Continuing Developments in the Science and Application of Austempered Ductile Iron (ADI)

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ABSTRACT

Austempered Ductile Iron (ADI) had its commercial genesis in 1972. Growth of ADI since then has been impressive with worldwide production in 2010 estimated at over 500,000 tons. Ongoing development of ADI has hinged on improving ductile iron technologies, increased knowledge of the Austempering process as applied to cast irons, and the deployment of technically improved, higher productivity, greener heat treating systems and technologies.

Keywords: Ausferrite, Austempered Ductile Iron, ADI, Carbidic ADI, fracture toughness, LADI™, CADI™, IADI, embodied energy

INTRODUCTION

This paper is compiled to inform the reader of ongoing developments related to design with, and the production and processing of Austempered Ductile Iron (ADI). Hundreds of papers have investigated specific aspects of ADI: microstructures, monotonic and dynamic properties, applications, etc. This paper is not crafted to provide an in-depth investigation of any specific technology, but is rather the macro analysis of ADI and the current state of the technology.

BACKGROUND

In the 1970's the Austempering process was first commercially applied to ductile iron. The earliest adaptations of the process were designed, tested and taken to market to solve specific product issues. No common standards existed. The monotonic properties obtained in commercial processes were erratic and dynamic properties were not yet quantified.

In the 1980's and 1990's numerous technical projects and conferences were undertaken to characterize the material and share information about the process and its affects on the properties. It was not until the 1990's that the first internationally recognized standards began to appear. Once standards were published, design engineers started to use the material with increasing confidence.

Meanwhile, the ductile iron founding process has continually improved concurrent with the evolution of highly efficient Austempering systems and ever increasing knowledge of the kinetics of the Ausferrite reaction.

DEVELOPMENTS IN AUSTEMPERED DUCTILE IRON (ADI)

New Standards and Technical Association References

ADI standards emerged out of an industrial need to define the emerging ferrous material that had a high strength-to-weight ratio and good wear resistance. The US-based ASTM standard[1] was formalized in 1990. Japan standard JIS G5503 was released in 1995 and a European standard EN 1564 followed in 1997. Subsequent ISO[2], SAE[3] (US), China GB/T standards and others have followed. Table 1 compares those standards in tensile strength (MPa), yield/proof strength (MPa) and elongation (%).

These standards contain useful appendices that describe the quality of iron necessary for Austempering. They also describe, in varying ways, some suitable uses for the various grades. The SAE standard includes photomicrographs of the various ADI grades. The ISO standard defines varying property minimums with section size and typical monotonic, dynamic and intrinsic properties.

Table 1: This table compares the ISO, SAE, ASTM and China standard grades for ADI (Tensile strength – yield strength- elongation).

ISO 17804 Issued 2005	SAE J2477 Issued 2003 Revised 2004	ASTM **A897/A897M** Issued 1990 Revised 2006	China Std. GB/T24733 Issued 2009
800-500-10	750-500-11	750-500-11	800-500-10
900-600-08	900-650-09	900-650-09	900-600-08
1050-700-06	1050-750-07	1050-750-07	1050-700-06
1200-850-03	1200-850-04	1200-850-04	1200-850-03
1400-1100-01	1400-1100-02	1400-1100-02	1400-1100-01
	1600-1300-01	1600-1300-01	

New standards and industry standard body sponsored information sheets are evolving to include gear and fatigue coefficients and exponents for finite and infinite life design. The information in these standards is just now reaching the textbooks and training information used at the university level. This marks a significant lag in dissemination of the technology to the future design community, one that the authors are working to correct.

Locally Austempered Ductile Iron

Surface Austempering techniques for ADI were developed first by GM in the 1980's for their L-4 engine cams. Since that time, millions of ductile iron automotive camshafts with a hard, Ausferritic surface layer have been successfully used in engines.

The surface Austempering process has historically been either flame or induction based with a salt quench. The standard processes utilize significant alloying in the casting to get the necessary heat treat response during quenching. A new, proprietary, induction-based process, referred to as LADI™, has recently been developed to address the cost and variability issues related to the current technologies. A machined, LADI™ processed cam lobe is shown sectioned and etched in Figure 1, revealing the Ausferrite case and the largely ferritic core. LADI™ requires no alloying and is designed to develop allowable contact stresses comparable to those for HRC 60 powdered metal cam lobes. This technology is evolving as of this writing. To date, the surface Austempering process has not moved much beyond camshafts.

Figure 1: This is a cross-section view of an LADI™ cam lobe that has been etched with 5% Nital to show the controlled-depth Ausferritic case on a largely ferritic core. (From Bixler et al[4])

Carbidic Austempered Ductile Iron (CADI™)

The Ausferrite structure in ADI has good wear resistance. ADI performs better in abrasive wear than its bulk hardness would imply. However, for applications that need even more wear to compete with materials like 27% chromium white irons, a material called Carbidic Austempered Ductile Iron (CADI™ is a registered trademark of Applied Process Inc.) has been found to be a cost-effective alternative in high-wear applications.

Developed in the USA in the early 1990's, Carbidic Austempered Ductile Iron has found applications in ground engaging, crushing, threshing and shredding applications. It can be produced by alloying to achieve inverse chill alloy carbides as-cast followed by an Austempering process that dissolves the carbides to a specified volume percentage in an Ausferrite matrix (Figure 2). Engineered (whole, crushed or sintered) carbides can cast into the part and then Austempered or various thermo-mechanical processes can be used to apply carbide surface layers to ductile iron castings that are subsequently Austempered.

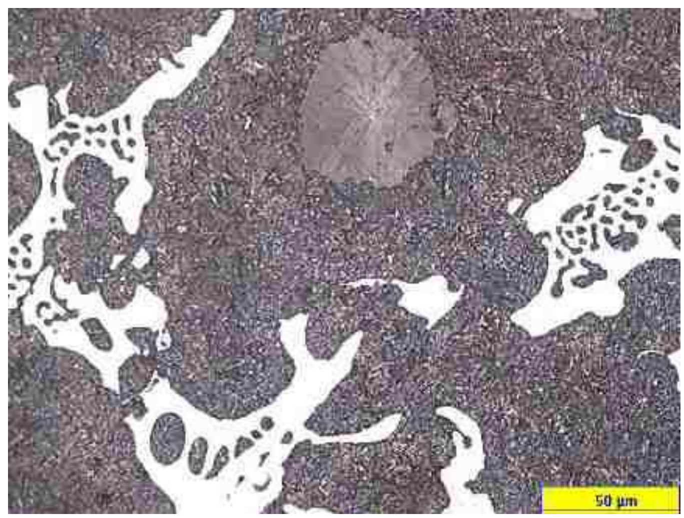

Figure 2: A photomicrograph of a Carbidic ADI microstructure showing as-cast alloy carbides, a graphite nodule and a matrix of Ausferrite is shown. (From Hayrynen et al[5]).

In North America, Carbidic ADI is widely used in agricultural ground engaging and threshing applications. In China, Carbidic ADI has been used extensively in grinding balls for ore mills.

No authorized standards currently exist for Carbidic ADI. This lack of written standards serves as a barrier for the application of this promising material.

Larger ADI parts

The demand for ADI has developed across broad ranges of markets. The relationship between alloy content in the ductile iron and section-size hardenability has been continually perfected. This has lead to the adaptation of increasingly larger ADI components. These one-piece ADI conversions can replace large steel castings, forgings and weldments at significantly reduced mass and cost.

The maximum envelope for ADI parts has historically been limited to a maximum work envelope of $2m^3$ and 2.7 metric tons maximum gross load. However, newer, larger Austempering systems have been pushing this envelope in the last decade.

In response to a specific market application, ADI Treatments in the West Midlands of England installed a $4.5m^3$ batch Austempering line with a 3.8 metric ton maximum gross load. As the design envelope was pushed even further they adopted a $5m^3$ batch Austempering system with a 7.5 metric ton maximum gross load. In 2011, a $5.6m^3$ batch Austempering line was installed at Jilin ADI in Changchun, China. This line has a four metric ton gross load capacity.

The steady march towards increased processing equipment size has taken another turn. The Applied Process group has added a unique batch Austempering system at its Monster Parts™ Division in Oshkosh, Wisconsin, USA. (See Figure 3.) This unit, the largest integral quench batch furnace in the world, has a working envelope of $7m^3$ and a maximum gross load of 9.1 metric tons.

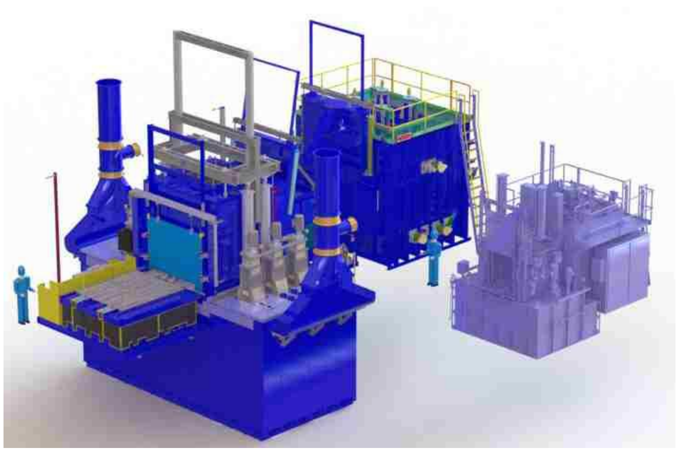

Figure 3: The AP Monster Parts™ Division's $7m^3$ AFC-Holcroft UBQA furnace is shown side by side with a 0.8 m^3 UBQ furnace for comparative effect.

These added capabilities have not only helped to increase productivity on current ADI components, they now make it possible for designers to consider ADI as an alternative to very large steel castings, forgings, weldments and assemblies. Opportunities for such large ADI components exist in, railroad, mining, construction, gearbox, and manufacturing machinery. Complete heavy axles, large compound gearbox carriers, gears and structural components for large stationary and mobile equipment, and even architectural applications could all benefit from cost effective ADI conversions.

ADI is a Green Alternative

Engineers are continually investigating designs that require less energy to operate or propel. Lost in that assessment is the fact that massive amounts of energy are consumed in the extraction and processing of the materials that make up the components assembled in the operating unit or system. The architectural community has for some years extensively used the concept of "embodied energy" to define the energy that is intrinsic to a kg of mass of that material (MJ/kg).

ADI is approximately 10% less dense than steel and similar in strength. ADI is approximately three times stronger than aluminum at only 2.5 times the mass. Therefore, we already know that ADI can be, in fact, a lightweight material. Numerous high profile examples of ADI replacing aluminum have been documented by the authors, but most in the engineering community neglect to consider the energy that is embodied in extracting the materials from the earth and turning them into functional products.

For example, the embodied energy in the manufacture of the components and assembly of a light vehicle can constitute about 20% of the life-cycle energy of that vehicle. (The balance of the life-cycle energy is its operation and the fuels, fluids and replacement parts it consumes during its life). When high strength, "lightweight" (read low density) materials such as aluminum forgings and magnesium and carbon composite sheet reduce mass and therefore the energy required to *propel* the device, but they dramatically increase the amount of energy embodied in the vehicle before it travels its first kilometer.

Table 2 ranks various industrial materials in order of embodied energy per unit of mass, typically expressed in MJ/kg.

New computer design tools allow engineers and designers to maximize designs with thinner sections and clever use of connecting members replacing bulky plate and buttress designs and taking full advantage of a material's true strengths. Armed with the necessary mechanical design coefficients and exponents and the material's embodied energy, a fully informed designer can maximize the energy efficiency of the component both in manufacture and in operation.

Table 2: Embodied energy in selected engineering materials expressed in Megajoules per kilogram (MJ/kg).

Material	MJ/kg
Wrought Aluminum (Primary, average)	255
Copper (average)	151
Structural Polymers (Primary, average)	84
Magnesium (average)	80
Stainless Steels (average)	79
Rubber (average)	70
Cast Aluminum (Primary, average)	58
Plain Carbon and Low Alloy Steels (average)	51
Structural Polymers (secondary, average)	42
Malleable Iron (average)	35
Glass (Primary, average)	30
Austempered Ductile Iron (ADI) (average)	30
Ductile Iron / CG Iron (average)	26
Cast Aluminum (secondary, average)	23
Gray Iron (average)	23

The cost of the energy embodied in the materials that we use is such a significant percentage of production that a nearly linear proportionality exists between a material/process combination's embodied energy and its average cost per unit of mass (Figure 4).

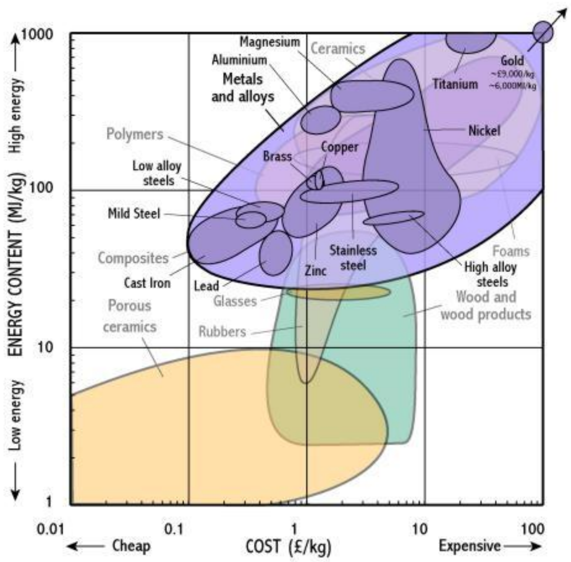

Figure 4: Energy content (embodied energy) is plotted versus cost (£UK) for various metallic materials from Cambridge University in this figure, www.msm.cam.ac.uk.

A sustainable design requires that we not only consider the amount of energy required to propel a device, but the amount of energy it takes to *build* the device. With its high strength-to-weight ratio, good stiffness, 100% recyclability and low embodied energy, ADI ranks well amongst sustainable engineering materials.

IADI

All of the ADI grades with greater than 800MPa tensile strength are achieved by fully austenitizing the part, allowing the time necessary to saturate the austenite with carbon, quenching rapidly enough to avoid the formation of ferrite or pearlite, then Austempering at a temperature above the martensite formation temperature for the time required to produce the desired Ausferrite structure. Grades 750 and 800 ADI are produced differently, having a mixed structure of pro-eutectoid ferrite and Ausferrite. This mixed microstructure is achieved by heating the part to a temperature range that is between the upper critical and the lower critical temperatures (approximately equal to the Curie temperature). At this temperature, austenite and ferrite are in equilibrium. When one then follows with a quench and Austemper, the proeutectoid ferrite is unaffected while the austenite transforms to Ausferrite as shown in Figure 5.

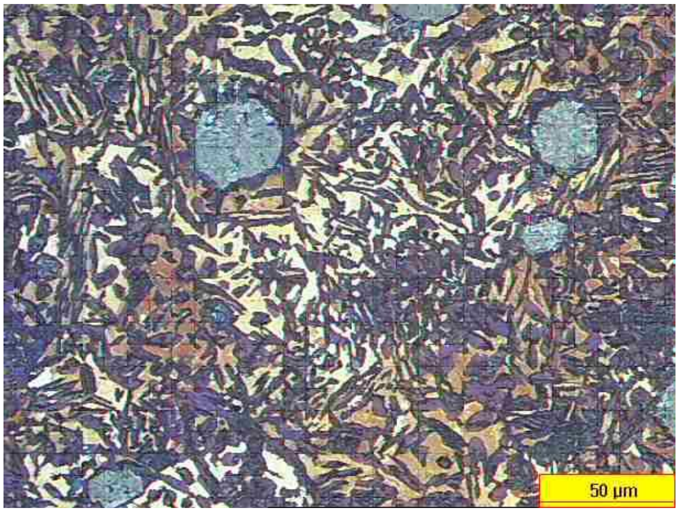

Figure 5: This microstructure of an ADI Grade 750 illustrates the mixed proeutectoid ferrite (light tan) and ausferrite (light brown to purple) microstructure.

This intercritically austenitized ductile iron (IADI) was developed in the late 1970's by Muhlberger in Germany to improve the machinability of Austempered iron. IADI became popular and was adopted in many designs in Europe. It offered reasonable strength, good toughness and machining similar to pearlitic ductile iron. For reasons related to local economies, this material became more popular in Europe where most of the ADI parts are machined completely after heat treatment. The IADI process has not been as popular in North America or Asia where most of the ADI components are machined complete before heat treatment.

A component requiring extensive machining and having tight tolerances can benefit from IADI by significantly reducing the post-heat treatment machining cost. The economic trade off is a significant increase in the need for alloying in the ductile iron casting. Carbon dissolved in the metal matrix is the most potent hardenability alloy. IADI parts have much less carbon dissolved in the matrix prior to the quench thus lowering the hardenability and requiring additional alloying elements such as copper, nickel and molybdenum to avoid the formation of pearlite instead of the desirable Ausferrite. Industrial researchers continue to investigate variations of IADI in search of a cost mitigating solution to the hardenability issue.

Gear Properties

In spite of the fact that one of the early high volume applications of ADI was that of gears in light vehicles, possibly the most under developed market for ADI is that of gears. Thirty five years after General Motors took the bold step of replacing carburized and hardened steel hypoid ring and pinion axle gears with ADI, there is still no formal ADI gear standard. ADI has been used for timing gears, worm gears and worm wheels, helical gears, and spur gears. It has been used for gears as small as 20mm in diameter and for mill gear wheels over 6 meters in diameter.

ISO 17804:2005, Founding Ausferritic Spheroidal Graphite Cast Irons was the first standard to reference gear properties and it was accomplished in Annex G, Table G-2. It provided guidance on contact and bending fatigue for four grades of ADI.

The American Gear Manufacturers' AGMA 6014-A06 Mill Gearing Standard[6] followed in 2006 and refers to ADI in Annex H, outlining bending and contact properties of a Grade 1200 ADI. ADI has been successfully used in large mill gear applications for over two decades with good success.

AGMA further addressed this issue in 2007 with an information sheet 939-A07 Austempered Ductile Iron Gears[7] in 2007. Although it is not a standard, it gives clear guidance to gear designers. As industrial experience is accumulated with ADI gears, work is being done to codify the ADI properties in an authorized standard that includes specified ADI properties in the body of the standard.

As one can see from Figures 6 and 7, ADI gear properties generally exceed those of neutral hardened, nitrided and induction hardened steel. When one considers that ADI is 10% lower in density, can be cast nearer to net shape (minimizing metal removal), and is considerably lower in cost, it can be concluded that ADI a suitable alternative material/process combination.

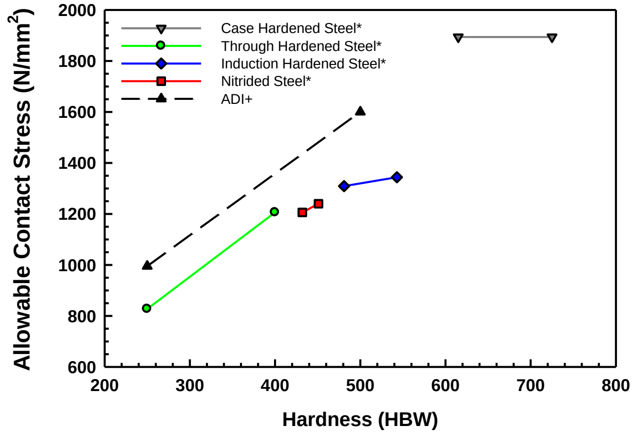

Figure 6: A comparison of the allowable contact stress vs. hardness for ADI and various steel-based material/process combinations.

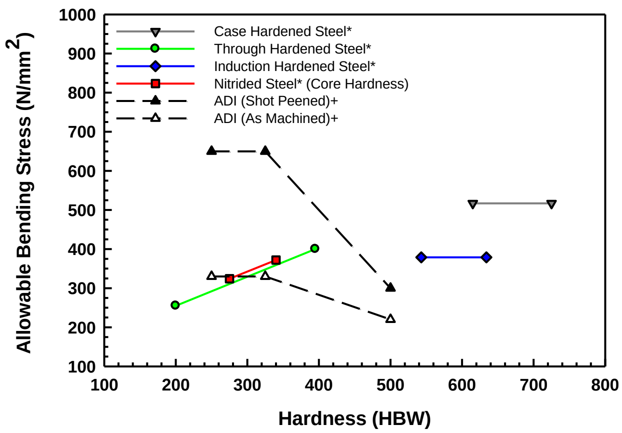

Figure 7: A comparison of the allowable Gear Tooth Root Bending Fatigue vs. hardness for ADI and various steel-based material/process combinations.

FEA based conversions / Strain limited fatigue properties

Designers' needs for the monotonic properties of ADI have been satisfied in numerous standards previously discussed in this work. Available data for the dynamic performance of ADI show it to be very competitive with other, well quantified, engineering materials (Figure 8). However, with the increased use of finite element analysis (FEA) modeling for design, the fatigue information has not been sufficient. The American Foundry Society completed research entitled "Strain Life Fatigue Properties Database for Cast Irons[8]" in 2003 that quantifies the strain-controlled (finite life) fatigue coefficients and exponents for most grades of cast iron, including ADI.

These numbers now allow designers to confidently consider ADI in dynamic applications.

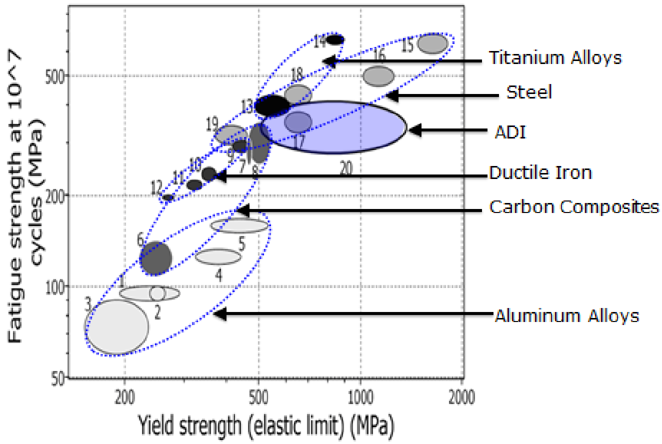

Figure 8: This figure compares allowable rotating bending fatigue vs. yield strength for various groups of materials. (Illustration derived from Keough et al[9].)

Unfortunately, property information for ADI is missing in engineering textbooks and, most importantly, in the drop-down menus of FEA design software, leaving the designer to plug in the numbers from other sources. Consequently, a mechanical engineer may have no knowledge of ADI and if the material does not appear as a choice in the software menu, it is essentially invisible to the user. ADI advocates within the industry are working hard to make sure that ADI properties are included in technical training information, manuals, textbooks and software; this after almost 40 years of commercial use. The importance of the dissemination of ADI information cannot be under emphasized.

Environmentally Assisted Failure (EAF)

Environmentally assisted embrittlement refers to a phenomenon where high strength ductile iron and/or ADI will fail prematurely when the following three conditions occur simultaneously:

1. A liquid is present in contact with ADI;
2. A stress is applied at or near the yield strength;
3. Loading occurs at a slow strain rate.

This phenomenon is of great concern when the aforementioned conditions can be met in service because reductions in UTS and elongation of 30 – 70% can be realized.

Initial experimental work revealed premature failure in contact with water when the stress and strain rate criteria were also met. Further work has shown that contact with isopropyl alcohol and automotive fluids (oils) will also be detrimental, but the effect is not as marked as with water.[10]

Prevention of EAF requires the removal of one of the 3 necessary conditions. When designing a component, efforts should be taken to ensure that a safety factor is employed to prevent loading near the yield strength. Furthermore, direct contact with a liquid could be altered by painting. However, the effectiveness of painting or other coating processes can be compromised as these protective layers can crack early when stressing above the yield point.[11]

Ferritic microstructures are immune to environmentally assisted failure. This would imply that a ferritic layer on the surface of a part would serve to mitigate the effects of EAF. While this may be true, other issues like lower strength, lower wear resistance and a residual tensile component for fatigue crack initiation/growth on the surface would result.

Intercritically austenitized ADI shows mixed results with respect to EAF. These results appear to be explained by the matrix microstructure. When proeutectoid ferrite is the continuous phase (HBW ≈ 200 HBW), there appears to be an improved resistance to EAF. For Grade 750 ADI, where proeutectoid ferrite is not a continuous phase, the results are similar to conventional ADI.[12]

To date, the cause of this embrittlement remains unexplained. Several researchers have proposed explanations including: hydrogen embrittlement, stress corrosion cracking and liquid metal embrittlement.[10,12]

Wear properties

The austenite component of the Ausferrite microstructure is thermodynamically stable. When a sufficiently high normal force is applied, a strain-induced transformation of this austenite to martensite at the contact surface will occur; resulting in the production of a high hardness, wear resistant surface. The depth of this surface is relatively shallow as shown in Figure 9.

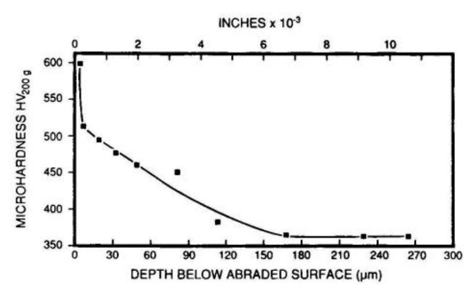

Figure 9: The depth of the transformed layer in ADI after exposure to a high normal force is illustrated by an increase in microVickers hardness near the surface. From the Ductile Iron Data Book for Design Engineers[13] – www.ductile.org.

Consequently, ADI tends to exhibit equivalent and/or superior wear performance to competitive materials in applications where this strain transformation to martensite can occur. This is best illustrated in the results for pin abrasion testing which provides a high stress abrasion environment. Figure 10 compares the performance of ADI to a number of competitive materials.

When examining the data in Figure 10, the overall slope of the curve for each material is significant. If a curve is relatively flat, then the overall wear resistance is independent of bulk hardness. A steep slope corresponds to the dependence of wear performance on bulk hardness or to materials that do not undergo a strain transformation at the contact surface.

The volume loss for ADI is approximately one-half that of as-cast ductile iron. The results for IADI are in between those of as-cast iron and ADI due to the presence of proeutectoid ferrite in the microstructure.

The performance of ADI can be improved by the addition of carbides i.e. producing Carbidic ADI (CADI™). In Figure 10, results are shown for two different levels of carbide, 5% and 18%. Note that as the percentage of carbide volume increases, the abrasion resistance becomes more competitive with a number of abrasion resistant (AR) irons. These AR irons have significant levels of expensive alloy elements allowing for CADI to replace them at rather significant cost savings when appropriate.

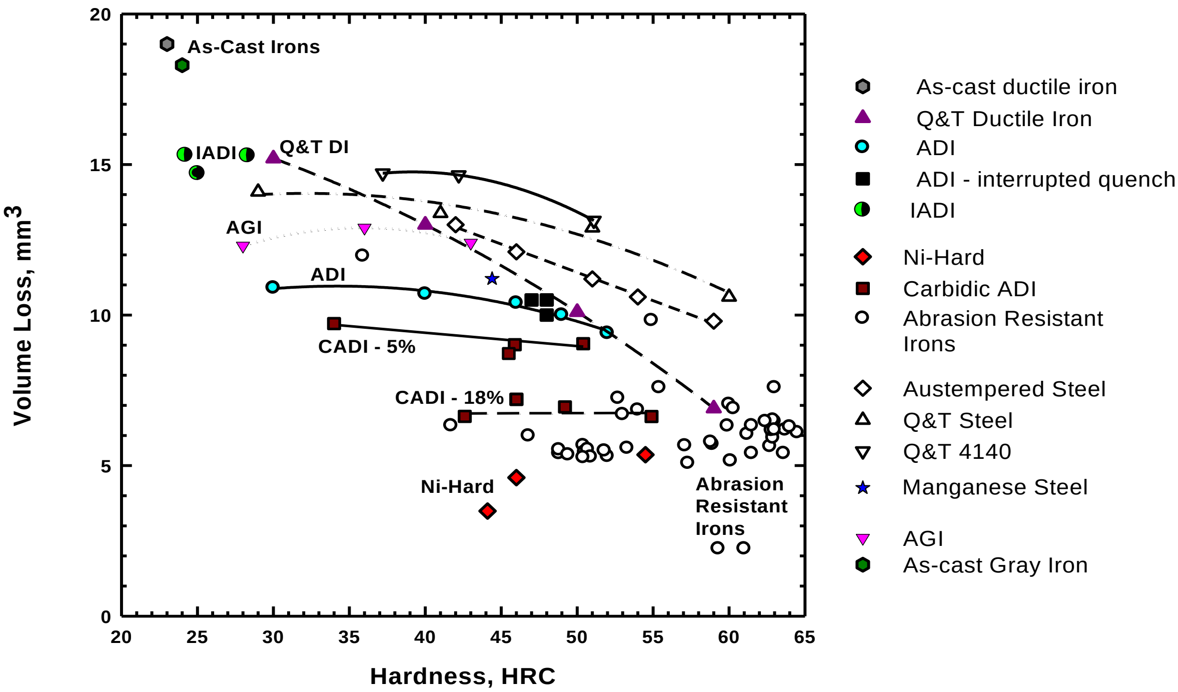

Figure 10: A comparison of the pin abrasion test results for ADI, IADI and CADI™ compared to competitive materials as a function of matrix hardness. Testing was completed in accordance with ASTM G132-96(2007).

Galling

Bronze has long been the material of choice in galling applications such as worm gearing. The unique properties of bearing bronzes give them excellent resistance to galling, but at a high price. With copper alloys costing several times more per unit of mass than ferrous alloys, the engineering community has long sought a cost-effective ferrous solution. Some initial galling research on ADI has yielded some interesting data that merits a deeper look.

Figure 11 shows a comparison of carburized and hardened and Carbo-Austempered™ steels, to Grade 900 and Grade 1600 ADI in a step-load galling test. All of the materials with the exception of Grade 900 ADI experienced the classic spike in coefficient of friction that denotes the onset of galling. It is hypothesized that the high austenite content in this particular Grade of ADI facilitates this behavior.

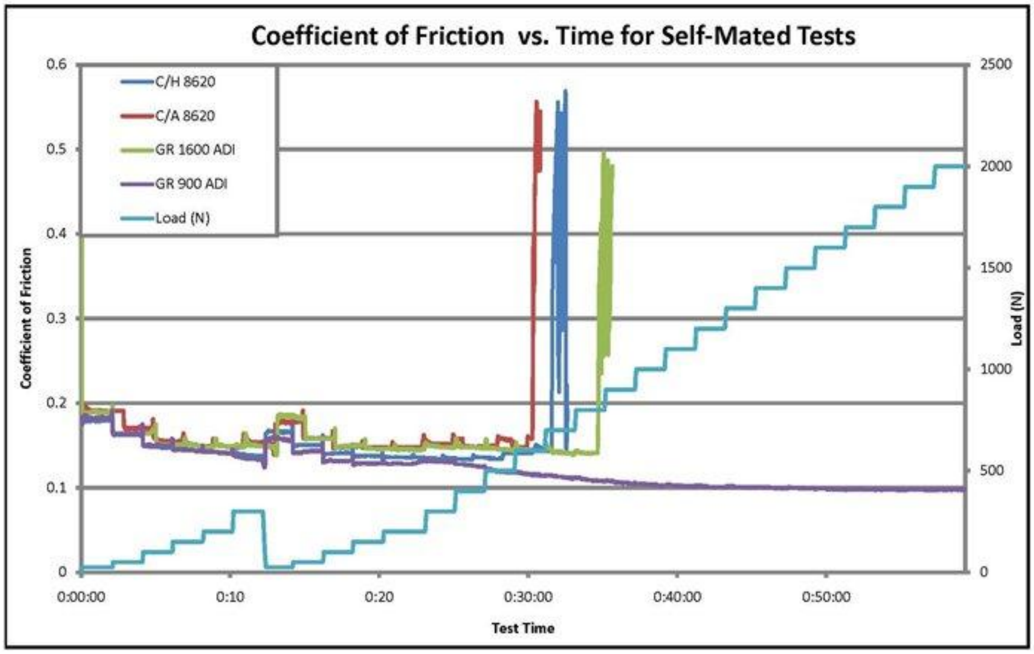

Figure 11: A comparison of carburized and hardened and Carbo-Austempered™ steels to Grades 900 and 1600 ADI in a step load galling test. The ADI 900 (purple line) did not gall in this test.

This galling test was a step-load, speed independent, test. Bronze has superior thermal conductivity compared to ADI which factors into galling behavior at speed. Although more work is needed to fully develop the galling behavior of ADI, if ADI could be used to replace bronze in industrial gearboxes, the cost implications could be significant.

Machinability

The issue of machinability has essentially created several branches on the ADI technology tree. As was previously discussed, the ferritic/ausferritic grades of ADI, Grades 750 and 800, were created to give ADI the benefits of the Ausferritic microstructural strength, while allowing for good machinability. This set the path of ADI development in Europe where more than 60% of all commercial ADI components are machined *after* Austempering. This evolution also forced a great deal of development in machine tools suitable for ADI.

In North America the ADI market developed around ADI grades 900, 1050, 1200, 1400 and 1600. This induced many designers to develop products that could be machined completely before Austempering, essentially trading a somewhat larger dimensional variation in exchange for simple machining with higher metal removal rates and longer tool life.

Armed with proper foreknowledge of the behavior of ADI during heat treatment and machining, engineers have developed new tool materials and scientific approaches to efficient metal removal. The essential knowledge related to the machining of ADI follows:

- ADI has a high yield (proof) strength yet a Young's Modulus (E) that is 20% lower than that of steel.
  - This requires a very stiff work holding set-up and short tool moments to minimize vibration during machining.
- When acted upon with a high normal force, ADI undergoes a strain-induced surface transformation that results in the austenite in the Ausferrite transforming to hard martensitic particles that are present in an acicular ferrite nest.
  - A thin chip may harden through its entire section while a thicker chip may harden only at the tool interface allowing the discontinuous chip to peel off presenting a new, more machinable, ADI surface to the tool,
  - This phenomenon makes thread rolling, perhaps, the most difficult machining operation with ADI.
- ADI has lower thermal conductivity than either ductile iron or plain carbon steels resulting in a high workpiece/tool interface temperature,
  - To maximize metal removal rate, the selected tools must have good toughness and be able to withstand high temperatures at the cutting face.

Tool manufacturers have now developed their own recommendations for machining ADI. The machinist, armed with the preceding knowledge can be successful machining ADI. Feeds, speeds, coolant and workholding can be optimized to efficiently machine a given component; even with conventional tool steels. Setting up to machine ADI based solely on hardness is a certain path to low throughput and poor tool life.

Charpy Impact vs. Fracture Toughness

There has been much discussion in the last decade about the efficacy of Charpy impact for use as a measuring test for ductile iron or ADI. Numerous publications have shown v-notched Charpy properties for steels to better than double those of ADI. However, when various steels and ADI are compared in fracture toughness, the results are nearly identical for a given hardness.

Charpy impact testing (developed by Charles Charpy in 1905) has been successfully used to qualitatively compare steels. It has been an essential tool in developing curves demonstrating the ductile-to-brittle transition temperature. As a result, many manufacturers have designated minimum Charpy values as a purchasing requirement for ferrous materials. (It does strike the authors that no such purchasing requirement of a Charpy minimum has been initiated for aluminum). The Charpy test puts ADI at a disadvantage compared to steel and unnecessarily dissuades designers from using the material in impact environments.

In monotonic testing, and unlike steel or aluminum, ADI does not exhibit necking (extreme plastic deformation local to the fracture site) when pulled to failure in a test bar. Rather, the entire gage length of the bar is reduced in cross section. While the reduction in area for a steel sample may be multiples of the measured elongation, the elongation and reduction in area for an ADI sample are typically similar.

In dynamic testing this effect plays out as lateral expansion of the fractured Charpy sample. A steel sample will exhibit significant lateral expansion at the fracture surface while an ADI sample will not.

Zanardi[14] has examined this phenomenon in a mechanical study of notched and un-notched fatigue performance and determined that, "The few available data suggest that ADI could perhaps show a (lower) notch sensitivity than steels of same yield (strength) and equal or better than steels and/or Aluminum having a yield (strength) of one half".

The question regarding the relative toughness of ADI to other competitive materials is, as yet, unsettled. As long as a Charpy test is used as a material selection tool ADI will remain at a disadvantage. In functional impact testing, as with fracture toughness testing, ADI has proven equal to or better than both wrought and cast steels with equivalent yield (proof) strength.

SUMMARY

Austempered Ductile Iron (ADI) traces its roots to the early 1970's. Since then it has grown into a substantial body of work and millions of tons of components processed. ADI is, in fact, a strong, light-weight, low-energy material. The tree that is ADI technology has grown new branches which are, in turn, leading to innovative metallurgical variations, clever product applications and fundamental new metallurgy. This evolution continues. With this work the authors have intended to give the reader an overview of the continuing developments so they might add their intellectual attention to the next new ADI development.

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ADDITIONAL RESOURCES

+ Applied Process Inc. internal research
+www.appliedprocess.com
+LinkedIn: ADI Mongers