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Unique microstructure and excellent mechanical properties of ADI

Jincheng Liu

(Russell Castings Ltd, Leicester, LE3 5EP, UK)

Abstract: Amongst the cast iron family, ADI has a unique microstructure and an excellent, optimised combination of mechanical properties. The main microstructure of ADI is ausferrite, which is a mixture of extremely fine acicular ferrite and stable, high carbon austenite. There are two types of austenite in ADI: (1) the coarser and more equiaxed blocks of austenite between non-parallel acicular structures, which exist mainly in the last solidified area, and (2) the thin films of austenite between the individual ferrite platelets in the acicular structure. It is this unique microstructure, which gives ADI its excellent static and dynamic properties, and good low temperature impact toughness. The effect of microstructure on the mechanical properties is explained in more detail by examining the microstructure at the atomic scale. Considering the nanometer grain sizes, the unique microstructure, the excellent mechanical properties, good castability, (which enables near net shape components to be produced economically and in large volumes), and the fact that it can be 100% recycled, it is not overemphasized to call ADI a high-tech, nanometer and "green" material. ADI still has the potential to be further improved and its production and the number of applications for ADI will continue to grow, driven by the resultant cost savings over alternative materials.

Key words: ADI; microstructure; mechanical properties; crystal structure; strengthening mechanism; nanometer

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It has been a mission for cast iron metallurgists to improve the properties of cast irons. For many years the strength of cast iron was very low, with a tensile strength of only 60-100 MPa in 1860. During World War I, the tensile strength was increased to 120-140 MPa, by adding scrap steel during melting. In 1922, inoculated iron was invented and the tensile strength of cast iron increased further to 300 MPa. Later, alloyed, inoculated grey iron reached strength of 400 MPa. Although White-heart and Black-heart malleable irons were invented in 1722 and 1826 respectively, initially these irons were capable of producing small and thin section castings only. In 1947 SG iron was invented by H. Morrogh by adding cerium to grey iron melts. In 1948, at the AFS meeting in Philadelphia, A.P. Gagnebin and K.D. Millis announced that SG iron had been produced by adding magnesium to molten iron. As a result of these inventions, the strength of cast iron increased to 600 MPa with 3% elongation. By adding selected alloys, SG iron, (now more commonly called ductile iron), can now reach a tensile strength of 800-900 MPa. In 1970, the development of ADI enabled the strength of cast iron to be further increased to 1 200-1 400 MPa, with moderate ductility, and the highest strength specified in the latest American Standard (ASTM897M-2003), is 1 600 MPa. Figure 1 shows the increase in the strength of cast iron since 1860 and it can be seen that during the past 140 years the strength of cast irons has increased approximately 20 times.

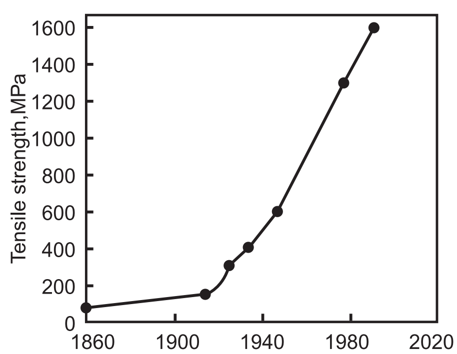

Fig.1 The increase of cast iron strength with year

It has been a dream for cast iron metallurgists to make cast iron as strong as steel and with the development of ADI this has become a reality. Figure 2 shows the comparison of ADI properties with plain carbon and alloyed steels and conventional ductile irons. It can be seen from Fig. 2 that ADI has twice the strength of ductile iron for the same level of ductility and has strengths comparable to alloyed steels. ADI and conventional ductile irons show less elongation than steels. The reason is that after the first crack appears during tensile testing, ADI and ductile iron specimens fracture quickly, but steel specimens continue to deform even after the first crack appears. The difference in elongation is due mainly to local deformation or "necking", after the first crack.

Jincheng Liu

Male, Ph.D. Being engaged in the research on ADI and metal solidification, casting alloy.
E-mail: jincheng.liu@russellductile.co.uk

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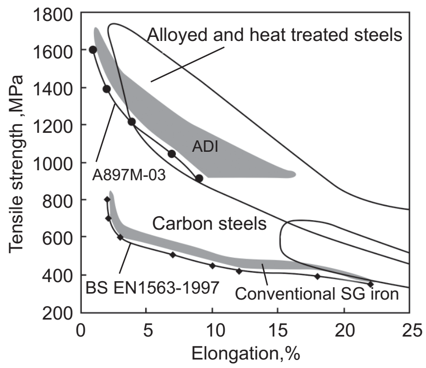

Fig.2 Comparison of ADI properties with steels and conventional ductile irons; ADI standard A897 M-03 and BS EN 1563-1997 also shown in figure

The production of ADI has increased by 15% per annum in recent years and to date, several hundred different ADI components within the weight range 0.5-5 000 kg have been produced and used successfully in various industries worldwide to replace cast steel, alloyed steel, steel forgings and fabrications and aluminium components. The application and development of ADI are due to its excellent mechanical properties, which result from the unique microstructure. The effects of microstructure on the mechanical properties of ADI are examined further by looking at the atomic scale. ADI still has the potential for further improvement through tighter control of the casting and heat treatment processes, to obtain a finer and more uniform microstructure. As a result of these improvements, the production and use of ADI will be further expanded.

1 Excellent combinations of strength and toughness

ADI has an excellent combination of strength and toughness. As a result of this combination, both the fracture toughness and fatigue strength of ADI are much greater than that of conventional ductile irons and equivalent or superior to comparable cast and forged steels. When subjected to surface treatments such as rolling or peening after heat treatment, the fatigue strength of ADI is increased significantly and is competitive to gas-nitrided and case-carburized steels. In conditions where friction needs to be minimized, in sliding wear such as gears, crankshafts, bushings etc, or where friction is used to advantage such as brakes, wheels, mining, construction, agricultural applications, etc, all grades of ADI show excellent wear resistance that is superior to competitive materials over a wide range of hardness; also the wear resistance is consistent throughout the component.

ADI also has good low temperature properties and can work at temperatures as low as minus 80 ℃ [1]. In general, ADI maintains at least 70% of its room temperature impact strength at minus 40 ℃, which compares favourably with most steels. ADI properties are not very sensitive to alloy content. Experiments have shown clearly that relatively pure ADI (almost without any alloying elements) can still produce good properties and reach the ADI standards for thin section castings [2, 3]. Therefore thin section ADI castings do not need alloy additions. The purpose of adding alloys such as Cu, Ni or Mo is to increase the hardenability of the matrix for thicker sections and to ensure a fully ausferritic microstructure throughout the whole section of the casting during the austempering process. These elements have only a marginal effect on the mechanical properties of ADI that has been correctly austempered. It is the austempering process, not alloying elements, which determines the properties after heat treatment.

2 Unique microstructure of ADI

The excellent properties of ADI result from its unique microstructure. There are three main metallic phases in cast iron: ferrite, cementite and austenite. Table 1 gives the crystal type and properties of these three main phases.

Ferrite has a non-close packed bcc lattice with a lattice parameter of 0.287 nm and a total of 48 slip systems. The movement of dislocations in ferrite is therefore easy and this makes it soft and ductile. Austenite has a close packed fcc lattice with a lattice parameter of 0.364 nm and a total of 12 slip systems. Although the total slip systems in ferrite are more than for austenite, the critical Peierls force to move a dislocation is less in an fcc lattice than that in a bcc lattice, therefore austenite is also very soft and ductile. Austenite is normally unstable at room temperature, but under certain conditions it is possible to obtain stable austenite at room temperature by the use of alloys. Cementite has an orthorhombic lattice with approximate parameters 0.451 65, 0.508 37 and 0.672 97 nm. There are twelve iron atoms and four carbon atoms per unit cell, corresponding to the formula Fe_3C. Each carbon atom is surrounded by eight iron atoms and each iron atom is connected to three carbon atoms. Cementite is a type of interstitial compound and is a

Table 1 Crystal type and properties of the three main phases in cast iron

	Ferrite	Austenite	Cementite
Crystal type	bcc	fcc	Orthorhombic
Close packed ? (packing efficiency)	No, (68%)	Yes, (74%)	-
Solid solution or compound ?	Solid solution	Solid solution	Interstitial compound
Unique, non-parallel slip planes and slip direction	6 {110} each with 2 <111> 24 {321} each with 1 <111> 12 {211} each with 1 <111>	4 {111} each with 3 <110>	0
Total slip systems	48	12	0
Hardness	Soft	Soft	Very hard
Ductile or Brittle ?	Ductile	Ductile	Brittle

hard and brittle phase. It tends not to deform plastically.

Conventional ductile irons have ferritic and/or pearlitic structures. Pearlite is a lamellar mixture of ferrite and cementite. Ferritic ductile iron has low strength, but high ductility. Yield in a pearlitic microstructure is associated with the movement of dislocations in the ferrite. When dislocation sources are activated in the ferrite plates, the glide paths of the dislocations are limited by the cementite plates because they cannot slip in the carbide. Instead they are forced to pile up at or near the ferrite/cementite interfaces. The consequence of the lamellar microstructure of alternating ductile and hard, brittle plates, is an increase in the yield stress of the material compared to that of the ferritic matrix because the inter-lamellar spacing is usually much smaller than the proeutectoid ferrite grain size. A fully pearlitic ductile iron has high strength and moderate ductility. Ductile iron with a mixed ferritic and pearlitic structure has properties in between.

ADI has a unique microstructure of ausferrite, which is a mixture of acicular ferrite and stable, high carbon austenite. The amount of ausferrite in ADI varies between 20%-40%, depending on the austempering temperature. Conventional ductile iron has no austenite in the structure. The austenite and ferrite in ADI are extremely fine and Fig. 3 shows a typical microstructure of ADI grade 1. Further study by Transmission Electron Microscope (TEM), shows that the acicular structure consists of a sub-unit structure in which fine ferrite plates are separated by a thin film of stable, high carbon austenite or by low disorientation/small-angle gain boundaries. Each fine ferrite plate is only approximately 0.2 μm (200 nm) thick and 10 μm long; the plates are parallel and of identical crystallographic orientation with a crystallographic habit plane {110}a parallel to {111}γ. With this habit plane, interface energy is minimised during austempering transformation. There are two types of stable, high carbon austenite in ADI: (1) the coarser and more equiaxed blocks of austenite (the white area in the matrix in Fig. 3) between non-parallel "sheaves" of ferrite platelets, which exist mainly in the last solidified area, and (2) the thin films of austenite between the individual ferrite platelets in the acicular structure. This thin film of austenite is extremely fine, only up to 10 nanometers thick. Figure 4 shows a sample austempered at 350 ℃ for 64 minutes in which sub-units of ferrite, separated by thin films of stable austenite, are clearly revealed [4]. These sub-units form the acicular structure. No carbides were observed in this sample. Low temperature austempered ductile irons have a finer structure and have some fine carbides existing within the ferrite plates.

Unlike conventional ductile irons, ADI does not contain the hard, brittle, plate type of cementite, but has about 20%-40% austenite in the form of blocks and thin films of austenite. Austenite has an fcc lattice in which close-packed planes correspond to large distances between those planes. This gives rise to relatively soft inter-planar bonds, so that the dislocation width is large, which makes austenite soft and ductile. The austenite and ferrite in ADI have a multi-slip system, which makes the structure ductile and tough. Therefore ADI has better ductility and toughness than conventional ductile irons. In high strength ADI austempered at low temperature, some carbide exists. However, these are isolated particles (not the plate type of carbides) and their effect on ductility is less than that of cementite in pearlite.

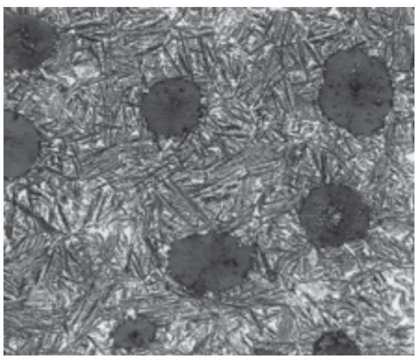

Fig. 3 Typical microstructure of ADI grade 1

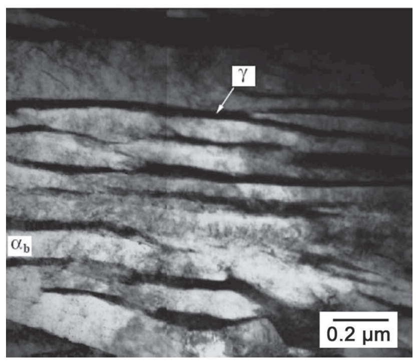

Fig. 4 TEM ADI microstructure showing ferrite plates in acicular structure, separated by thin films of austenite [4]

The high strength in ADI results from its extremely fine grain sizes. The ferrite plates in ADI are only about 0.2 μm, (200 nanometers), and the thin films of austenite between the ferrite plates are even finer at only 10 nanometer. Fine grains increase grain boundary area, which are obstacles for movement of dislocations from one grain to another, because the slip planes in one grain don't line up with the slip planes of the neighbouring grains. The very high dislocation density also is an important mechanism of strengthening. The acicular ferrite plates have very high density of moveable dislocations. In bainitic steels, generally, the dislocation densities in the acicular ferrite plates are about 10^{10}-10^{11} cm^{-2}. Dislocation densities of 1.7×10^{10} - 6.3×10^{11} cm^{-2} have also been documented in the acicular ferrite plates in bainitic steel [5]. In ADI, dislocation densities of 6×10^{9}-1.0×10^{10} cm^{-2} in the ferrite plates were measured under different austempering temperatures and the density increased as the austempering temperature was decreased [6]. The excellent combination of strength and toughness gives ADI a much greater fracture toughness and fatigue strength than conventional ductile irons and it is equivalent or superior to comparable cast and forged steels.

The blocky austenite and thin film austenite in ADI both contain about 1.8%-2.2% carbon. Also, a large amount of carbon remains trapped in acicular ferrite [7]. These interstitial solids will increase the yield strength by hindering the movement of dislocations past them. Normally, alloying elements will strengthen conventional ductile iron by making the structure finer and by substitutional solid solution strengthening. Since the structure of ADI is already extremely fine and solid solution strengthening by interstitial carbon and by displasive silicon play their roles already, other alloying strengthening from copper, nickel and molybdenum is much less sensitive. Nevertheless, adding alloying elements such as copper, nickel or molybdenum to ADI is necessary for thick section castings, to increase hardenability and to obtain a fully ausferritic microstructure throughout the whole section during the austempering process.

Under stress, if the yield strength is exceeded and deformation occurs, the austenite in ADI will absorb energy and transform into martensite by stress-induced transformation. This will benefit strength and ductility and will also increase hardness. During wearing service, the surface of ADI components will become very hard as a result of stress-induced martensite transformation. As the hard surface is worn away, the new surface will undergo the same phase transformation, therefore providing excellent wear resistance, and this wear resistance is consistent throughout the component. This is why ADI has better wear resistance compared to other materials with a similar hardness.

It is clear that the strengthening mechanisms such as fine grain strengthening, grain boundary strengthening, dislocation strengthening, solid solution strengthening, second phase strengthening and phase transformation strengthening all play their role in enhancing the properties of ADI. It is the unique microstructure that gives ADI its excellent properties.

Table 2 shows the relationship between dislocation width and yield strength temperature sensitivity for different materials [8]. As can be seen, fcc metal with close packed lattice has a lower yield stress and impact temperature sensitivity because of the wide dislocations compared to a bcc crystal with non-close packed lattice. ADI has 20%-40% austenite and this is one of the main reasons why ADI can work at minus 80℃ [1] and retain at least 70% of its room temperature impact strength at minus 40℃. As the dislocation moves it drags with it the regions of compressive and tensile distortion in the lattice around it. This is accompanied by a sort of frictional drag, giving rise to a resistance to dislocation motion known as the Peierls force. This force is dependent on such factors as the crystal type and the temperature, and this plays an important role in determining the yield stress of the material. As can be seen in Table 2, materials that have wide dislocations also have very small Peierls forces, since the distortion is spread out over a large volume and the forces are much less intense at the crystal core. Since ADI has a certain amount of austenite in the matrix, it is less yield stress and impact temperature sensitive compared to conventional ductile irons and most steels. Also, fine grain sizes decrease the ductile-brittle transition temperature and improve impact toughness. It is believed that the stable austenite and extremely fine grain sizes are the main factors that contribute to better low temperature impact toughness for ADI.

Normally if a material contains a certain amount of nanometer particles and its properties are changed dramatically by these particles it can be considered as a composite nanometer material. Considering the unique microstructure, the nanometer grain sizes, the excellent mechanical properties and good castability (which enables near net shape components to be produced economically and in large volumes), and the fact that it can be 100% recycled, it is not overemphasized to call ADI a high-tech, nanometer and "green" material.

Table 2 Relationship between dislocation width and yield strength temperature sensitivity for different materials [8]

Material	Crystal type	Dislocation width	Peierls stress	Field stress temperature sensitivity
Metal	fcc	Wide	Very small	Negligible
Metal	bcc	Narrow	Small	Strong
Ceramic	Ionic	Narrow	Small	Strong
Ceramic	Covalent	Very narrow	Very large	Strong

3 ADI developments at Russell

Established in 1864, Russell Castings was one of the first foundries in the world to produce SG iron on a commercial scale. Russell has also developed ADI components since the early 1990s and is now a major producer in the UK. To date, several thousand tons of many different ADI components (many for safety-critical applications) have been successfully manufactured and supplied to customers with varied applications. Equipment having Russell ADI components in it, is operating successfully around the world. Through close control of chemical composition, nodulising, inoculation and heat treatment processes, all the ADI components meet the USA and European standards and the special requirements of some customers.

Figure 5 shows more than 1 000 test data from 22 months continuous production at Russell. It can be seen that the ADI properties are excellent, all much higher than the minimum requirements of USA and European standards. The various ADI applications have helped Russell's customers to solve their engineering problems by improved component performance, so reducing cost and increasing profit.

4 Further development of ADI

ADI can now be successfully produced on an industrial scale and some ADI has excellent and much better properties than current standards. For example, materials having the following mechanical properties have been produced by Russell: UTS-1 253 MPa, 0.2% proof strength - 980 MPa, 24.3% elongation; UTS - 1 060 MPa, 0.2% proof strength -766 MPa, 21% elongation, notched impact energy - 9 J, hardness - 302 HB. Tensile strengths as high as 1.733 GPa, with an elongation of 1.1% have been reported [4] and there is still the potential to further increase ADI properties by obtaining a more uniform

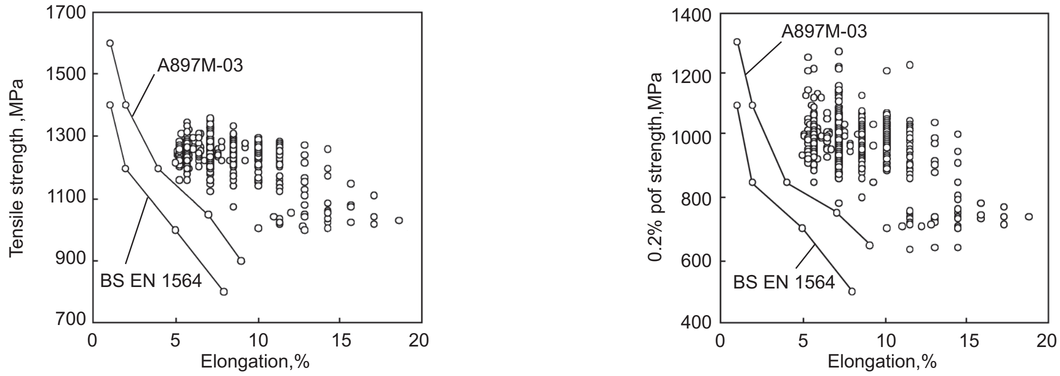

Fig. 5 ADI tensile strength *vs* elongation (left) and 0.2% proof strength *vs* elongation (right)
(*Data from 22 months continuous production in Russell castings)

and even finer structure. This requires additional control at both the casting and heat treatment stages.

At the casting stage, it is important to closely control the chemical composition, nodulising and inoculation processes to obtain a uniformly distributed microstructure with high nodule count, and minimal defects and carbides. A uniformly distributed and high nodule count will benefit by accelerating the ausferrite reaction and by obtaining a more uniform and finer microstructure. Careful selection of alloying elements (cobalt for example [9]), will accelerate the ausferrite reaction and the use of copper, nickel and molybdenum will increase hardenability for thicker sections.

At the heat treatment stage, there is a need to increase quench speed or quench medium severity to enable the castings to be quenched more quickly and uniformly; this will produce a finer structure, free from carbides and will enable the production of thicker section ADI components with lower alloy content. Changing the heat treatment cycle is another way to further improve ADI properties. For example, a very low austempering temperature of 190 ℃ has been tried and although the result was not ideal, it was possible to obtain a UTS of 2.3 GPa [4]. ADI with a fully ferritic microstructure (austenite free) has been developed using a novel process consisting of austempering and isothermal tempering below the inter-critical (A1) temperature [10]. ADI with a completely ferritic microstructure is not available commercially although this microstructure has imparted excellent machinability and thermal-shock resistance, together with good ductility and toughness. ADI has a unique microstructure and excellent properties, and still has the potential to be further improved through improved control of both the casting and heat treatment processes.

5 Conclusions

ADI has a unique microstructure of ausferrite, which is a mixture of acicular ferrite and stable, high carbon austenite. It is the extremely fine acicular ferrite, the high carbon thin films and the blocky austenite, which give ADI its excellent combination of strength, toughness, wear resistance and low temperature impact toughness. Considering the nanometer grain sizes, the unique microstructure, excellent mechanical properties and good castability (which enables near net shape components to be produced economically and on a large scale), and the fact that it can be 100% recycled, it is not overemphasized to call ADI a high-tech, nanometer and "green" material. There is still the potential to further improve ADI properties through tighter control of the casting and heat treatment processes to produce a microstructure that is much finer and more uniform.

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