ABSTRACT

By the turn of the century, the ADI market had begun to rapidly accelerate from a modest beginning in the early 1970’s to an estimated worldwide production level of 125,000 tons annually. This growth is expected to continue with the world production of ADI reaching 300,000 tons by the end of the decade (2010).

The expansion of the ADI market can be attributed to a number of factors including: collaborative R&D programs to document the properties of this material, international symposia devoted to ADI, developments in commercial Austempering equipment, adoption of specifications by international standards organizations as well as success stories of conversions to ADI.

This paper will discuss the latest property information available for ADI, including the recent developments in Carbidic ADI (CADI) and Grade 800 ADI, along with the continually expanding markets and applications of ADI.

INTRODUCTION

This paper is an updated version of the paper presented at the Ductile Iron Society’s 2003 World ADI Conference co-sponsored by AFS held in Louisville, Kentucky in September 2003.

HISTORICAL MILESTONES IN ADI DEVELOPMENT

The invention of ductile iron was announced concurrently by International Nickel and the BCIRA in 1948. The INCO process utilized Mg for spheroidization of the graphite and was patented in the US and other countries. While protecting INCO’s intellectual property, this patent also retarded the growth of ductile iron. When the patent expired, ductile iron production in North America rose rapidly. The US Ductile Iron Society was formed in 1963 to assure the continued production of high quality ductile iron.

The Austempering process has been employed for the heat treatment of steels since the 1930’s. However, it was the “commercialization” of the process in the 1960’s of equipment and newly found process knowledge lead to increased application of the process, particularly for the heat treatment of light springs and stampings. International Harvester’s groundbreaking work on Austempered Ductile Iron (ADI) track shoes for military vehicles in the 1960’s demonstrated both the opportunities for, and complications with the ADI process.

In the late 1960’s, General Motors initiated development work on a low-cost replacement for carburized and hardened steel hypoid ring and pinion differential gear sets for passenger cars. This included considering the possibility of Austempered malleable iron and evolved into an ADI gear development program.

In 1972, to address a fatigue strength shortfall on its ductile iron compressor crankshafts, Tecumseh Products began installing ADI crankshafts in their hermetically sealed Type AE compressors. These small shafts (Figure 1) were cast in ferritic ductile iron at Wagner Castings Company (Decatur, Illinois), machined complete at Tecumseh Products (Tecumseh, Michigan), Austempered at Controlled Atmosphere Processing (in Detroit, Michigan) and then returned to Tecumseh Products for installation in their compressors. This component, by all accounts, was the very first commercial application of ADI.
In 1977, after completing extensive lab and taxi fleet testing, General Motors began production of ADI differential gear sets, (Figure 2), at the Pontiac Motors facility in Pontiac, Michigan. These ADI gear sets replaced carburized and hardened AISI 8620 steel.

The parts were cast in alloyed ductile iron, machined complete, Austempered, and finished in sets in lapping compound. (The expensive press quenching procedure required for the carburized steel parts was eliminated). Over the next few years, GM produced over one million sets of ADI gears with no known warranty failures. A documented cost savings in excess of 20% was realized (Table 1). In 1980 General Motors ceased to produce rear wheel drive vehicles at Pontiac and this “home-grown” process for the production of rear differential gears was discontinued.

Meanwhile, GM had identified an alternative application for ADI using the same process. The US demand for four wheel drive vehicles was just beginning to grow and ADI constant velocity joints produced to the same process as the differential gears proved technically adequate and low in cost. Production of ADI constant velocity joints (Figure 3) by General Motors, (and later Delphi) has continued to date with over 9,000 of these components being assembled every day.

As these earliest of commercial ADI developments were unfolding, miscellaneous ADI applications began to appear here and there as worldwide research started to focus on the potential properties of ADI. But it would take improved process knowledge, more efficient equipment and the establishment of profitable business networks to make ADI grow.

In the 1970’s and early 1980’s heat treat equipment manufacturers were all developing more efficient equipment for commercial Austempering. In 1983 Advanced Cast Products chose semi-automated salt-to-

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**Table 1- Documented Manufacturing Cost Savings of ADI Gear Sets vs. Carburized and Hardened Steel Gears**

<table>
<thead>
<tr>
<th>Operation</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinion Blanking</td>
<td></td>
</tr>
<tr>
<td>Center Press</td>
<td>30%</td>
</tr>
<tr>
<td>Drill</td>
<td>35%</td>
</tr>
<tr>
<td>Rough Lathes</td>
<td>70%</td>
</tr>
<tr>
<td>Finish Lathes</td>
<td>50%</td>
</tr>
<tr>
<td>Grind</td>
<td>20%</td>
</tr>
</tbody>
</table>

**Ring Gear Bearing**
- Bullard Turning 200%
- Drilling 20%
- Reaming 20%

<table>
<thead>
<tr>
<th>Operation</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gleason Machining</td>
<td></td>
</tr>
<tr>
<td>Roughing Pinion</td>
<td>900%</td>
</tr>
<tr>
<td>Finishing Pinion</td>
<td>233%</td>
</tr>
<tr>
<td>Roughing Ring</td>
<td>962%</td>
</tr>
<tr>
<td>Finishing Ring</td>
<td>100%</td>
</tr>
</tbody>
</table>

**Figure 1- Air compressor crankshaft for Type AE Tecumseh Compressor (Courtesy of Tecumseh Products), circa 1972.**

**Figure 2- ADI Hypoid Ring Gear and Pinion set (Courtesy of General Motors Corp.)**
salt technology as the basis for their CastTuf™ product. In 1984 Getrag Gears of North America began the production of ADI diesel engine timing gears (Figure 4) utilizing Ipsen atmosphere-to-hot oil equipment.

In that same year, Atmosphere Furnace Company (now AFC-Holcroft) introduced their Universal Batch Ausquench furnaces that integrated an atmosphere controlled batch furnace with a highly agitated nitrite/nitrate salt quench (Figure 5).

The AFC equipment prompted the creation of a fledgling division, Applied Process, which was incorporated in 1984. Applied Process’ focus was the growth of the batch Austempering market and, particularly, that of ADI.

Meanwhile, in 1984, ASM International sponsored the 1st International ADI Conference in Chicago, Illinois, USA. In that same year, the ASME Gear Research Institute had initiated a collaborative ADI gear development program that included their sponsorship of the 2nd International ADI Conference in Ann Arbor, Michigan, USA in 1986.

By 1989 both the ASME Gear Research Institute and the Gas Research Institute had published the results of their multiple-year studies on the ADI process and its properties. Extensive data was compiled on process requirements and the engineering properties of the material.

Throughout the 1980’s, North American ADI applications continued to multiply. The driving force behind the rapid growth was the rather large price differential between steel components and ductile iron. The price per unit of mass for medium volume ductile iron parts was essentially half that for steel parts. When the additional cost of Austempering and transport was added, the ADI components still yielded double digit cost savings to the purchaser. This marked price differential between steel and ductile iron parts was (and is) much lower in Europe and other industrialized regions of the world. Thus the “accelerant” for ADI growth is, even today, greater in North America than in other markets.

What DID we learn about ADI? (The 1980’s)

All of these studies, proprietary developments and collaborative research initially focused on three aspects of ADI production, 1) the base iron, 2) the heat treat process, and 3) the properties of the Austempered material.

The Iron

The variables that affect as-cast ductile iron also affect ADI. In other words, the characteristics that result in good quality ductile iron also promote good ADI. In simple terms, the critical characteristics for the manufacture of either as-cast ductile iron or ADI can be generalized as follows:

-Consistent chemical analysis
-100 nodules/mm² minimum
-90% minimum nodularity
-0.5% maximum carbides & inclusions
-1% maximum micro-shrinkage
-Consistent pearlite/ferrite ratio

A consistent chemical analysis allows for a fixed heat treatment cycle. Significant variations in chemical analysis can affect the heat treat times and temperatures and the hardenability of the iron.

A high nodule count tends to reduce microsegregation, (Figure 6), thus minimizing cell boundary carbides, micro-shrinkage and other types of solute segregation. It also gives the iron increased toughness both as-cast and
after Austempering. Ductile irons with high nodule counts will machine much more readily than comparable irons with low nodule counts. A high percentage of spheroidal nodules increases the strength and toughness of the iron.

Figure 6- Microsegregation between nodules, a graphical representation.

A consistent pearlite/ferrite ratio minimizes the variation in mean volumetric expansion during Austempering. (Figure 7 demonstrates that for a given Austempering cycle a fully ferritic microstructure will grow more than a fully pearlitic microstructure). For a component that is Austempered after machining, a consistent pearlite/ferrite ratio will result in predictable growth during heat treatment.

Figure 7-Linear Dimensional Change during Austempering in ADI for a given pearlite content and Austempering condition.

The Austempering Cycle

Research showed that the optimum austenitizing temperature is a function of the iron chemistry. The austenitizing time is a function of the iron chemistry, the nodule count and the section thickness (or modulus). The Austempering temperature is a function of the strength grade desired. The Austempering time is a function of the Austempering temperature, the iron chemistry and the nodule count.

Additional research has centered on the role of the common alloying elements Mn, Cu, Ni and Mo and their relative effects on iron hardenability, properties and the heat treatment cycle.

The Properties of ADI

In the 1980’s, significant property data was compiled and various world-wide specifying bodies contemplated ADI standards. The first US standards, ASTM 897/897M, were released in 1990. They specified five, standard grades in both in-lb (897) and SI (897M) units. (Figure 8 shows the 1990 897M,SI standard).

These standards finally gave the designer something that he/she could use to actually specify the material. Prior to this the purchaser had to either specify a certain trade name (Kymenite, CasTuf) or fully specify the material chemistry and heat treatment on the drawings. Both of these alternatives tended to restrict the use of ADI, so the
development of these standards promoted increased use of ADI.

**The Five ASTM Standard ADI Grades (ASTM 897M-90)**

<table>
<thead>
<tr>
<th>GRADE</th>
<th>TENSILE* STRENGTH (MPa)</th>
<th>YIELD* STRENGTH (MPa)</th>
<th>ELONGATION* (%)</th>
<th>IMPACT ENERGY** (Joules)</th>
<th>TYPICAL HARDNESS (BHN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>850</td>
<td>550</td>
<td>10</td>
<td>100</td>
<td>269-321</td>
</tr>
<tr>
<td>2</td>
<td>1050</td>
<td>700</td>
<td>7</td>
<td>80</td>
<td>302-363</td>
</tr>
<tr>
<td>3</td>
<td>1200</td>
<td>850</td>
<td>4</td>
<td>60</td>
<td>341-444</td>
</tr>
<tr>
<td>4</td>
<td>1400</td>
<td>1100</td>
<td>1</td>
<td>30</td>
<td>388-477</td>
</tr>
<tr>
<td>5</td>
<td>1600</td>
<td>1300</td>
<td>N/A</td>
<td>N/A</td>
<td>444-555</td>
</tr>
</tbody>
</table>

* MINIMUM VALUES  ** UN NOTCHED CHARPY BARS TESTED AT 22°F ± 4°C

Figure 8 - ASTM 897M-90 Table of Minimum Properties and Typical Hardness.

Another clarifying act was the naming of the microstructure in ADI. (Figure 9). The microstructure consists largely of acicular ferrite and carbon stabilized austenite. This differs from Bainite (found in steels) which is acicular ferrite and carbide. However, in the 1970’s and 1980’s the ADI microstructure was being alternately called Bainite, pro-bainite, bainitic ferrite, and acicular ferrite and austenite. The ASTM formalized the name “Ausferrite” which has since been the adopted and recognized term for the unique ADI structure.

Figure 9-Comparative Microstructures of Grade 1 and Grade 5 Ausferrite (same magnification).

In these early years, proprietary work on fatigue properties was widely being done, but rarely being published. This too, restricted the application of ADI in components that were subjected to dynamic loading. It is known that ADI is more “flaw-sensitive” than its as-cast ductile iron counterparts, but users have mitigated this concern by machining, grinding, fillet rolling and/or shot peening in highly stressed areas.

A Technical “Fork in the Road”

A defining technical event in the 1980’s assured a different course of development for the US and Europe. The European approach had been one utilizing iron with low Mn levels, alloyed with significant levels of Ni and/or Mo. The iron was then austenitized at a relatively low temperature before Austempering. This resulted in a mixed structure of pro-eutectoid ferrite, acicular ferrite and austenite, (Figure 10), a relatively low hardness (250 HB), and low strength (800 MPa tensile strength).

Figure 10-The Ferrite-Ausferrite Matrix of Grade 800 ADI (Courtesy of Applied Process Inc. Technologies Div.)

This grade of ADI was machinable with only minor machining adjustments. Today, somewhat more than half of the European ADI is of the Grade 800 type. Therefore, most European applications are machined complete AFTER Austempering. (There is some anecdotal evidence that this form of ADI may be marginally less flaw-sensitive than a fully ausferritic ADI).

In the US, however, the aim was a low cost, ADI component. So on average, the Mn levels were (and are) higher and less alloy was used. The lowest strength ASTM grade of ADI is approximately 300HB with a 900 MPa tensile strength. This form of ADI is lower in cost to produce but somewhat more difficult to machine. The
vast majority of iron produced in North America is fully ausferritic and more than half of all ADI components produced in North America are machined complete BEFORE Austempering.

North American Commercial Development of Ductile Iron and ADI in the 1980’s and 1990’s

As more process knowledge, better controls and improved heat treating equipment became widely available in the 1980’s, a wide variety of relatively simple, ADI applications began to emerge. At first, the applications (with some distinct exceptions) were simple wear parts and ground engaging components. Fertilizer knives with cast-in steel tubes (Figure 11), digger teeth (Figure 12), metal-on-metal railroad suspension parts (Figure 13), plow points, snowplow shoes, tillage points, crusher and grinder applications were simple, cost effective replacements for heat treated steels, Mn Steel, hard-face welded steels and irons, and assembled parts.

In 1991 the American Foundry Society sponsored a World ADI Conference in Chicago, Illinois. Unlike the prior conferences in 1984 and 1986, (which centered on microstructure, heat treatment and laboratory results and testing), the attendees heard dozens of papers related to the application of ADI in various components, its machining and resultant performance properties.

In 1992 the first application of Carbidic ADI (CADI) was developed (Figure 18). CADI can be produced several ways, but consists of a final microstructure that is a mixture of Ausferrite and carbides. Its primary function is wear resistance. That first application, a small plow point for Carroll Ag, was developed as a cost-effective, long-life replacement for hardfaced or Mn steel components.

Figure 11-Anhydrous Ammonia (Fertilizer) Knives (Courtesy of Gothic Millhouse)

Next came dynamically loaded applications replacing steel castings, forgings and weldments. Engine mounting brackets (Figure 14), suspension components, (Figure 15), material handling conveyor components, (Figure 16) and gear carrier hubs, (Figure 17), exemplify those conversions.

In 1993 the Ductile Iron Society (US) authored and published an ADI process Certification Standard for the US Army. This document outlined the requirements that one would specify when purchasing ADI components. Pump components, sprockets, rollers, heavy duty suspension control arms and steering knuckles began to appear. Medium and heavy-duty truck suspension components were being converted wholesale and North
American ADI production had exceeded 30,000 tons per year.

Figure 14 - ADI Engine Mounting Bracket for a light vehicle (Courtesy of Ford/Mazda United Motors)

Figure 15 - ADI Suspension U-Bolt Bracket for a Medium Duty Truck (Courtesy of General Motors)

Figure 16 - ADI Material Handling Conveyor Parts (Courtesy of Dearborn Midwest Conveyor)

Figure 17 - ADI Tractor Axle Gear Carrier Hub (Courtesy of Dana Corporation).

Figure 18 - CADI Plow Point (Courtesy of Carroll Ag)

In 1995 a new, state-of-the-science facility dedicated to the Austempering process was commissioned in Oshkosh, Wisconsin. This facility, AP Westshore, capitalized on all of the knowledge accumulated to that time. Its aim was, high-efficiency, environmentally-friendly production of Austempered components.

Counter to the prevailing wisdom, a modern, atmosphere-to-salt heat treating system is very “green”. These systems recycle all of their quench salts, cooling water, waste metals and waste gases and put nothing down the
drain. Such systems produce very little smoke and no oily or hazardous residues. Another advantage of the atmosphere-to-salt systems is their safe operation. One “family” of commercial heat-treating companies in the US employing only this technology since 1969 have operated without a fire, (the equivalent of over 250 furnace-years), a record un-matched in commercial heat treating. Traditional oil and polymeric heat treat quenching systems create hazardous fumes and wastes and salt-to-salt Austempering units create a hazardous sludge that must be handled as a hazardous material.

Through the middle 1990’s more dynamic applications of ADI appeared as the coefficients and exponents for FEA designing with ADI became available. By 1997 ductile iron production in the US alone had exceeded 4 million tons and by 2000, North American ADI production was estimated to have exceeded 75,000 tons. This ADI production is being produced by over 200 foundries and Austempered in over 50 captive and commercial heat treats throughout North America.

In 1999 another North American, process-dedicated, batch-Austempering facility was commissioned in Elizabethtown, KY. That facility, AP Southridge, is currently operating four independent Batch Ausquench lines on a 24 hour, 7-day schedule.

Economic Forces Driving the North American ADI Market

Ultimately, the growth of ADI is as much an economic as a technical event. In North America a typical savings for converting a medium volume steel component to ADI is approximately 20%. That savings rises to 30% or more when replacing Aluminum with ADI. The relative pricing of engineering materials in North America (Figure 19) makes the high strength-to-weight ratio ADI material an attractive alternative. When you consider that, with proper design, ADI can replace aluminum at equal or lower weight, the economic opportunities are apparent.

![Figure 19-Relative Material Prices (North America)](image)

Foundries have an economic incentive to produce ADI. The value added Austemper heat treatment is sold as a “margin added” enhancement (Figure 20), thus increasing the producer’s profits while providing their customer with a “double digit” cost savings. Furthermore, (in the cases where commercial heat treating sources are used), a foundry that already produces good quality ductile iron can enter the ADI market with no additional capital or personnel costs.

![Figure 20- Comparison of Price/Margin, As-cast Ductile Iron vs. ADI vs. Forged Steel](image)

The capital equipment costs for the Austempering of ductile iron are rather high. Therefore, a very large volume of ADI must be produced by one source to cost-justify the investment of a captive Austempering facility. In North America, transport of goods over large distances has been cheap and timely. This has made the outsourcing of
ductile iron castings for commercial Austempering a relatively low-cost alternative. Over 90% of all ADI produced in North America is Austempered in commercial heat treating shops.

As long as the economies of producing components in ADI are good, its growth in North America will continue. However, ADI does not sell itself. The vast majority of the engineering community is still unaware of the capabilities of this material, (including the engineering faculty at colleges and universities). The marketing of ADI will be an on-going educational process; teaching the engineering and producer communities about the technical and economic advantages of the material. In many circles high performance cast irons are considered old and “low tech”. On the contrary, with ADI we have a high-performance material that replaces some of the perceived “high tech” materials at double digit cost savings. So what capability defines high tech?

The 2000’s and Beyond

At the beginning of the first decade of the new millennium, ADI applications are taking on a set of decidedly eclectic, new challenges.

Tow hooks for light trucks (Figure 21) have proven to be low-cost, durable AND, with their high impact resistance, have improved crash results for the automotive manufacturers. (This last result was an unexpected benefit of an ADI component).

Suspension components have evolved from machined designs that replaced forgings, to heavy ADI casting designs requiring no machining, to elegant, thin FEA designs that are both light-weight and cast to shape (Figure 22). The installation of FEA designed ADI upper control arms in the Ford Mustang Cobra (Figure 23) was a very visible application. The ADI was employed when FEA design indicated that the thicker aluminum component that was originally conceived would not fit in the vehicle package.

Since the very earliest days of ADI production, the agricultural community has welcomed it. Of late, the agricultural applications have evolved from ground engaging and “brute strength” applications to dynamically loaded applications such as feature-rich brake backing plates, tractor suspension components (Figure 24) and power transmission components. (Meanwhile, agricultural applications of CADI are starting to grow rapidly).

Figure 21- Tow hooks on light trucks (Courtesy of General Motors)

Figure 22- Machined vs. As-cast vs. FEA designs.
Thin walled, fine featured, castings using hard sand, core sand, shell and investment casting technologies are resulting in lightweight high performance designs in a variety of markets. An industry goal is to produce dimensionally accurate castings with 3mm minimum wall thickness. ADI components employing this strategy could compete with steel stampings and could replace a large number of aluminum forgings, castings and weldments. This would allow the designer to utilize the higher density ADI to replace lower density aluminum components at equal or lower part weights. How can a material whose density is 2.5 times greater than that of aluminum replace it at equal weight? ADI has 2.3 times the modulus; over three times the yield strength, over 5 times the fatigue strength (at 10MM cycles) and better noise damping.

The educational effort continues on many fronts. As of this writing, the ASTM A897 ADI standard (first released in 1990), is undergoing revisions and a new Society of Automotive Engineers standard, SAE J2477 is undergoing balloting. Both define five standard grades of ADI ranging from a 900-650-09 grade to a 1600-1300-01 grade. There is, however, significant discussion around a “grade 800” or “grade 750” iron. The ISO/CD 17804 worldwide specification that is currently under development contains a “Grade 800” (or 250-310 HBW) ADI. Only the future will tell if these irons, first developed in Europe, will prove popular with North American manufacturers.

Another intriguing opportunity for ADI may be in very large castings. The ductile iron industry has made many great inroads into the large casting industry. However, all of the very large, ductile iron parts are based on ferritic as-cast strengths and are very large in section. ADI, on the other hand, has been successfully replacing steel forgings, weldments and assemblies up to about one meter in diameter. ADI applications in structures larger than one meter have been sections, or parts that are keyed in or bolted on to a much heavier ductile iron or steel structure. The possibility exists for processing much larger ADI parts (Figure 25). This allows one to entertain the possibility of ADI hydraulic shovel booms, very large gears, motor housings and even structural architectural castings.
By the late 1990’s the transportation industry had dominated production of ADI in North America with light, medium and heavy-duty on-highway vehicle components comprising 55% of all applications. Construction and mining applications followed at 19% with Miscellaneous Industrial applications at 10%. Although currently growing at higher rates than the aforementioned categories, Railroad and Agricultural applications followed with 8% and 7% of the market respectively. North American Defense and Aerospace related activities in ADI have been minimal, (Figure 27).


<table>
<thead>
<tr>
<th>Category</th>
<th>Market Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Manufacture</td>
<td>11%</td>
</tr>
<tr>
<td>Const./Mining</td>
<td>8%</td>
</tr>
<tr>
<td>Agricultural Equip.</td>
<td>14%</td>
</tr>
<tr>
<td>Railroad Equipment</td>
<td>16%</td>
</tr>
<tr>
<td>Light Vehicle</td>
<td>25%</td>
</tr>
<tr>
<td>Heavy Vehicle</td>
<td>26%</td>
</tr>
<tr>
<td>Miscellaneous Industry</td>
<td>10%</td>
</tr>
</tbody>
</table>

From an engineering perspective it would appear that significant opportunities for ADI still remain in markets where the producers are unaware of the properties of this remarkable material. In various engineering and manufacturing circles certain material/process combinations dominate because of their “institutional longevity” and written standards that effectively exclude the consideration of competitive materials. Some examples of these are discussed in the following paragraphs.

**Gears and Powertrain Components**

The production of gears and powertrain components is a vast industry that is largely untapped by ADI. Carburized and nitrided steels dominate this field. AGMA and other gear standards relegate ductile iron to only the lowest rated gears and ignore ADI. It is only now that the SAE and ISO are producing standards that recognize the properties of ADI. ADI has significant advantages that are, as yet, unexploited.
ADI gears are cost effective. The machining of ductile iron produces a compact, discontinuous chip that is 100% recyclable. When components are machined before Austempering they can be subsequently ground, shot peened or fillet rolled to produce significant increases in surface compressive stresses and, thus, increased bending fatigue. ADI gears are quieter than steel gears because of the presence of graphite and austenite in the matrix. While, in some cases, the lower modulus of ADI (compared to steel) is a disadvantage, in gear applications it can result in a larger contact area for a given load, thus reducing the actual contact stress for a given input load. Furthermore, this “conformance” due to the lower modulus offsets minor dimensional discontinuities resulting from the manufacturing process. This creates the very real possibility of producing quieter gears for a given gear finish.

Today, in order to produce quieter powertrains, the manufacturing community is moving toward more rigorous manufacturing regimes. In automotive manufacturing this has been reflected by the need to move to higher AGMA gear “classes”. It has been estimated that the difference between an AGMA Class 8 gear and an AGMA Class 13 gear is an effective doubling of the manufacturing cost. This is due to the additional operations required to produce the higher accuracy and smoother surface finishes of a Class 13 gear. It is a real possibility that ADI gears could be manufactured to Class 8 finish and deliver the reduced noise level of a Class 13 steel gear. This interesting possibility deserves further investigation by the engineering community.

It is true that carburized steel allows for higher contact and bending stresses than ADI. However, the powertrain engineering community has, over time, adopted nitrided steel and powdered metal gears which both have lower allowable loads than ADI. Those conversions happened due to persistent efforts by the specific producers of a given material/process combination. That same effort would be required for large-scale conversion to ADI gears. However, if the ductile iron community is persistent in its efforts, ADI could be used to produce low-cost, quiet, high performance gearing.

Agricultural and Ground Engaging Components

The agricultural community has, at some level accepted ADI (and its offspring, CADI) for its components. However, the vast majority of all ground engaging parts are made of cast, forged, welded and/or heat treated steel, many with hard-face welding and/or brazed on carbides.

Ground engaging components will always be at the heart of agriculture. As North America’s population grows by about 2% annually, the need for increased grain crops will grow commensurate with that population. That, combined with the positive economics related to converting components from their current material to ADI or CADI should result in continued growth in this market. Unlike crankshafts, or gears or other durable goods, ground engaging parts, by definition, wear out. If we can produce a cost effective product that wears as well, or better than the current product the opportunities are significant.

Dynamic Components in High Performance Applications

As described earlier in this work, ADI has excellent dynamic properties. However, with the exception of some highly visible examples discussed earlier, its application in components undergoing cyclic loading has been rather limited.

This is due to the engineering community’s pre-conceived notions about cast irons and their ignorance of ADI. In many cases ADI is absent from the pertinent material standards. In addition to the aforementioned AGMA gear standards, a relevant example would be that of the automotive material fatigue standard SAEJ1099. That standard lists the fatigue coefficients and exponents necessary for FEA modeling for hundreds of engineering materials, including dozens of aluminum alloys. However, the values for gray iron, ductile iron and ADI are not included in the standard. Fortunately, this is expected to change within the near future. A DOE/CMC sponsored program to determine the fatigue coefficients and exponents in 18 different cast irons (including Grades 1 – 4 ADI) will finish within months of this writing. Upon completion, this strain-life fatigue information is scheduled to be added to SAEJ1099.

The general adoption of ADI into the “portfolio” of design engineers will only be accomplished as a result of sustained activity by the ductile iron manufacturing community. Pro-active involvement in the technical associations and their standards committees is one aspect of that activity. Another is the need for sustained and widespread technical marketing and education about the material’s capabilities and advantages.

CADI - Expanding the Property Ranges for ADI

To date, the primary focus of the property database development in North America has concentrated on the conventional Grades 1 – 5 of ADI. While a small number of companies have used variants of ADI like CADI,
attempts to widen the database and commercialize the CADI market have only recently begun.

New test results document improved wear resistance in both pin abrasion and wet sand rubber wheel abrasion testing for CADI over ADI. In addition, the abrasion results of CADI are very promising versus heavily alloyed abrasion resistant (AR) irons as shown in Figures 28 and 29. CADI rivals the performance of a number of AR irons, but not all of them. However, the unnotched impact energy of CADI has been shown to be 2-10 times that of AR irons. Thus, CADI is finding a niche where one needs excellent wear along with adequate toughness.

The Future for ADI

Following its historical growth rates, it is estimated that North American ADI production could approach 200,000 tons per year by the end of this decade and exceed 300,000 tons per year by 2020 (Figure 30).

In the fall of 2002 the World Conference on ADI sponsored jointly by the Ductile Iron Society and the American Foundry Society was held in Louisville, Kentucky USA. Scores of new applications were reviewed. New research on machining was presented that implies that new tools and techniques may allow us to machine ADI at much higher metal removal rates than previously considered. Grade 800 ADI and Carbide ADI are starting to find applications worldwide. End users, and their suppliers, are adapting the material and its various grades to a whole host of new engineering demands.

The future of ADI, it seems, is only limited by our ability to fully exploit the properties of this unique material.

ACKNOWLEDGMENTS

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ADDITIONAL RESOURCES

+ Applied Process Inc. internal documents/research
+ www.appliedprocess.com
+ www.ductile.org/didata
+ www.afsinc.org
+ www.ironcastings.org
+ www.matweb.com

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