Austempered Ductile Iron: Fact and Fiction

Realizing the full potential of austempered ductile iron calls for a more thorough understanding of its capabilities and overcoming some common misconceptions about its production.

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Austempered Ductile Iron, ADI, has received much publicity during the past few years.[1-20] Yet, it remains a very misunderstood material. The purpose of this paper is to describe ADI and the related process in such a way that anyone with some technical background will understand and appreciate both.

Most of the misunderstanding stems from a misconception that cast iron is a special steel with graphite particles of different shapes dispersed in it. The most important revelation during the development of ADI was that steel metallurgy, in many cases, not only delayed the development of ADI for many years, but caused a seemingly unresolvable confusion among foundrymen. This paper will attempt to clarify not only what ADI is, but just as importantly what ADI is not.

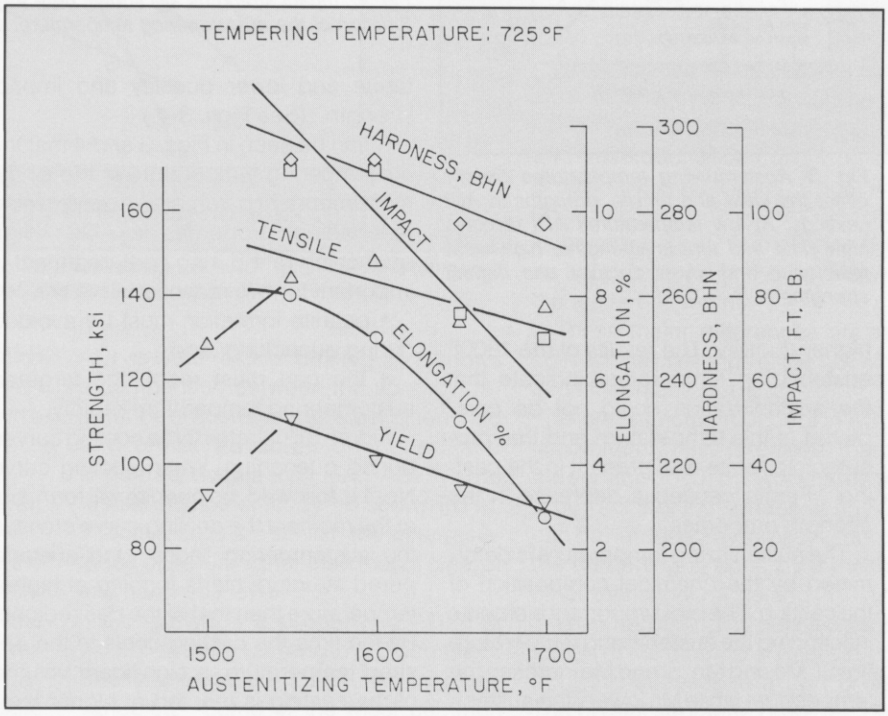

Fig. 2. As shown here, the austenizing temperature greatly influences the mechanical properties of an ADI casting.

Casting of ADI

ADI is an alloyed and heat treated ductile cast iron. The chemical composition of the base iron for ADI is similar to that of the conventional ductile iron: about 3.6 C, 2.5 Si, 0.3 Mn, 0.015 maximum S, and 0.06 maximum P. Alloying elements such as Cu, Ni and Mo are added to the base compostion individually or in combination. These elements are added not to increase strength or hardness, but to enhance the heat treatability. Large castings cool slower during quenching and require more alloying than small castings.

All other casting process variables such as molding, nodulization, inoculation and pouring temperature are the same for ADI as they are for ductile iron. Alloying elements are often added to the ladle and the rest of the casting process is unaltered on a ductile iron line. The addition of the alloying elements does not change the castability of the iron and does not increase the presence of casting defects. Good inoculation and increased nodule count, however, will make heat treating easier and will result in higher strength properties in ADI.

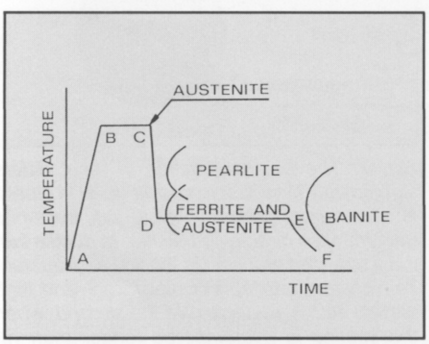

Fig. 1. This schematic diagram illustrates the various phases of the ADI heat treat cycle.

Heat Treating

A schematic diagram of the ADI heat treat cycle is shown in Fig. 1. The casting is heat treated (A-B) to a temperature range of 1550-1750F and held (B-C) at temperature for one to three hours. During this period the casting becomes fully austenitic and the matrix becomes saturated with carbon.

The time duration of the austenitization depends on two factors: the matrix structure of the casting prior to austempering; and the ability of the carbon to move between the nodules and the matrix. If the matrix of the castings is highly ferritic prior to heat treatment, it will take more time to saturate the matrix with carbon than in a pearlitic matrix which already has about 0.7% carbon prior to austempering. However, the microstructure prior to heat treating *does not* affect the final mechanical properties. The other factor determining the time duration of the austenitization is the freedom of carbon to migrate from the nodules to the matrix. The nodules serve either as carbon supplies or carbon sinks. There are some elements, such as Sb, Sn and Cu which segregate at the graphite-metal interface and create a thin shell betweeen the nodules and the matrix. These shells act as carbon diffusion barriers. In the presence of the above elements the saturation of the matrix with carbon will take significantly longer time.[21,22]

To obtain good properties in ADI, the casting must be fully austenitized. The austenitizing temperature has a marked influence on the mechancial properties. Figure 2 illustrates this influence. Generally, lower austenitizing temperatures result in higher strength properties and

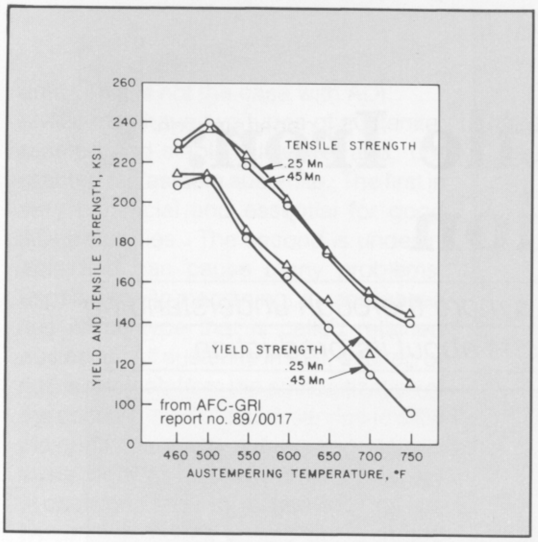

Fig. 3. Austempering temperatures greatly effect the yield and tensile strengths in ADI castings. At low temperatures ADI displays high yield and tensile strengths, high wear resistance and lower ductility and impact strengths.

higher ductility. The results of the 1500F austenitizing temperature indicate that the austenitization could not be completed at this temperature and that proeutectoid ferrite was present in the casting. Ferrite caused a decrease in the strength properties.

The austenitizing temperature is determined by the chemical composition of the casting. The most important elements influencing the austenitizing temperature are Si, Mo and Mn, Si and Mo increase the temperature while Mn lowers the austenitizing temperature. It is important to know the chemical composition when the austempering heat treat cycle is designed.[23,24]

After the casting is fully austenitized, as shown in Fig. 1, it is quenched (C-D) in a quenching medium at a temperature range of 460-750F, and held (D-E) at temperature for one-half to four hours. This temperature is called the austempering temperature. The austempering temperature and the holding time determine the final microstructure and properties in an ADI casting.

Figure 3 illustrates the effect of the austempering temperature on the yield and tensile strengths. Strength increases rapidly by lowering the austempering temperature. The decrease in strength at 460F is the result of a partial strain induced martensitic transformation of austenite during tensile testing and possibly the formation of bainitic carbide and/or martensite.

High austempering temperatures result in high ductility, high fatigue and impact strengths and relatively low yield and tensile strengths. At low austempering temperatures ADI displays high yield and tensile strengths, high wear resistance and lower ductility and impact strength. (See Figs. 3-4.)

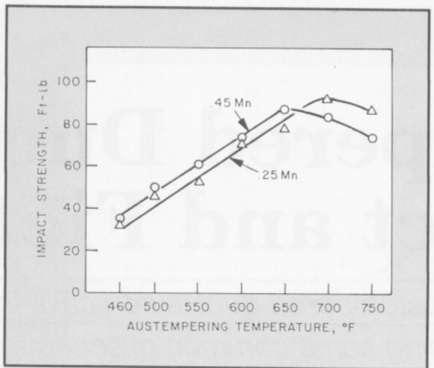

Fig. 4. mpact strengths are shown here as a function of the austempering temperature.

It can be seen in Figs. 3 and 4 that the austempering temperature is the single most important parameter in determining mechanical properties in ADI. High quenching rate during heat treatment is important for two reasons:

- pearlite formation must be avoided during quenching; and
- the part must reach the targeted austempering temperature rapidly.

Figure 5 illustrates three cooling curves during quenching. When cooling curve No. 1 is followed, no pearlite will form, but at the moment the cooling curve crosses the austempering "nose," the austempered structure starts forming at higher temperature than that of the desired one. By the time the casting cools to the desired temperature, a significant volume of the casting is reacted at higher temperature and the properties will be determined by a mixed ADI structure.

When cooling curve No. 3 is followed, all ADI structure will form at the desired temperature. The strength properties in the second case can be significantly higher than in the first case. After the isothermal austempering the casting is cooled to room temperature as illustrated by E-F in Fig. 1.

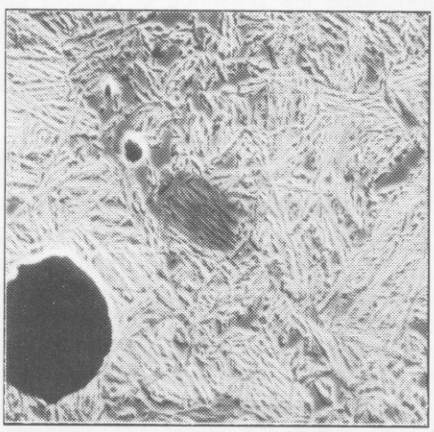

Fig. 6. A typical ausferritic matrix of an ADI casting is shown in this photomicrograph (500x). This sample was austenitized at 1600F for two hours and austempered at 675F for two hours.

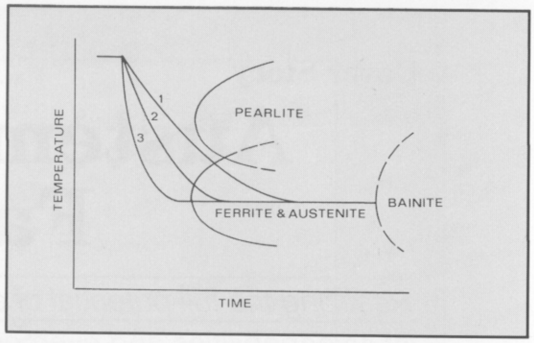

Fig. 5. This schematic diagram shows the effect of the quench severity on the austempering reaction.

Microstructure of ADI

The microstructure of ADI is unique to cast irons. It consists of acicular ferrite and high-carbon stable austenite. With this combination ductile iron displays remarkable strength and ductility. A typical ADI microstructure is shown in Fig. 6.

The ADI microstructure is often and erroneously called bainite. It is *not* bainite. The bainite transformation in steel is different from that of ductile iron. The bainitic reaction in steel is a one-step process: austenite decomposes directly to bainite, i.e., to acicular ferrite and carbide. There are two steps in ductile iron. In the first step austenite transforms to a structure of acicular ferrite and high-carbon stable austenite. This is the desired structure in ADI. This is the structure that provides the remarkable properties in ADI. In the second step when the casting is austempered longer than required for the above structure, the matrix transforms to bainite as in steel (Fig. 7). *Bainite in ADI is detrimental and undesirable.*

The misunderstanding of the ADI structure stems from the following:

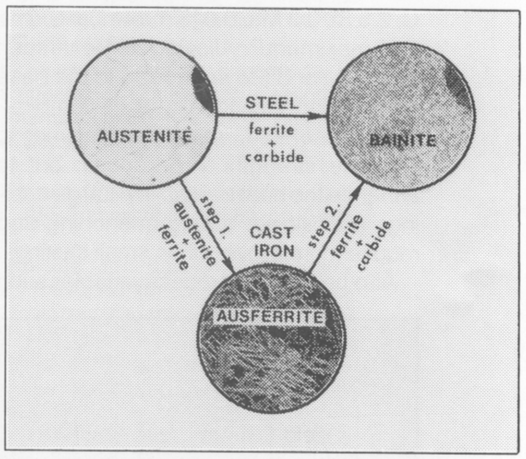

Fig. 7. The bainite reaction in steel differs significantly from that in ductile iron. In steel it is a one-step process where the austenite decomposes directly to bainite. In ductile iron it is a two-step process. In the first step austenite transforms to an acicular ferrite and high carbon stable austenite. In the second, when the casting is austempered longer than required, the matrix transforms to bainite as in steel.

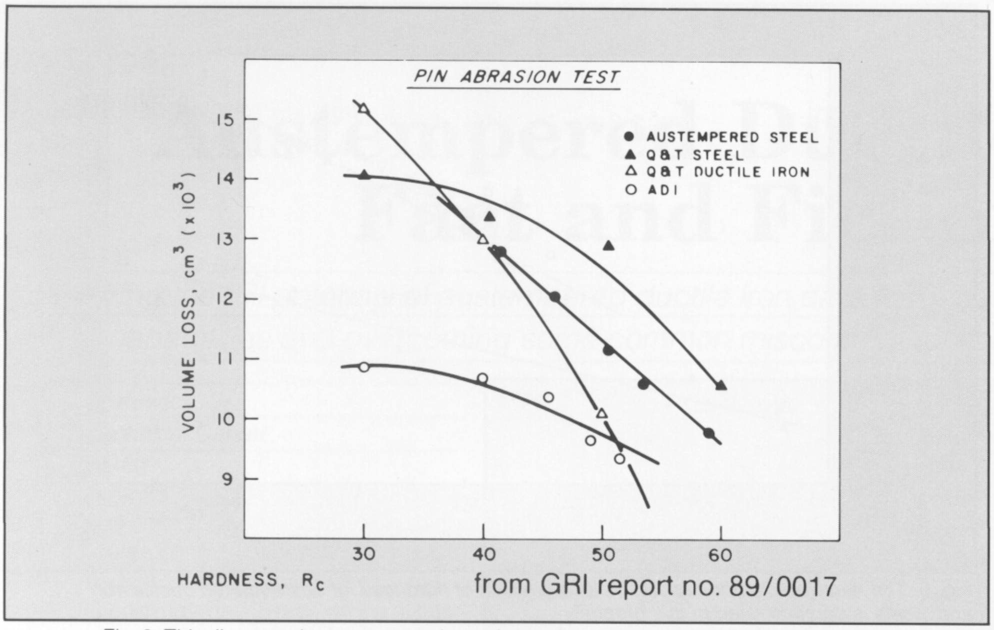

Fig. 8. This diagram shows a comparison of abrasion resistance in ADI, quenched and tempered ductile iron, quenched and tempered steel, and austempered steel.

- It forms at the bainitic transformation temperature.
- It appears similar to bainite through a light microscope.
- It does not exist in steel.

It is important to understand, however, that the high ductility associated with high strength in ADI is the result of the unique microstructure which is not bainite. To avoid some of the confusion in the future, it is proposed here that ADI microstructure be called "ausferrite," implying that it is largely a mixture of austenite and ferrite.

Mechanical Properties of ADI

One of the most beneficial features of ADI is that the same casting can be heat treated to display vastly diverse mechanical properties. Table 1 shows the various property ranges which can be achieved routinely on the production line without changing the process variables.

The strength properties and ductility in ADI are affected by the section size of the casting. The effect in castings up to 3 in. section sizes is minimal, especially when the nodule count is low, both the strength properties and the ductility may be reduced significantly.

One of the outstanding properties of ADI is wear resistance. Figure 8 shows a comparison between the abrasion resistance of austempered steel, quenched and tempered steel, quenched and tempered ductile iron, and ADI.[22] The results of another study[25] is shown in Fig. 9. Both results are similar, the wear resistance of ADI is higher than that of steel at any hardness level.

Elongation is a property in ADI that would require a lengthy discussion. Briefly, elongation is affected by many variables. Some of the most common causes for a reduction in elongation are: shrinkage, dross/slag, eutectic carbide, unreacted metastable austenite, martensite and rough tensile bar surface.

Common Misconceptions

There are several common misconceptions regarding ADI. One of them was already discussed. That is the mistaken belief that cast iron is a special steel. It is not. The major differences between steel and cast iron include the following.

- The carbon concentration in steel is constant, regardless of the heat treat cycle. (The exception is intentional carburization.) Because of the presence of graphite particles, the carbon content of the cast iron matrix may vary between 0.01-1.7% depending on the thermal history of the casting. In other words, the cast iron matrix has a variable carbon content.
- Steel solidifies as a single-phased solid. Cast iron solidifies through an eutectic process. The solute distributions in the two materials are vastly different due to the different mode of solidification. The solute distribution alters the carbon kinetics in cast irons.
- With the exception of some electrical applications such as transformer cores, silicon is considered detrimental in steel and is avoided. Silicon, on the other hand, is essential in cast irons. There is about 2.5% silicon in ductile iron. Silicon inhibits bainitic carbide formation and it plays an important role in the development of the ausferritic matrix.

These major differences are responsible for the presence of the ADI structure in cast iron and not in steel.

There is another concept in ADI which is commonly misinterpreted: hardening the surface of ADI by "work hardening." It is correct that the surface of an ADI part can be hardened by stressing but most of the hardening is done by a mechanism other than work hardening.

Work hardening by definition is the distortion of the existing crystal structure by applying stresses in a part or sample. The crystal structure, however, does not change. In ADI the mechanism is different. Stresses cause a change in the crystal structure, a phase transformation from austenite to martensite takes place. The hardening is not work hardening.

It is believed by some that the second step (the bainitic reaction) in ADI occurs rapidly and the mechanical properties drop quickly from the appearance of the bainite. It is not so. The deterioration of properties is a gradual and slow process and it takes hours or even days of heat treatment before significant reduction in properties is observed. The big "bluff" in properties due to over-austempering is a myth.

Still another misconception is that the matrix structure in a casting prior to austempering affects its final properties. If the austempering heat treatment is done correctly, i.e., the casting is fully austenitized and austenite is saturated with carbon, the final properties will be same regardless of the prior structure.[22]

"Retained Austenite"

The term "retained austenite" is often used in conjunction with ADI. This is unfortunate. Retained austenite in steel is one of the most undesirable constitu-

Table 1. Room Temperature Mechanical Property Ranges in ADI

Yield Strength, ksi,	80	-	220
Tensile Strength, ksi,	120	-	260
Elongation, percent,	1	-	16
Modulus (Young's), ksi,	22,000	-	23,500
Hardness, BHN,	250	-	550
Fatigue Strength, ksi,	45	-	100*
Impact Strength, ft-lb	30	-	130

*100 ksi can be achieved by fillet rolling or shot peening ents. This is not the case with ADI.

ADI may have two types of austenite: reacted and stable austenite; and unreacted metastable austenite. The first is very beneficial and essential for good ADI properties. The second is undesirable and can cause many problems, especially with machining. In most cases this is the type that is called retained austenite. All austenite in ADI, desired or not, is retained from the austenitization of the casting. It would be a service to all in the casting industry if the term "retained austenite" was deleted from the glossary of cast iron. The proper terms for the two types of austenite should be: reacted stable austenite, and unreacted metastable austenite. These names are both descriptive and technically correct.

What ADI Is Not

The following is a list of what the ADI process is not:

• It is not a remedy for casting defects. It does not weld cracked castings, nor does it fill shrinkage holes. It does not eliminate eutectic carbides.

• It is not a substitute for process control. On the contrary, it requires tight and strict process control. Any discrepancy in the casting process will be amplified by the subsequent heat treating.

• Although ADI has a broad range of applications, it is not a solution to every engineering problem.

What ADI Is

Austempered ductile iron is a material which is strong, light, wear resistant, a good conductor of heat, and a better damper of vibration than steel. In addition, ADI provides high design and manufacturing flexibility, and is relatively inexpensive.

In general, ADI may be characterized as an alloyed and heat treated ductile cast iron with properties that are highly versatile. It is a material that exhibits remarkable strength, ductility and wear resistance. Its ausferritic matrix is unique to cast irons, and it should not be viewed as a special steel with graphite particles dispersed within it. Steel metallurgy often does not apply to cast irons.

Acknowledgements

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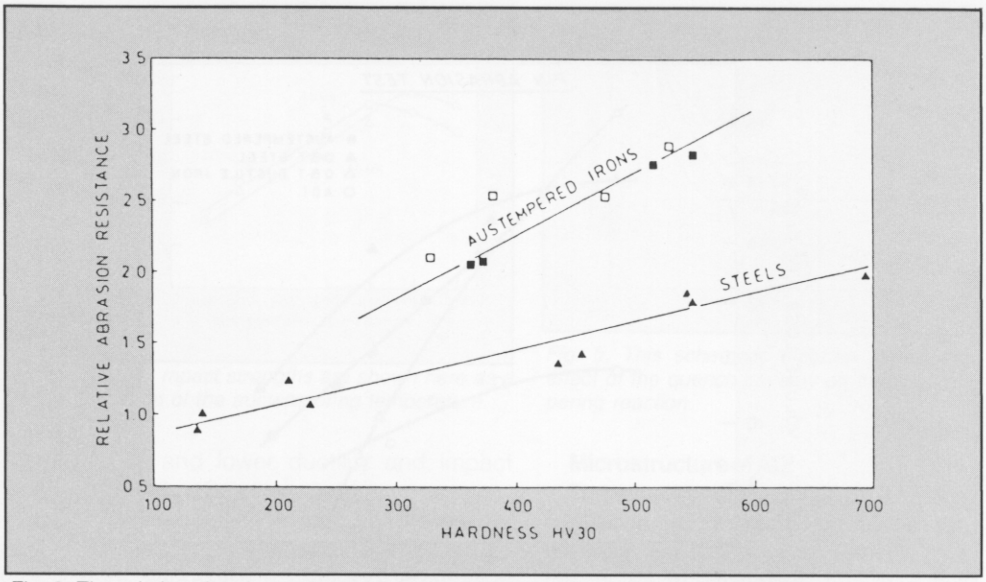

Fig. 9. The relative abrasion resistance as a function of hardness for austempered ductile iron and steels is demonstrated in this graph.[25]

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