ausferrite structure can be obtained up to a particular section size, beyond which

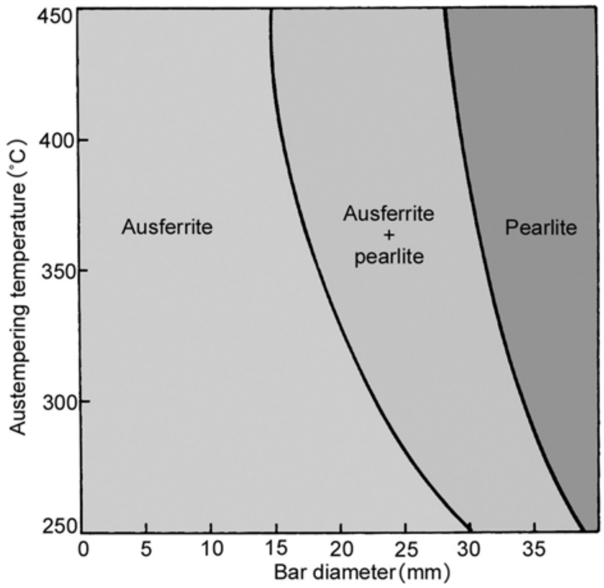

Fig. 3. The effects of austempering temperature and bar diameter on the microstructures produced at the bar centre.

increasing amounts of pearlite are formed [8]. The undesired formation of pearlite is prevented by adding small amounts of Ni, Cu and Mo, either alone or, more commonly, in combination [8]. However, there are limitations to the use of alloying elements. Although Mo has a strong effect on the 'austemperability' (i.e. the ability to quench without forming pearlite), it not only forms carbides but also segregates very strongly to the intercellular areas where it seriously delays the austempering reaction; this results in a heterogeneous microstructure with inferior properties. Most foundries restrict Mo additions to a maximum of 0.3%. The use of Cu is restricted by a limited solid solubility, whereas the use of Ni is restricted by cost. Mn is present in many ductile irons and although it increases the 'austemperability', it also segregates (like Mo) and the Mn content is usually restricted to a maximum of 0.4%, although some foundries find it beneficial to use much lower levels. Figure 4 shows [9] the effect of various combinations of Ni, Cu and Mo.

The following recommendation [10] has been made for the composition of ductile iron suitable for austempering:
C: 3.60% ($\pm$0.20%), Si: 2.50% ($\pm$0.20%), Mn: $\leq$ 0.35% ($\pm$0.05%) if section size $>$ 13 mm or Mn $\leq$ 0.60% ($\pm$0.05%) if section size $<$ 13 mm: Cu: $\leq$ 0.80% ($\pm$0.05%); Ni: $\leq$ 2.00% ($\pm$0.10%); Mo: $\leq$ 0.30% ($\pm$0.03%).

It should be noted that the alloying additions suggested in Fig. 4 were obtained by quenching simple shapes into a well-agitated salt bath where the volume of salt greatly exceeded the volume of castings being quenched. In industrial production, the metal:salt ra-

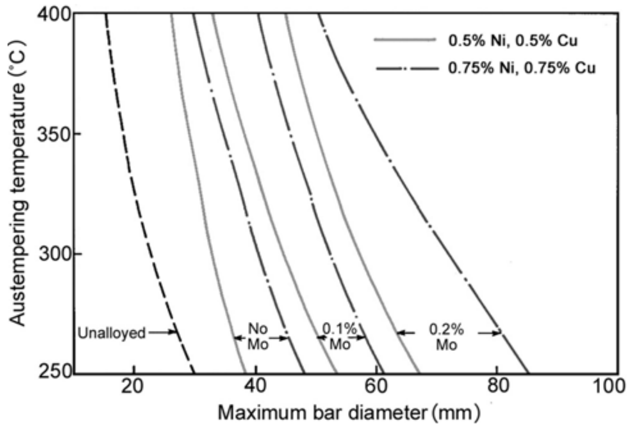

Fig. 4. Effect of combinations of Ni, Cu and Mo on the maximum bar diameter that can be austempered without the formation of pearlite [9].

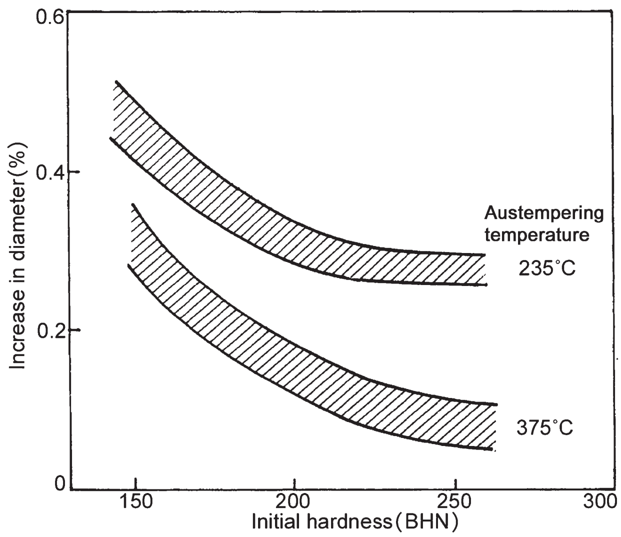

Fig. 5. Effect of initial structure and austempering temperature on the change in diameter of a 150 mm diameter disc [9].

tio will be considerably higher and components may be more complex; both factors will result in a reduced quench rate which may necessitate higher alloy additions. On the other hand, some commercial austempering companies add water to the salt to increase the quench rate and a technique has been developed [11] to super-saturate the salt with water. This enables the alloy addition to be reduced with obvious economic benefits [12]. It is therefore important that the person selecting the alloy composition (usually the foundry) liaises closely with the heat treater.

Although careful attention must be given to all stages of the production of any ductile iron casting, this is even more important in the case of components which are to be austempered. It must be stressed that austempering should be used to develop high levels of mechanical properties in good quality ductile irons, but not to 'rescue' poor quality castings. One guideline [10] is that the nodule count should be ≥ 100 nodules/mm^2 to minimise an uneven response to austempering caused by the micro-segregation of alloying elements; the foundry should exploit modern inoculation methods and materials to achieve this. Likewise, the nodularity should be $\geq 90\%$, the carbide and inclusion content should be $\leq 0.5\%$, and the porosity should be $\leq 1\%$. The foundry should exploit techniques such as computer simulation and filters to help them to achieve these targets.

It is often beneficial for the foundry to ensure a consistent as-cast structure so that the microstructural response and dimensional changes during austempering are reproducible. As shown in Fig. 5, the phase change during heat treatment results in growth of the castings by an amount which depends on the initial (as-cast) microstructure and the austempering temperature [8]. Hence, if the as-cast structure varies, the dimensional change during austempering will not be consistent. In some cases, it is wished to machine the castings before austempering but this is only feasible if the growth is predictable. Some [13, 14] have found it cost-effective to anneal the castings prior to machining since the lower hardness ferritic matrix increases machinability and the dimensional changes during austempering are consistent.

2.2. Heat treatment

Process. In the conventional austempering process, Fig. 1, castings are firstly heated into the austenite phase field and held for long enough to ensure a fully austenitic matrix structure with a uniform carbon content. The latter is a function of the austenitising temperature and affects the subsequent transformation to ausferrite. Typical parameters are 1 hour at 900 ℃. However, it should be noted that the upper critical temperature varies with composition, particularly the Si content, so this must be adequately controlled to avoid the need to adjust the austenitising temperature. The austenitising time depends on 3 main variables:

– The section thickness: thicker sections will need to be 'soaked' for longer times;

– The nodule count: high nodule counts reduce the austenitising time since they reduce the distance that C needs to diffuse to obtain a uniform C content;

– The initial microstructure: austenitisation occurs more rapidly in a pearlitic as-cast matrix structure.

In some cases, austenitisation is deliberately carried out in the $\alpha + \gamma$ range so that the final microstructure contains some pro-eutectoid ferrite to improve machinability.

Once austenitised, castings are quenched to the austempering temperature. This is below that for transformation to pearlite and above that for transformation to martensite (M_s) and usually in the range 235–400 ℃. It is important to miss the pearlite 'nose' (Fig. 1) by ensuring that the castings are appropriately alloyed and transferred rapidly into a quench medium having a high heat extraction capability. During isothermal holding at the austempering temperature, ferrite platelets nucleate and grow into the austenite and the excess carbon (arising from the different solid solubilities of C in ferrite and austenite) diffuses into the untransformed austenite. Whereas in steels the carbon precipitates as carbides to form 'bainite', the higher Si content of ductile iron delays carbide precipitation. Hence the austenite carbon content is progressively increased, reducing its M_s temperature. If castings are held for long enough, the M_s temperature is depressed to below room temperature and the final matrix structure will consist of bundles of ferrite platelets set in a matrix of retained austenite which has been stabilised by a high carbon content (γ_{HC}); this is called 'ausferrite'. The reaction is known as the Stage I reaction: $\gamma \rightarrow \alpha + \gamma_{HC}$ and is shown schematically [15] in Fig. 6a. The end of Stage I is defined as that time when no martensite is present in the room temperature structure.

As the austempering time is extended, the Stage II reaction eventually occurs in which the austenite decomposes to form more ferrite and carbides are precipitated: $\gamma_{HC} \rightarrow \alpha$ + carbides. This results in a deterioration in the mechanical properties. The period between the end of Stage I (t_1) and the start of Stage II (t_2) is known as the 'processing window' and has been the subject of extensive research. It is clear that the optimum combination of mechanical properties is achieved when the austempering time falls between these two values.

As the austempering temperature is reduced, the driving force for the formation of ferrite increases and the diffusion rate of carbon decreases. This can result in the excess carbon remaining trapped in the ferrite and the precipitation of silico-carbides at the same time as the ausferrite, Fig. 6b. This is analogous to the lower bainite formed in steels and produces a hard grade of ADI having relatively low ductility and toughness.

A variety of ausferritic matrix structures with different amounts and distributions of ferrite and retained austenite can be produced, particularly by varying the austempering temperature. These different structures control the mechanical properties obtained.

Micro-segregation in more highly alloyed ductile irons will result in different transformation rates in different parts of the microstructure and it is possible for the undesirable Stage II reaction to start in the low alloy areas before the desirable Stage I reaction is

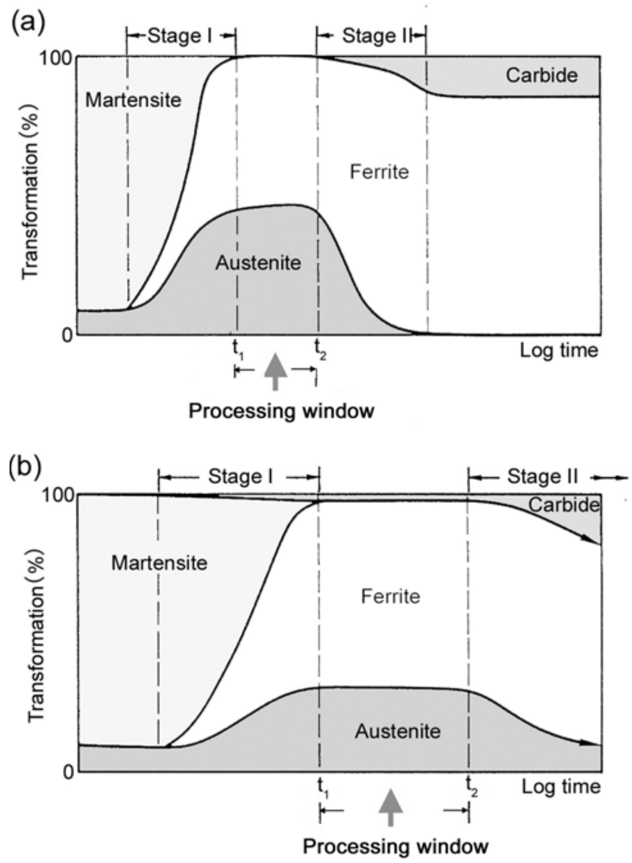

Fig. 6. Developments in the microstructure when austempering ductile iron at (a) high temperatures, (b) low temperatures. After Voigt [15].

completed in the high alloy areas, i.e. the 'processing window' is closed, leading to an overall reduction in the properties. This can be reduced by ensuring a high nodule count and carefully selecting the alloying elements and heat treatment.

Austempering plant. A variety of different plant designs can be used for the commercial production of ADI. The most commonly used technique is "atmosphere-to-salt" in which components are austenitised in a controlled atmosphere furnace to prevent scaling and decarburisation, and then quenched into a molten salt bath where it is held for the duration of the isothermal reaction. Various mixtures of sodium and potassium nitrites and nitrates are used. A specialised 'ausquench' furnace has been developed [16] as shown schematically in Fig. 7. This is a derivation of the sealed quench furnaces used for carburising steels but with the normal oil quench tank replaced by a heated molten salt bath, usually with the addition of water as described above. A number of these furnaces have been installed throughout the world by either foundries or specialised sub-contract heat treaters.

The world's largest sealed quench austempering furnace, Fig. 8, has recently been installed [17] by the

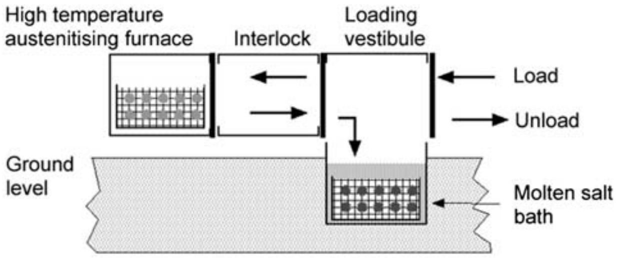

Fig. 7. Schematic view of an 'atmosphere-to-salt' austempering furnace.

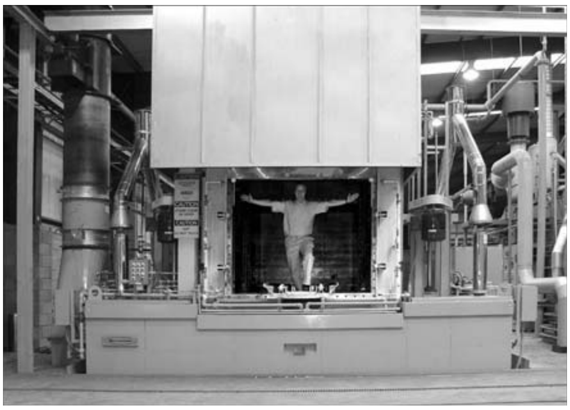

Fig. 8. Austempering furnace recently installed in the UK [17]. Courtesy of ADI Treatments Ltd., UK.

leading European sub-contractor (ADI Treatments Ltd., UK) at a cost exceeding £1M. Components up to 1.8 m and gross loads of up to 2.75 tonnes can be treated. Particular attention has been given to the circulation in the salt quench tank to ensure homogeneity of the process and final material properties. One advantage of this type of furnace is that it can be used for other heat treatments which is useful when the throughput of ADI is being developed or fluctuates. If surface scaling and decarburisation can be tolerated, it is possible to use less sophisticated equipment, such as a high temperature furnace without atmosphere control, but this is unsuitable for most automotive components.

The second most commonly used technique is "salt-to-salt" in which the components are austenitised in a high temperature salt bath (containing sodium chloride and barium or potassium chloride) and then quenched into the nitrite/nitrate austempering salt bath. Such an arrangement is less sophisticated and uses less expensive capital plant, but can provide a cost-effective means of austempering and has been used by various companies [18, 19]. There are various technical and economic advantages and disadvantages of the "atmosphere-to-salt" and "salt-to-salt" techniques and careful consideration must be given to these by any company wishing to enter this market.

The first high volume automotive application of ADI was for rear axle gears used in cars produced by General Motors [3, 13]. After austenitising in a multi-station 'pusher' controlled atmosphere furnace, these were quenched and austempered at ~ 238 ℃ using a hot oil which was specially developed for the purpose. Hot oil was also used when producing ADI timing gears for certain diesel engines manufactured by Cummins [14]. The main limitation of using hot oil is the maximum austempering temperature of ~ 250 ℃ which therefore restricts its use to the hardest grades of ADI. It has been suggested [20] that it is possible to quench briefly into hot oil and then to transfer to an air muffle furnace set at a higher austempering temperature, but this idea does not appear to be used commercially.

Molten salts have various disadvantages, particularly the need to ensure that components are thoroughly washed to remove all traces of salt which would otherwise lead to subsequent corrosion. This generates large volumes of salt-contaminated water and further equipment is then required to reclaim the salt before the water can be discharged [16]. Although there has been some interest [21] in using fluidised beds for both the austenitising and austempering stages to avoid these environmental problems, the significantly lower quench rate appears to have precluded industrial use.

It can be noted that some components only require the austempered structure in particular areas, examples being the mating faces and roots of gear teeth and the surfaces of camshafts. The concept of 'selective austempering' has therefore been developed [20, 22] in which induction heating is used to austenitise the area of interest prior to conventional quenching and isothermal transformation. An important advantage of this is the reduced heat treatment cycle time. CWC Textron (Muskegan, USA) has developed and patented [23] a selective austempering technique for ductile iron camshafts as a cost-effective alternative to forged steel camshafts.

Finally, there has been some interest in removing castings from the mould whilst they are still hot, and charging them directly into the heat treatment line [24]. As well as reducing the cycle time, there is the potential for significant energy savings since castings do not have to be re-austenitised (although it may be beneficial to hold them for a short time in an austenitising furnace to improve the temperature homogeneity). This idea has re-surfaced in a recent EC-funded research project [25] which has involved the use of squeeze casting to produce near-net shape castings with minimum porosity. It has been found that the mechanical properties exceed those of conventional ADI.

2.3. Machining

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, this phase rapidly work hardens and can transform to martensite; this can thereby reduce the machinability compared with a steel of equivalent hardness.

ADI components are now used in a very wide range of applications having an equally wide range of requirements regarding accuracy and surface finish. Figure 9 summarises the options regarding the integration of the machining operations into the ADI production route. At one end of the scale, substantial numbers of ADI components do not require to be machined; examples include ground-engaging agricultural and earth-moving tools. However, most automotive components will need to be machined. Most of those made in the softer grades of ADI can be machined after heat treatment using appropriate machine tools and inserts. This becomes progressively more difficult as the hardness increases and it is often preferable to machine before heat treatment by making an allowance for the dimensional growth, assuming that this is predictable and that there is no significant distortion. If the dimensional growth is not sufficiently consistent, the only option is to do most of the machining before austempering, and to finish machine any critical dimensions after austempering. This can create logistical difficulties if the casting, machining and heat treatment are done by different companies located at some distance from each other. Nevertheless, this route has been widely used for ADI gears which must be extremely accurate for them to operate quietly and to have a long life. It can be noted that the North American approach [16] has generally been to use a higher Mn base iron than in Europe to reduce the foundry costs, but the resulting ADI is harder to machine, so more than half of the ADI components produced in North America are finish machined before austempering. In contrast, many European ADI castings are machined after heat treatment.

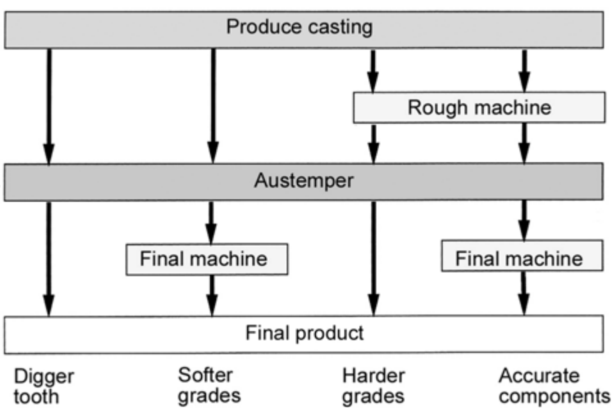

Fig. 9. Options for integrating casting, machining and heat treatment of ADI components.

It is considered [26] that the limited use of ADI for high volume applications is partly due to machining difficulties. There have been two different approaches to remedy this: to establish the best machining tools and conditions and to develop machinable grades of ADI.

Machining practice. One approach has been to optimise the machining operations, particularly the selection of the optimum cutting tools and parameters. A considerable amount of research (see, for example [27–29]) has been done in this area and has been digested in the form of simplified guidelines [30–33]. It is normally recommended that the aim should be to ensure that the tool cuts below the hardened surface layer in ADI by selecting a higher depth of cut (typically 50% more) and using a slower speed (typically 50% less) than would be used for a 'conventional' material of the same hardness. Careful consideration should also be given to tool material and geometry and the use of cooling lubricants by discussion with appropriate suppliers. As one example, Kammermeier [28] found that a silicon nitride ceramic with a multi-layer CVD coating gave the least wear when turning ADI 800 but CBN and PCD tools were not suitable. As another example, Klocke and Klöpper [29] found that wear resistant cemented carbides (K10, based on tungsten carbides) with wear resistant coatings (Al_2O_3 TiCN or TiAlN) can be successfully used at low cutting speeds, whereas Al_2O_3 ceramics, mixed ceramics and whisker-reinforced ceramic materials gave good results at higher cutting speeds.

It is recommended [33] that the workpiece must be rigidly clamped and a rigid toolholder should be used to minimise vibration during machining and thereby reduce tool wear, improve surface finish and reduce dimensional variations. The suggested tool materials are shown in Fig. 10 as a function of hardness. This also provides useful advice about the starting machining conditions if the machinist already has experience of machining ductile iron. The graph is used to give the ratio of the machining surface speed coefficients for the ADI (M_{ADI}) and the known ductile iron (M_0) and this is used to suggest a machining speed for ADI (S_{ADI}) from the acceptable surface speed for the known material (S_0). This suggested value can be subsequently increased in steps of 5% until tool wear or surface finish become unacceptable.

T a b l e 1. Effect of shot peening on the residual stress of a lower ausferritic ADI [38]

Surface treatment	Residual stress (MPa)	Fatigue limit (MPa)	
		Mean stress, σ_{m}	Stress amplitude, σ_{a}
None	+143 (±10)	156	±127
Rolled, 5 kN load	−78 (±20)	183	±150
Rolled, 9 kN load	−216 (±29)	211	±172
Peened to 6 Almen A intensity	−241 (±49)	212	±173
Peened to 16 Almen A intensity	−248 (±10)	283	±231

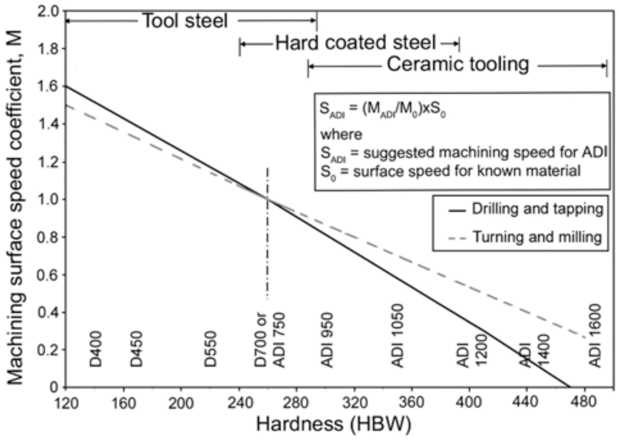

Fig. 10. Suggested tool materials and machining conditions for ADI [33]. Courtesy of Applied Process Inc.

Machinable ADI. The other approach has been to optimise the composition and heat treatment to maximise the machinability. In the 1980's, Muhlberger developed [34] and patented [6] a machinable grade of ADI by careful selection of the composition (low Mn) and heat treatment variables, and at least one European foundry [35] has exploited this development in commercial production. More recently, two grades of a machinable ADI have been developed [26] in the US (and patent protection [36] applied for). These are specifically aimed at increasing the use of ADI for automotive applications such as chassis components and crankshafts. There are some differences between the two approaches, although the matrix structure contains a considerable amount of ferrite in both cases. The interest in machinable ADI has been confirmed by Aranzabal *et al.* [37] who have described research in Europe to develop a mixed ferritic-ausferritic ductile iron for automotive suspension parts, and expect it to be validated on such a component in the near future.

2.4. Surface treatment

It is well known that cold working operations such as controlled shot peening (*not* uncontrolled shot blasting as used by foundries to remove mould materials from castings) or fillet rolling can improve the fatigue properties of engineering components by introducing a favourable compressive stress. It is quite clear that ADI also responds favourably to such treatments. Components treated at low austempering temperatures (235–300 °C) can have a tensile residual stress at the surface [13, 38], but this can be changed to a compressive residual stress by surface rolling or shot peening with a significant increase in fatigue strength [38]. Table 1 shows that increasing the intensity of cold working resulted in an increasingly compressive residual stress and an increase in the fatigue limit. Although the effect was not linear, it is possible that this was due to scatter in the residual stress measurements.

Components treated at the higher end of the austempering temperature range also benefit from similar cold working treatments. In addition to any direct effect on the residual stresses, it appears that there may be an additional benefit from the compressive stresses brought about by the strain-induced transformation of retained austenite to martensite. This has been demonstrated in gears [4] and crankshafts [39]. For example, Warrick *et al.* [40] have reported that the endurance limit of an ADI crankshaft could be increased from 414 MPa to 1,000 MPa by fillet rolling. They also shot peened upper control arms to improve the fatigue strength of unmachined casting surfaces. Brandenberg *et al.* [41] have provided information on the effect of shot peening a Grade 4 ADI.

Clearly, the use of these surface treatments will add further cost, so a careful cost benefit analysis should be carried out before applying them.

2.5. Quality control

The successful production of reliable ADI components requires careful attention to ensure that the foundry, heat treatment and machining operations are carried out consistently. Although test bars are routinely processed with each batch of castings, one concern among some end-users is the difficulty of ensuring that *every* component meets the minimum specified properties. There has been some research on the use of non-destructive testing techniques to assess the microstructure and/or properties of ADI compon-

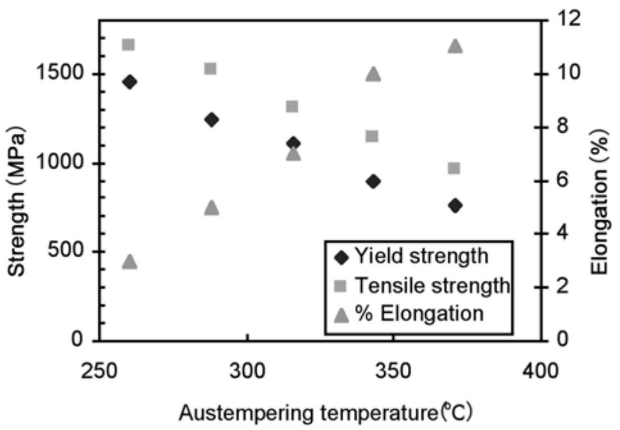

Fig. 11. Typical tensile properties of ADI as a function of the austempering temperature. Based on data from Rundman [44].

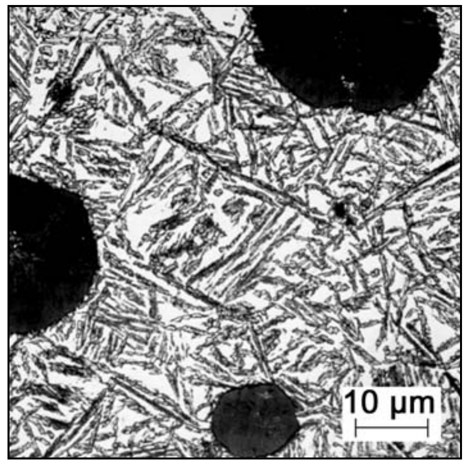

Fig. 13. Typical microstructure obtained by austempering at a high temperature (375 °C).

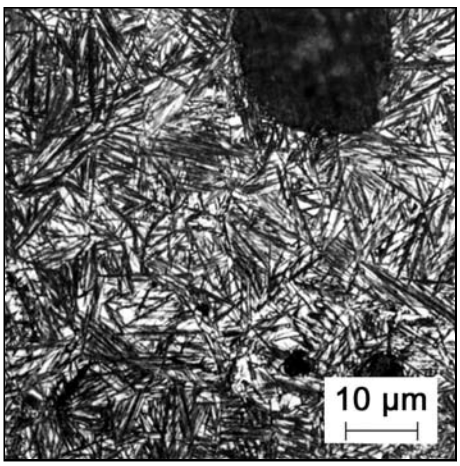

Fig. 12. Typical microstructure obtained by austempering at a low temperature (260 °C).

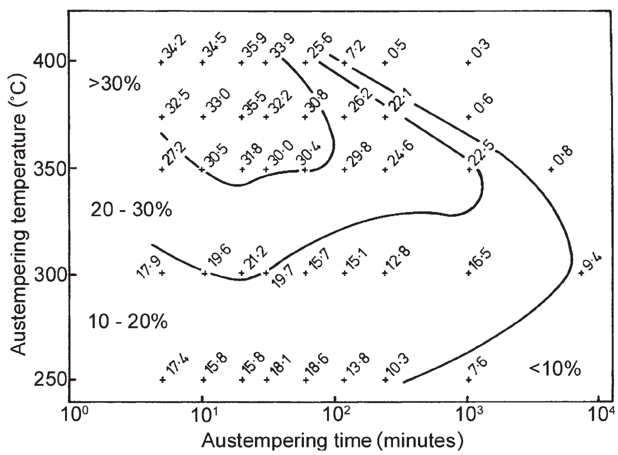

Fig. 14. Effect of austempering parameters on the retained austenite content. Ductile iron alloyed with 1% Ni [45].

ents. An extensive investigation has shown [42, 43] that multi-frequency eddy current testing is a powerful technique, although it cannot completely replace conventional tensile testing. This was used by Warrick *et al.* [40] to check that every ADI upper control arm had been properly austempered.

3. Properties of ADI

There have been many studies of the mechanical properties of ADI and it is clear that these depend on a number of interlinked factors. As well as the austenitising and austempering temperatures and times, these include the as-cast structure, the composition and the section size. Of these, the austempering temperature is the most important and Fig. 11 shows its effect on typical [44] tensile properties. These variations in properties can be related to the changes in microstructure. At low austempering temperatures, an acicular (needle-like) ferritic phase is formed, Fig. 12, 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 strengths and hardness but only limited ductility. As the austempering temperature is progressively increased, the ferrite becomes coarser and increasing amounts of retained austenite (up to $\sim$ 40%) are formed; the typical 'ausferrite' structure is shown in Fig. 13. This results in a substantial increase in ductility and a reduction in strength and hardness. Once the austempering temperature exceeds a certain value (typically 375–380 °C), the Stage II reaction occurs very rapidly, resulting in a reduction in the retained austenite content and a corresponding decrease in ductility. The unique properties of ADI are

Table 2. Mechanical properties specified in ASTM A897M-03

Grade	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Unnotched Charpy impact energy (J)	Typical hardness (BHN)
1	900	650	9	100	269–341
2	1050	750	7	80	302–375
3	1200	850	4	60	341–444
4	1400	1100	2	35	388–477
5	1600	1300	1	20	402–512

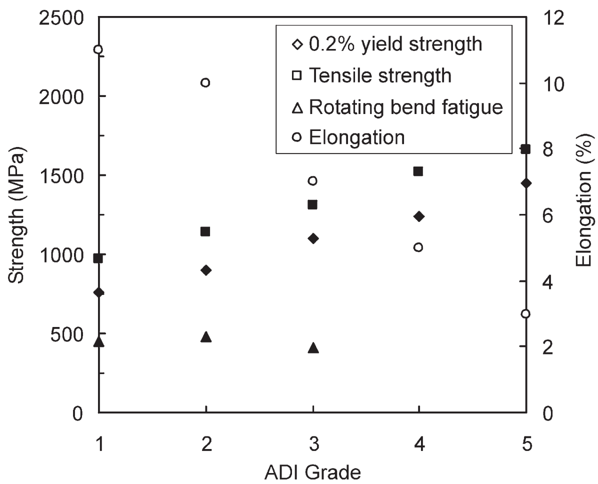

Fig. 15. Typical values of the tensile and fatigue properties of ASTM A897M-03 grades of ADI using data from [50].

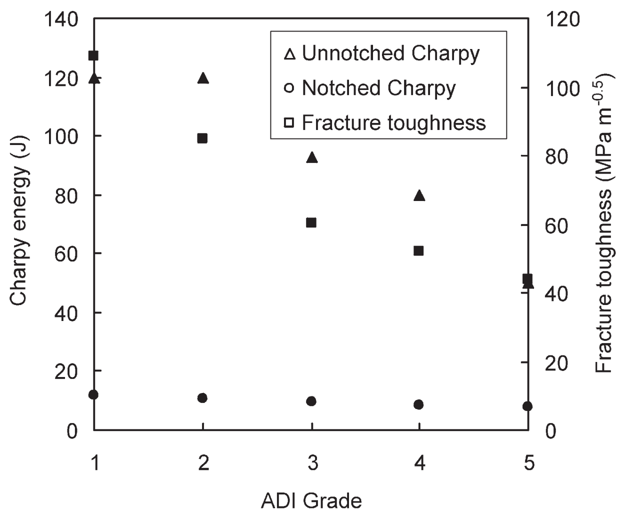

Fig. 16. Typical values of the impact and fracture toughness properties of ASTM A897M-03 grades of ADI using data from [50].

closely related to the retained austenite content which is controlled mainly by the austempering temperature and time, as shown by the map [45] in Fig. 14.

It was recognised early in the development of ADI that specifications for specific grades were required by the buyers and suppliers of these materials. The most widely used specification is probably that developed by ASTM in 1990 and subsequently updated [46] in 2003. This is in both inch-pound (ASTM A897–03) and SI units (ASTM A897M-03). The latter is shown in Table 2. Dorn *et al.* [47] have reviewed and compared the SAE and ISO Standards for ADI. There are also European [48] and Japanese [49] standards.

There are numerous papers on the Charpy impact, fracture toughness and fatigue properties of ADI and it has generally been found that these also generally increase with the retained austenite content. Figures 15 and 16 show typical values of these properties [50] for the various ASTM grades of ADI. The QIT design guide [31] gives further useful information. There has also been a considerable amount of research to measure the bending and contact fatigue properties of ADI gears and to compare these with other materials [31].

Good wear resistance is usually obtained in any material by ensuring a high hardness. Low austempering temperatures (235–250 ℃) produce hard ADI (∼ 480–550 BHN) and such grades would be selected when good wear resistance is the main requirement. As the austempering temperature increases, the hardness decreases, resulting in more wear. However, the softer grades of ADI (typically 280–320 BHN) contain large amounts of retained austenite and, as already indicated, this can work harden and/or transform to martensite when subjected to mechanical strain at the surface. This results in the wear resistance being significantly better than would be expected. This is illustrated by the results of abrasive and impact-erosion wear tests [8] in Figs. 17 and 18 respectively. Although this effect is a disadvantage when machining, it can be very beneficial for certain ADI components since as the surface is worn away, it is continuously replaced by a freshly formed, hardened layer.

Figure 19 compares the tensile properties of the ASTM grades of ductile iron with those of conventional ductile irons and a wide range of forged steels and shows the very competitive position of ADI compared with the mid-strength forged steels. Of course, the selection of materials is usually based on a much wider range of factors including other mechanical properties, physical properties such as density and

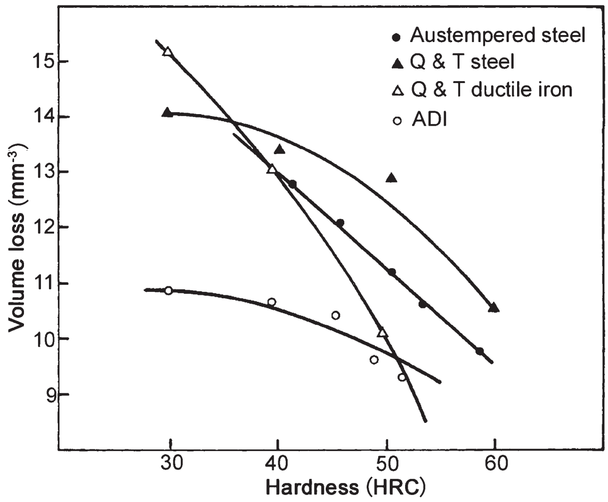

Fig. 17. Pin abrasion wear tests on ADI, ductile iron and two steels [8].

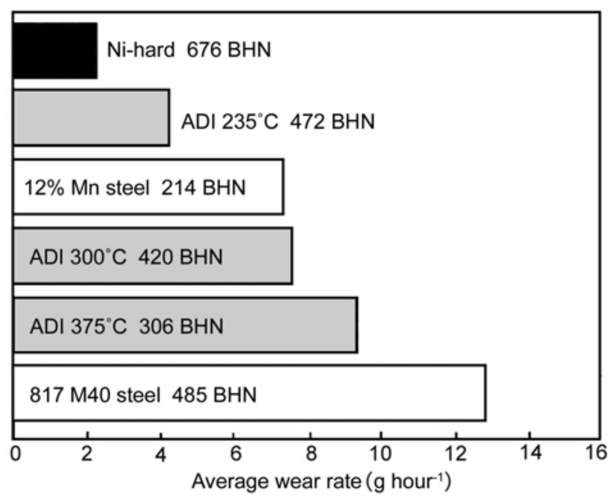

Fig. 18. Impact erosion wear tests on ADI and competing materials [8].

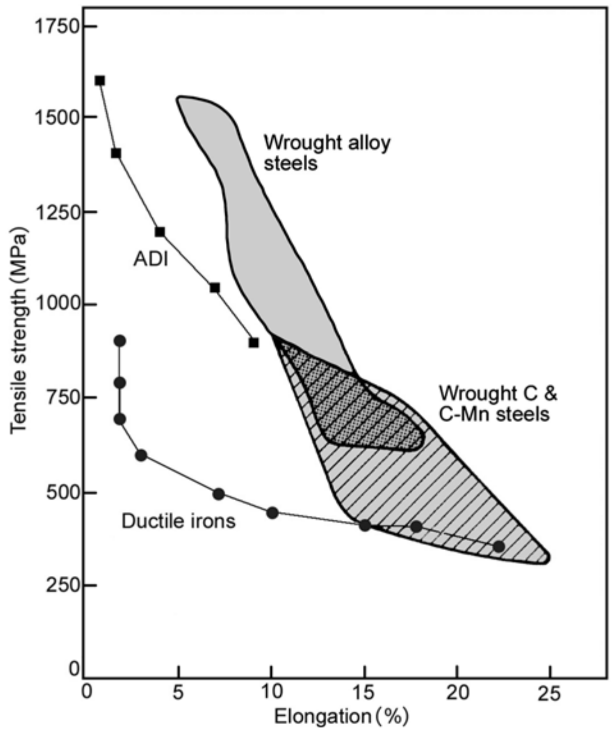

Fig. 19. Comparison of the minimum tensile properties of ADI (ASTM A897M-03), ductile irons (EN1563:1977) and forged steels (BS970:1983).

cost. Keough and Hayrynen [51] have provided the data shown in Figs. 20 and 21 which demonstrate the competitive position of ADI compared with forged steel and cast and forged aluminium alloys.

Finally, it has recently been found [52] that ADI can be embrittled when in contact with water and some other liquids such as oils and alcohol, as revealed by a drop of up to 30% in the tensile strength and up to 70% in the elongation. The phenomenon is also found in conventional ductile irons (apart from those with a ferritic matrix) but is not yet fully understood. It is claimed [52] that the machinable ADIs developed recently are less susceptible. Martinez *et al.* [53] have provided a useful review of the current understanding and have proposed that it is linked to micro-cracking in the last-to-solidify zones at applied stress levels above the yield strength. However, since engineering components are normally designed so that they do not exceed the yield stress, it does not appear that this apparently alarming discovery is particularly significant.

4. Advantages and disadvantages of ADI

This aspect has been covered in many papers on ADI, but it is nevertheless useful to reiterate some of the key points. In brief, the advantages include:

– Lower tooling costs and improved tool life compared with steel forgings

– Lower raw material costs compared with steel or aluminium

– Lower energy costs compared with steel casting or forging

– Higher foundry yield (less feed metal, lower scrap) compared with steel or aluminium castings

– More component design freedom compared with forging, including the ability to make hollow shapes, to use reduced draft angles, and the ease of incorporating strengthening ribs and webs and lightening windows

– Improved ability to cast net shape components compared with steel

– Improved machinability in the as-cast condition

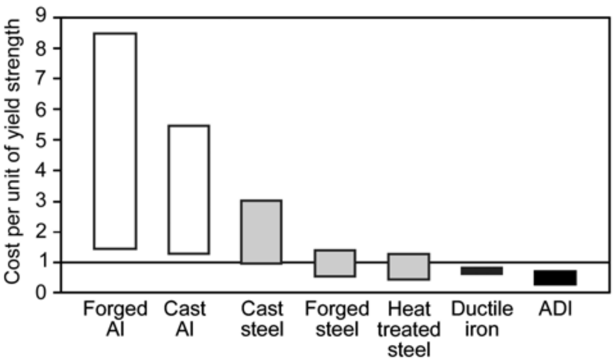

Fig. 20. Comparison of the cost per unit of yield strength for different materials. Courtesy of Applied Process Inc.

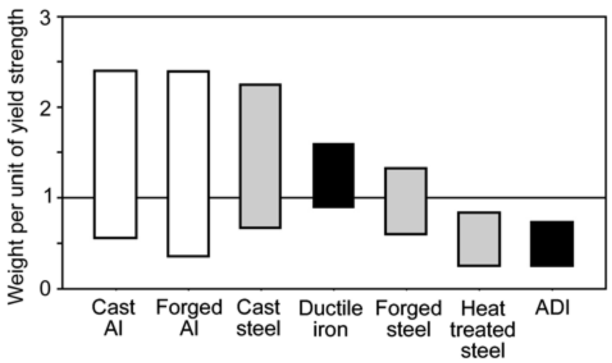

Fig. 21. Comparison of the weight per unit of yield strength for different materials. Courtesy of Applied Process Inc.

– Less distortion and risk of cracking during austempering compared with quenching and tempering treatments used for steels

– Lower density than steel

– Better noise and damping characteristics compared with steel

– Ability to work harden in service.

In contrast, the disadvantages include:

– Relatively poor machinability in the austempered condition which can lead to difficulties in inter-linking the foundry, machining and heat treatment operations

– The high cost of austempering when done in small quantities

– The high capital cost of austempering plant means that it is often difficult to justify an in-house facility, although good sub-contract austempering facilities are now available in the US, Europe and Australia

– Lower elastic modulus than steels which may require the component design to be modified to increase the stiffness (although the increased flattening that takes place between mating surfaces usefully reduces the contact stresses)

– In common with most cast irons, ADI has poor weldability, thereby precluding the use of welding as part of the assembly process or for in-service repair

– The service temperature range is limited to about −40 ℃ to +200 ℃ due to the risk of microstructural changes leading to a change in properties (although occasional excursions to 300–350 ℃ are permitted)

– In spite of considerable publicity, the material is still largely unknown amongst many potential end-users.

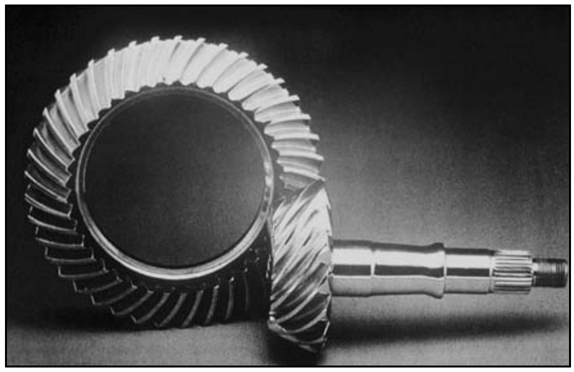

Fig. 22. ADI hypoid pinion and ring gear pair.

5. Automotive applications of ADI

Since its introduction in the 1970's, ADI has been used in many wear resistant and engineering components in many different sectors including automotive, trucks, construction, earthmoving, agricultural, railway and military. Keough [54] has estimated that the worldwide production of ADI reached 125,000 tonnes/year in 2000, and it has been predicted [16] that ADI will grow to 200,000 tons/year in USA and 300,000 tons world-wide by 2010. This paper will only consider the documented automotive applications.

5.1. Gears

In December 1976, General Motors (USA) announced [3] the first high volume automotive application for ADI in which it would replace a case-carburised forged steel for hypoid pinion and ring gear pairs for use in the 1977 models of certain Pontiac cars, Fig. 22. The material was austempered at 235 ℃ to give a hardness of 56–61 HRC, and the roots of the gear teeth were shot peened to improve the bending fatigue strength. Various benefits were claimed for this substitution including a weight saving of 0.6–0.9 kg per gear pair, reduced transmission noise, a 50% reduction in energy consumption during manufacture, an improved machinability and tool life, and a cost saving [16] of $\sim$ 20%. Similar substitutions were also made on other models, and over 5.5 million gear pairs had been used successfully by 1984 when there was a large-scale switch to front wheel drive cars.

Related successful high volume (but not strictly automotive) applications of ADI include rear axle hypoid gears in Chinese trucks [5] and timing gears for diesel engines [14] produced by CDC (a joint US venture between Cummins and Case). The latter gave cost savings of 30% over induction hardened or case-carburised forged steel gears.

Johansson [55] has reported that ADI bevel gears have been used successfully in a Ford Escort rally car to replace a case hardened forged steel.

5.2. Crankshafts

Conventional ductile iron has competed successfully for many years with forged steel for manufacturing crankshafts for petrol engines for passenger cars, but has generally not had sufficient strength for more highly stressed diesel engine crankshafts. Twenty years ago there was great interest in an announcement [56] by the Ford Motor Company (USA) that they had carried out extensive R&D on ADI crankshafts and that these would be replacing forged steel for diesel engine crankshafts in 1987. The ADI crankshafts were found to have double the fatigue strength of pearlitic ductile iron and to perform successfully at engine torques 10% higher than those specified for the forged steel crankshafts. The cost saving was estimated to be between $80–160 per part. However, full scale production never materialised, apparently because the much awaited Thunderbird Super Coupe was running behind schedule and over budget so the ADI crankshaft was dropped in favour of an imported steel forging [51].

Chrysler Corporation [57, 58] and most major automotive manufacturers, including GM, Ford, Nissan and Toyota [51] have also undertaken extensive development on ADI crankshafts, apparently without leading to any subsequent industrial production. An extensive project carried out in the 1990's in the UK showed [59] that ADI crankshafts thermally expand about 20% more than conventional ductile iron or steel crankshafts and this must be allowed for when designing the oil clearance tolerances in the bearing areas to prevent engine seizures.

However, a successful low volume automotive application has been reported [60, 61] where ADI has been used to replace forged steel for the crankshaft in the 4 litre, 350 bhp in-line 6-cylinder engine in the TVR Tuscan Speed Six sports car manufactured in the UK. Advantages include a 4.5 kg weight saving (13%), lower manufacturing costs, and improved NVH (Noise-Vibration-Harshness) properties. The castings are rough machined, austempered, then finish machined and finally fillet rolled. This is apparently [60, 61] the only known production automotive application for ADI crankshafts. Tests showed the ADI crankshafts to have a fatigue strength of 427 MPa, compared with 324 MPa for a 800/2 pearlitic ductile iron and 400 MPa for a forged steel.

Bahmani *et al.* [62] have provided a detailed account of a study of the use of ADI to replace induction hardened forged steel for crankshafts for a 4 cylinder petrol engine and a single cylinder diesel engine. The latter is being produced for rice farm vehicles in Iran. The estimated cost saving is about 30%. Warrick *et al.* [40] have reported that Intermet has produced over a million austempered compressor crankshafts, but few details are available. European interest in ADI crankshafts continues. For example, an EC-funded CRAFT project called 'Synergy' involves a number of partners and is developing hollow ADI diesel engine crankshafts using the lost foam casting process [63]. The aims include reducing the weight, cost and manufacturing time. It is confidently expected that ADI crankshafts will be used in European cars within the next few years.

5.3. Connecting rods

Martinez *et al.* [64] have described the development of a hollow ADI connecting rod weighing 400 g to replace a forged steel design weighing 600 g for an innovative 2 cylinder, 55 HP engine. Extensive testing on prototype engines has given excellent results, but there is no evidence that these components have reached production.

5.4. Camshafts

A wide variety of ferrous materials is used for camshafts depending on the valve train design. GM (USA) first used ADI camshafts for the L-4 engine [51] in the 1980's. This camshaft was employed for the production life of the L-4 engine and exceeded the requirement of 1,750 MPa contact stress at 10 million cycles with no pitting. It was produced for them by Intermet Corporation (USA). In 2000, it was reported [40] that they had produced over 500,000 selectively austempered camshafts, but is not known whether this was for more than one engine design.

Mazda [65] have used ADI camshafts for V6 petrol engines and have achieved cost savings and better pitting fatigue resistance than induction hardened forged steel or chilled cast iron. In 1991, it was reported that over 300,000 had been produced.

5.5. Timing gear support

ADI is used for manufacturing wheel cassette assemblies, Fig. 23, for a Volkswagen V10 diesel engine [66]. This supports part of the gear train which is used in place of the normal toothed belts to link

Fig. 23. ADI wheel cassette components for diesel engines. Courtesy of ADI Treatments Ltd.

Fig. 24. ADI tripot housing used in Delphi Corp. constant velocity joints. Courtesy of Applied Process Inc.

the twin camshafts, alternator, air conditioning compressor and the water, steering and oil pumps. Advantages of a gear train include a more compact design, improved fuel efficiency and an improved life (no need to change belts). ADI was selected on the basis of its mechanical properties, damping (leading to quieter operation), and ease of producing complex geometries cost effectively. Production currently stands at 7500–9000 sets per year (2 parts per set).

5.6. Engine mounts

ADI has been used [65] for engine mounts by Mazda, Japan to replace steel weldments with weight and cost savings. It has also been reported [16] that ADI engine mounting brackets are used by GM, Ford and Mazda in the US.

5.7. Transmissions

Following their success with ADI hypoid gears, General Motors (USA) started producing tripot housings, Fig. 24, in 1979 using the same hard grade of ADI. These form part of the constant velocity joints used in 4 wheel drive cars and light trucks made by GM, Dodge, Jeep and Audi [51]. It was reported [16] in 2003 that production by Delphi Corporation continues at 9,000 parts per day.

ADI has been used [65] for the centre differential casing on Mazda 4 wheel drive vehicles where the conventional pearlitic ductile iron was inadequate when the engine power was increased. George Fischer have also reported [20] that ADI has been used for limited slip differential casings for 4 wheel drive cars; these are selectively austempered [22].

5.8. Suspension components

ADI has been used for numerous suspension components in heavy goods vehicles, but according to Seaton and Li [67] there has been little interest until recently in using ADI for automotive and light truck suspension components. Instead, the emphasis has been on converting ductile iron components to aluminium for weight savings at higher cost. However, with a changing emphasis to cost reduction, ADI may offer a cost and weight competitive alternative.

Warrick *et al.* [40] have provided a very detailed account of the development of an ADI upper control arm for a limited edition of the 1999 Ford Mustang Cobra sports car. Various design iterations using finite element modelling led to a 25% weight saving in this safety-critical component. A Grade 1 ADI was selected and shot peening was used to increase its fatigue strength. Competing materials were a ferritic ductile iron, a steel forging and an aluminium casting. It is not clear whether this component is still in production.

Seaton and Li [67] and Spada [30] have described the design and testing of a Grade 1 ADI lower control arm for the 2003 heavy duty Dodge Ram pick-up truck as an alternative to the planned stamped steel weldment. This substitution would have led to 54% lower tooling costs and a small reduction in part weight (6%) and cost (2%). Unfortunately, errors during the development stage led to a delay in developing an acceptable ADI part and the opportunity for vehicle testing was missed. As a result, the stamping was chosen for the application, but it is considered that the experience gained would enable ADI to be considered for future applications and as a replacement for aluminium. Hayrynen [68] has provided brief details of the use of a Grade 1 ADI for a torsion bar adjuster for the Dodge Ram 4 × 4 pick-up truck.

Kurikuma has detailed [69] the development of ADI for automobile suspension system components at Aisin Takaoka, particularly ball joint sockets which are traditionally made from a low C forged steel. A 15% cost saving and a 10% weight saving were

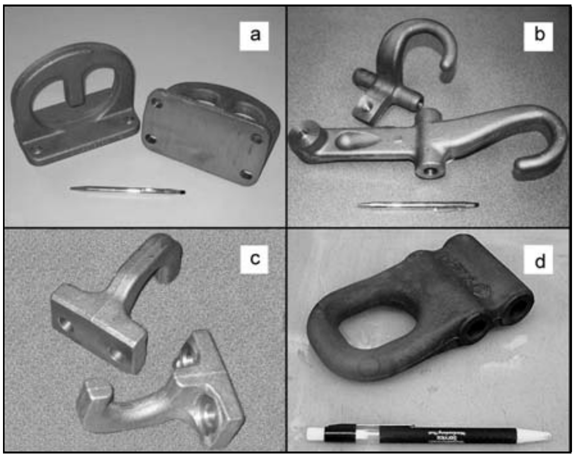

Fig. 25. ADI towing hooks for (a) Jeep Liberty, (b) GM, (c) Chevy Equinox, (d) Hummer. Courtesy of Applied Process Inc.

achieved. It appears that this part, as well as torque arms and engine mounting brackets, entered production. Aranzabal *et al.* [37] have described recent research to develop a mixed ferritic-ausferritic ductile iron for automotive suspension parts. ADI has also been used successfully for similar components (hollow front uprights) for racing cars in the 2001 Argentinian championships [64].

5.9. Tow hooks

It has been reported [61] that ADI is now used instead of steel to make towing hooks for a variety of light trucks, Fig. 25. As well as doubling the load carrying capacity of the previous hooks, the crash testing performance of the vehicles has been improved. Production started in 2000 and is reported to exceed 2 million parts per year, making it the highest volume ADI automotive part in the world.

6. Concluding comments

The available production statistics suggest [16] that light vehicles represented 25% of applications for ADI in the US in 2003. Although this is quite respectable, it would seem to be a relatively small fraction of the potential market. With the exception of tow hooks and some medium volume components, it does not appear that there are any ADI automobile components being currently produced in high volume anywhere in the world. There are numerous reasons for this, including the following:

1. A car manufacturer – or its foundry supplier(s) or a sub-contractor – will need to invest in dedicated heat treatment plant capable of austempering the large numbers of components required. Clearly, such capital expenditure requires a high level of confidence in the process and the product and a commitment by all parties involved. The most successful high volume automotive application was the rear axle hypoid gears for General Motors; in this case, the heat treatment plant was installed by GM.

2. The different machining techniques required for forged steel and ADI components mean that it is not easy to transfer easily from one material to another, particularly on a high volume machining line dedicated to the production of one specific product, such as a crankshaft. This was one of the motivations in the development of a machinable ADI [26]. A lack of experience of the high volume machining of ADI adds uncertainty to the costs and production rates and the early experience of ADI exposed some inconsistencies in the machinability. However, these problems can be minimised by collaboration with a knowledgeable foundry and heat treater. There is growing confidence [28, 33] that the correct selection of machining tools and conditions enables ADI with a tensile strength of 750–800 MPa to be machined as easily as a pearlitic ductile iron with a tensile strength of 700 MPa.

3. There has been a sustained effort worldwide to use lightweight materials in the automobile industry which has eroded the market for cast irons due to their higher density. ADI has suffered from being incorrectly conceived as a 'conventional' cast iron. However, as shown by Fig. 21, when the high strength of ADI is taken into account, it is possible for it to compete successfully with lightweight alloys. This point has yet to be fully appreciated by many design engineers and this is exacerbated by a decline in the number of engineers who are trained in the production and use of castings.

4. In the early days of ADI, the austempering facilities in many countries were inadequate and the heat treatment cost was relatively high. However, a recent cost breakdown has shown [16] that, for medium volume production in the US, the cost of ductile iron castings is about half that of forged steel and even when the costs of austempering and transport are allowed for, ADI components typically give 20% savings to the purchaser. This rises to $\geq$ 30% when ADI replaces aluminium.

In summary, ADI is a family of cast materials which offer high levels of mechanical properties at a competitive cost. They have already been used successfully for high volume automotive applications and it is confidently expected that further applications will be developed as their attributes become more widely appreciated.

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