Automotive Applications of Austempered Ductile Iron (ADI): A Critical Review

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ABSTRACT

Austempered Ductile Iron was first commercially applied in 1972. By the mid 1970’s it had found its way into Chinese Military trucks and into commercial truck applications in Europe. By 1978, austempered ductile iron had been applied to light cars and trucks in the US. Today, it is estimated that over 50,000 tons per year of austempered ductile iron components are installed in cars and trucks world-wide. That production appears to be growing at a rate of exceeding 10% per year.

As a family of materials, austempered ductile iron capably addresses the issues of weight, strength, stiffness, noise, cost and recyclability. From the first differential gear sets installed by General Motors in 1978, to light-weight truck-trailer wheel hubs, to high performance automobile suspensions, austempered ductile iron has found itself in many unique applications. This paper will review those applications, the reason(s) for the conversions, and the performance of those components.

INTRODUCTION

There have been numerous papers and works specifically related to Austempered Ductile Iron (ADI), its properties and its applications. This paper undertakes to critically review past, current and attempted automotive applications and discuss the results from a design fitness perspective. The authors begin by discussing the historical and technical background necessary for a reference basis. Then, applications, both successful and unsuccessful, are analyzed for the benefit of the reader to learn from precedent examples in the automotive industry.

HISTORY OF DUCTILE IRON / AUSTEMPERED DUCTILE IRON

The first commercial applications of Austempered Ductile Iron (ADI) occurred in 1972. However, the history of the development of ADI spans from the 1930’s to the present. Pioneering heat treatment work with steel (1930’s) and the discovery of ductile cast iron (1940’s) are included among the important events which lead to the development of ADI.

In the 1930’s, work was conducted by Bain et al on the isothermal transformation of steel. A new microconstituent was discovered that was described as “an acicular, dark etching aggregate.” This new microstructure exhibited promising properties as it was found to be tougher, for the same hardness, than tempered martensite.

In the 1940’s Keith Millis was assigned the task of investigating elements to substitute for chromium in the production of Ni Hard cast iron at the International Nickel Company (INCO). This investigation eventually lead to the treatment of gray cast iron with magnesium. On examination, spheroidal shaped graphite was found in this cast iron. The first magnesium treated ductile iron had been produced.

At the same time that Millis was conducting his experiments, Henton Morrogh et al were attempting to understand how to modify the shape of flake graphite in cast iron to a spheroidal form for the British Cast Iron Research Association. Morrogh presented a paper describing this work at the 1948 American Foundrymen’s Society meeting. The announcement of ductile iron stated that “A cast material, possessing high strength, high elastic modulus and, in appropriate compositions, a substantial amount of ductility, has been developed.” Until this time the work of Millis had been done in secrecy. A formal announcement of his work was soon made. 1948 marked the birth of ductile (spheroidal graphite) iron.
INCO patented the work of Millis and licensed the process to make ductile iron. When the patent expired in 1966, there were 651 licensees in 31 countries producing 2.1 million tons of ductile iron per year. The production of ductile iron continues to grow. By 1968, it had surpassed the production of malleable iron. In the year 2006, US shipments of ductile iron are forecasted to exceed 5 million tons per year. This would approach or possibly exceed gray iron shipment rates.

Although the knowledge about the austempering process had existed since the 1930’s, the technology to accomplish it on an industrial scale lagged behind. It was not until the 1960’s that the austempering process was widely applied to steel parts due to the improvements in the capacity and quality of commercial austempering equipment. Another decade would pass before the process was commercially applied to ductile iron.

In 1972 Tecumseh Products austempered a 0.5 kg ductile iron compressor crankshaft. In this instance, austempering was viewed to be a solution to a specific product problem. This first commercial application of ADI marked the beginning of many to follow. As of this writing, it is estimated that worldwide production of ADI is now exceeding 100,000 tons per year.

**DEFINITION AND PROPERTIES OF ADI**

Austempered ductile iron has a unique microstructure called ausferrite. This ausferrite microstructure sets ADI apart from as-cast ductile iron, quenched & tempered or surface hardened ductile iron. Excellent property combinations of strength, ductility, and toughness are produced from ausferrite.

The range of properties available for ADI are dependent on the choice of heat treatment parameters. In 1990 ASTM established five standard grades of ADI (ASTM 897-90 and 897M-90) which are listed in Table 1. An official European standard (EN-1564:1997) did not become available until 1997. Note Table 2.

When normal stresses are applied to an ADI part in service, a localized strain induced transformation which hardens the material can occur. As a result, ADI exhibits excellent abrasion resistance. ADI provides equivalent levels of abrasion resistance to both austempered and Q&T steels at lower hardness levels as shown in Figure 1.

The toughness of ADI is significantly better than that of conventional ductile iron. It is comparable to cast and forged steels, but the ductility of ADI can be lower.

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**Table 1- ASTM 897 / 897M: 1990 (USA)**

<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 (BH)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>850</td>
<td>650</td>
<td>10</td>
<td>80</td>
<td>280-321</td>
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<tr>
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<td>60</td>
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<tr>
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<td>1200</td>
<td>550</td>
<td>4</td>
<td>60</td>
<td>340-444</td>
</tr>
<tr>
<td>4</td>
<td>1400</td>
<td>1100</td>
<td>1</td>
<td>35</td>
<td>380-477</td>
</tr>
<tr>
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<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 72 +/- 7F

**Figure 1- Relative abrasion resistance of ADI compared to other material/process combinations.**

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**Table 2- EN 1564:1997 (Europe)**

<table>
<thead>
<tr>
<th>GRADE</th>
<th>TENSILE STRENGTH (MPa)</th>
<th>YIELD STRENGTH (MPa)</th>
<th>ELONGATION (%)</th>
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<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 +/- 4C
The fatigue strength of ADI is equal to or greater than that of forged steel. ADI responds favorably to shot peening which can further increase the fatigue strength. It should be noted that ADI does not exhibit a true endurance limit for high cycle fatigue applications.

In the high cycle range, a slight drop-off occurs; however, this can be accommodated for in early design stages. In fact, ADI’s fatigue curve is significantly higher and flatter than that of aluminum in the low load / high cycle region.

A component weight reduction of 10% can be realized by using ADI in place of a steel forging. Figure 2 shows the relative weight per unit of yield strength for a variety of materials. (For this analysis forged steel has been normalized to 1.) Figure 2- Comparative weight per unit of yield strength.

If weight per unit of yield strength is considered, ADI performs remarkably well. It is interesting to note that aluminum, which is perceived as a lightweight engineering material, is unable to match the weight per unit of yield strength of ADI in most instances.

Relative cost per unit of yield strength for aluminum, steel, ductile iron and ADI are given in Figure 3. (Ratios are based on steel forgings normalized to 1.) In most instances, ADI is the best buy per unit of yield strength.

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THE IMPLEMENTATION OF ADI IN AUTOMOTIVE APPLICATIONS

Figure 3- Comparative cost per unit of yield strength.
After the groundbreaking application of ADI to compressor crankshafts by Tecumseh products in 1972, a flurry of engineering activity was undertaken. In those early years the process was not well quantified and ADI was met with only mixed success. However, in a project originally started in the 1960’s, GM was methodically developing an ADI gear program. After a decade of design development, prototyping and testing, in 1977 GM released a hypoid ring and pinion gear set (Figure 4) in ADI for installation in all mid-sized vehicles produced at the Pontiac Motors complex in Pontiac, Michigan. This gear set ran successfully with no known warranty failures until rear wheel drive vehicle production ceased at Pontiac.

The Pontiac process was unique and home-grown. It utilized a conventional high volume pusher-type furnace with a hot oil quench. The oil was limited in temperature to 243°C (470°F) so the resultant material matrix was a hybrid of austempered (ausferritic) and quenched and tempered (martensitic) structures. The 47Rc hardness gears performed as well as the 60Rc carburized and hardened gears that they replaced on durability tests for the load ranges used on the subject vehicles. In addition, the austempered gears could be quenched free standing, thus eliminating the need for expensive quench pressing. Additional savings were achieved in improved machinability of ductile iron as compared to forged 8620 steel. They were documented by Lottridge and Grindahl at GM² as follows:

<table>
<thead>
<tr>
<th>Operation</th>
<th>Improvement</th>
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<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>
<tr>
<td>Ring Gear Bearing</td>
<td></td>
</tr>
<tr>
<td>Bullard Turning</td>
<td>200%</td>
</tr>
</tbody>
</table>

It is important to note that these ADI gears were processed with the same equipment and used the same routing as the precedent steel gears. The press quenching was the only operation eliminated by switching to ADI.

These gears exhibited the ability to withstand contact loads at ten million cycles of over 1,680MPa (240 ksi). Today, with higher austempering temperatures and longer austempering times we can improve these allowable loads by at least 10%. However, in many current automotive applications even these contact strengths are acceptable.

When GM shifted from rear wheel drive to front wheel drive in 1980 the ADI ring and pinion gears were a casualty. But by 1979, the GM engineers had found another use for their Pontiac austempering operation. They began producing inboard constant velocity joints (Figure 5) for four wheel drive light trucks from ADI.

These “tripot housings”, as they are called, have today been re-engineered to reduce weight, (Figure 6), and
are still produced by Delphi (Saginaw, Michigan) at a rate of over 8,000 per day.

Figure 6- GM’s ADI constant velocity joint has been re-engineered to reduce weight for today’s production.

They are cast in ferritic ductile iron at a nominal 150 BHN hardness, machined complete, austempered to about 450 BHN, cleaned and, (in some cases), seal ground and installed. Over the years these components have found their way into GM, Dodge, Jeep and Audi vehicles.

Meanwhile, in Europe, the Jot Companies had begun coordinating ADI developments for truck applications. By working with Oy Sis-Auto Ab (Finland), they developed a differential spider (Figure 7) that replaced carburized steel. Meehanite Metal Corp. indicated that the manufacturing process was cut from ten steps to two. In-service testing of these components showed a measurable decrease in wear due to the improved sliding properties of ADI-to-steel as compared to steel-to-steel.

Figure 7- ADI differential cross (spider)

Jot also reported that ADI used in annular gears (Figure 8) yielded a peculiar benefit in addition to lower manufacturing cost. With its modulus of elasticity approximately 20% lower than that of steel, ADI showed a 5% lower contact stress for the same input torque due to the “conforming” of the ADI gear teeth. With their 10% graphite matrix, the ADI annular gears also ran quieter than the conventional gears. (Chrysler Corporation later produced millions of Austempered Malleable Iron (AMI) annular gears for the automatic transmissions in their popular mini-vans).

Figure 8- An ADI annular gear.

Further applications applied in Europe as early as the late 1970’s included suspension spring seats and support brackets for Saab-Scania trucks. This technology has since been adopted for spring, torsion bar and engine brackets by other European truck manufacturers such as Iveco, Volvo and Daimler-Benz. (Figure 9). In fact today, the heavy truck and trailer industry world-wide uses ADI for hundreds of bracketry applications.
Soon ADI production in North America began to outstrip production in Europe and Asia combined. North American auto producers were no exception, employing ADI for engine brackets at GM, Ford and Mazda.

In the 1980's GM first applied ADI for an engine component. They chose the camshaft for the L-4 engine. This camshaft was produced for GM by Intermet Corporation and exceeded the requirement of 250ksi (1,750 MPa) contact stress at ten million cycles with no pitting. This camshaft was employed for the production life of the L-4 engine.

In addition to the ADI timing gears, Cummins found another practical use for ADI in its engines. Shell cast, ADI injector clamps (Figure 12) turned out to be a weight and cost savings for the Cummins engine designers.
From its commercial birth in 1972, ADI had grown most quickly in the non-automotive sectors. Companies like International Harvester (now Navistar and Case), John Deere, Caterpillar and others had pushed the technology. In the middle to late 1980’s with the understanding of ADI growing and commercial capacity for its production increasing, the pace quickened in the automotive sector. Trac-Tech found ADI to be the perfect component material for their popular Detroit Locker differential (Figure 13).

Aftermarket suppliers like Trailmaster began to offer ADI suspension lift kits for heavy duty off-road, four wheel drive trucks (Figure 14).

In the 1980’s, Ford had successfully developed a high performance ADI crankshaft. (Figure 15). In fact, during the development of the ADI crank at Ford, as Bela Kovacs, the development engineer then at Ford commented, “the only thing we failed to do was to fail an ADI crankshaft”. Unfortunately, the much awaited Thunderbird Super Coupe was coming in behind schedule and over budget so the ADI crank was dropped in favor of a “known quantity”; an imported steel forging. Since that time, GM, Ford, Chrysler, Nissan and Toyota have all developed race-tested ADI crankshafts, but NONE are in production.

By the mid-1990’s the Motor Industry Research Association (MIRA) had completed work on an ADI crankshaft development program\(^4\). That program produced the proper material, process and design characteristics necessary for a successful ADI crankshaft implementation except for one tiny detail. The coefficient of thermal expansion for ADI is about 20% greater than that of conventional ductile iron or steel. Therefore, when the ADI crank was put on test, once it heated to operating temperature it grew until there was negative oil clearance in the bearing areas and the engine seized. Unaware of this phenomenon, the MIRA work ended with no explanation for this failure. As of this writing, a new MIRA work is under consideration to resolve that mystery and prove out the design.

Today, to the knowledge of the authors, only tiny TVR Ltd., a sports car manufacturer in West Midlands, England is producing production automobiles with ADI crankshafts. These ADI cranks are used in their...
production V-8 and are being tested in their in-line six cylinder engines with good results.

By the 1990's Navistar, Freightliner, Kenworth, GM, Iveco, Volvo and other heavy truck manufacturers had adopted ADI as a high performance, low cost material for spring hanger brackets and u-bolt brackets, (Figure 16), accessory brackets, and shock absorber brackets (Figure 17). North American as well as various European suppliers, had adopted ADI for brake spiders (Figure 18), steering knuckles (Figure 19) and steering arms (Figure 20). Kenworth chose ADI for the heavy duty sway bar bushing shown in (Figure 21). Note that this part is machined completely before austempering and includes a precision spline and Acme threaded ID.

As outlined previously, ADI is not always the choice in the high stakes, competitive manufacturing world. When Ford contracted with Simpson Industries to produce a light-weight, low cost, one-piece knuckle/spindle (Figure 22) for one of its North American vehicles, ADI seemed to be the clear choice. The ADI spindle was about 10% lighter than its micro-alloyed, forged steel counterpart. The ADI outperformed the steel in cold weather impact, yield strength and fatigue strength. The as-cast ductile iron machined much more readily than the micro-alloyed forging steel. However, the non-symmetrical nature of the part resulted in an unacceptable level of dimensional variation after austemper heat treatment. Before the dimensional variations could be resolved, the German forging producer reduced the price of the forging by something in excess of 20%, effectively killing any further development on that product. That product is, today, made from micro-alloyed forged steel.
Similarly, Caterpillar, a major user of ADI, attempted to produce ADI rocker arms for its diesel truck engines. The engine design was an existing design, thus the “envelope” for the part was prescribed. On paper the ADI should have been a good material in this application. However, fatigue testing proved otherwise. It so happened that at the common operating range of 2,000 to 3,000 rpms, the ADI, with its lower Young’s Modulus, reached its natural frequency and failed in resonance. In a “clean sheet” design the engineer would have been able to address this issue by changing the section modulus. However, in this existing design that change was not possible, thus precluding the use of ADI as a cost effective alternative. Examples such as these are all illustrative of the issues that design engineers face when changing to new materials such as ADI.

The dynamic grades of ADI are more than three times stronger than the strongest grades of forged or cast aluminum. Furthermore, ADI’s density is only 2.5 times that of aluminum and its stiffness is 2.3 times that of aluminum. Therefore, the opportunity exists for a properly designed ADI part to replace an aluminum part at an equal or lesser weight. With aluminum, on average costing roughly two to three times more per unit weight than ADI, the cost savings potential becomes rather inviting. Of late, design engineers have begun to exploit that cost per unit of strength advantage.

Walther EMC a small, US manufacturing company, produces a product that they call the Duralite Wheel Hub (Figure 23). This hub, utilized on light weight truck trailers, is an ADI hub that is 2% lighter than its aluminum counterpart and costs roughly 30% less.

A major North American truck components manufacturer needed a tough, low cost material for a clutch collar and differential case to engage and disengage all wheel drive on heavy trucks. Two materials were tried. The first, a fully machined, carburized and hardened 8620 steel forging failed on a “dead skid”, full load test. An ADI set with as-cast teeth (Figure 24) passed the test and is in production today as a “substantial” cost savings.

When GM switched to hydro-formed rails on their new light truck models, they created a need for a new design of tow hook. The precedent hook had been constructed of bent square steel wire. A new ADI design (Figure 25) allowed the engineers to slide the hook between the frame rails for attachment without the need for a second.
The ADI hooks passed all pull and crash testing requirements and are now in production.

Figure 25- ADI tow hooks for trucks and sport utility vehicles.

Truck and trailer engineers have aggressively employed ADI in their designs. Pintle hooks for multiple trailer truck rigs (Figure 26) have performed without failure for nearly ten years. ADI consumer trailer products like the load leveling hitch component shown in Figure 27 have proven to be safe, light-weight and cost effective.

Figure 27- ADI load leveling hitch components

The "lost foam" casting technique is being used to produce the large, complex ADI truck suspension bracket shown in Figure 28. The shell casting process is being used to produce the ADI trailer jack stand gears with as-cast teeth shown in Figure 29.

Figure 28- A complex ADI Truck suspension bracket made using the "lost foam" casting process.

A. T. systèmes, (France), did a direct comparison between aluminum and ADI for a next generation automotive engine bracket (Figure 30). The aluminum design was ultimately 10% lighter than the ADI design, but the cost and the acoustical performance of the ADI part made it the best selection in this application.
This ADI engine bracket for a next generation European passenger car proved to be the economical choice over aluminum.

Finally, in the area of passenger car suspensions, GM demonstrated the feasibility of using ADI suspension control arms (Figure 31) by successfully installing them on Cadillac Limousines since 1995. Recently, however, Bentler was contracted by Ford to produce a lightweight, cost effective, independent suspension system for its high performance Mustang Cobra sports car. ADI was chosen for the upper control arms (Figure 32) for its combination of low weight (approximately 3 kg finished), noise damping and low manufacturing cost.

Figure 30- This ADI engine bracket for a next generation European passenger car proved to be the economical choice over aluminum.

Figure 31- ADI suspension control arms for Cadillac limousines.

Figure 32- Lightweight ADI upper suspension control arms for the Ford Mustang Cobra.

SUMMARY

Like any material, ADI is not the answer for every difficult design. However, ADI offers the design engineer an intriguing new alternative to conventional materials.

The higher strength grades of ADI compete with carburized and hardened steels for wear resistance, while exhibiting better noise damping capabilities and a generally lower manufacturing cost.

The lower strength, "dynamic" grades of ADI compete favorably with forged steel as a cost and weight savings, although its lower stiffness needs to be addressed in the initial design phase.

Replacing aluminum with cast iron at equal weight is truly a new paradigm. As casting technology continues to improve, the range of applications for high strength, light weight ADI castings will increase.

Cast ADI components with three millimeter walls can compete at equal unit weight with aluminum sand and die castings, aluminum forgings and normalized and heat treated steel stampings, forgings and castings. Three millimeter wall, high integrity castings produced at automotive volumes represent the "next frontier" being explored by the casting industry.

In some automotive circles, cast iron has been "given up for dead". Meanwhile the average amount of ductile iron per vehicle is increasing and ADI is being found in new applications throughout the car and truck industry each year each year. Its high strength to weight ratio, low cost per unit of strength and 100% recyclability make this material difficult to ignore.
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REFERENCES


ADDITIONAL RESOURCES
