Unleashing ADI's Conversion Potential

This article examines two conversion opportunities for austempered ductile iron (ADI) and details property and design considerations to rely on for future product development.

Alfred Spada
Editor-in-Chief

Austempered ductile iron (ADI) is a metal fit for conversions. The material, which essentially is a cast ductile iron that undergoes a specially designed austempered heat treatment, offers design engineers an alternative to steel, iron and aluminum when high strength and low wear are required.

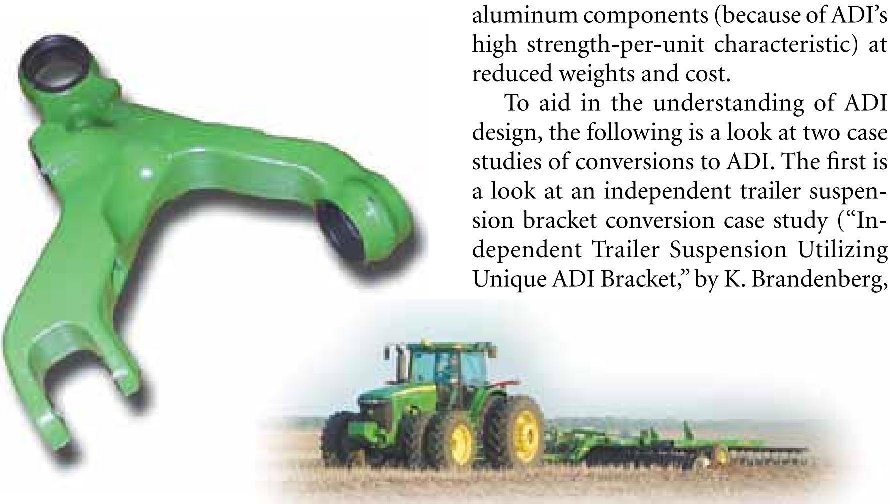
You may ask, "How can one cast metal replace the other three?" It can't in all applications. But for some, it can offer up to a 50% cost reduction as well as an overall component weight reduction (even for aluminum). This is because of the properties the material possesses.

ADI is ideal for a number of high-strength, low-wear industrial applications. For example, this material is an alternative to steel for gear applications. High-stress applications require high-contact rolling and tooth bending fatigue properties in addition to high fracture toughness impact strength. The fatigue properties for ADI are comparable to heat-treated steels. In addition, all grades of ADI exceed the notched impact resistance and low temperature properties of carburized and hardened 8620 steel.

While ADI can be produced with hardness from 30-50 Rc, the wear resistance for a given hardness level is superior to many conventional materials. In some applications, ADI with 42-46 Rc has replaced 60 Rc carburized and hardened 8620 steel. Following this, the heat treatment for ADI allows the material to have excellent rolling contact fatigue performance that allows it to function in applications with contact stresses exceeding 250 ksi.

The key to any of these material property enhancements is to properly design the component to take advantage of what the material offers. The design is what allows ADI to replace steel stampings and aluminum components (because of ADI's high strength-per-unit characteristic) at reduced weights and cost.

To aid in the understanding of ADI design, the following is a look at two case studies of conversions to ADI. The first is a look at an independent trailer suspension bracket conversion case study ("Independent Trailer Suspension Utilizing Unique ADI Bracket," by K. Brandenberg, J. Keough, I. Lee, D. Maxwell and P. Newman) presented at the 2002 Society of Automotive Engineers World Congress (SP-1684). The second is a look at a heavy duty truck lower control arm conversion opportunity ("An ADI Alternative for a Heavy Duty Truck Lower Control Arm," P. Seaton and X. Li) presented at the 2002 American Foundry Society World Conference on ADI.



This 145-lb suspension control arm for John Deere is produced in ADI. Originally conceived as a steel forging, the cast design provided a weight savings while meeting all necessary mechanical properties.

Suspension Bracket

Trucking in the Australian Outback means taking on rough and isolated terrain with distances that can be exceptionally long between service stops. When making a 3500 km trip between Sydney and Perth, the greatest challenge is to make the trip safely while effectively using the trailer space.

The Australian truck designers utilize a different type of arrangement than those typically used in the U.S. Their "road train" beds are longer and need to use space more efficiently. As a result, the suspension systems need to be designed to provide even more cargo space. Instead of filling the underbody of the truck with axles and suspension hardware, an independent suspension provides more flexibility. But for an independent suspension, the suspension brackets must be able to handle the rough terrain and the suspension system must be stable enough to keep the trailers on the road.

The original independent suspension bracket design was a welded fabrication made from low carbon steel. This first design iteration was a 50 mm thick, v-shaped swing arm. In its first trial—a drive from Sydney to Perth and back—the suspension component allowed the wheels to splay out under the truck before the truck was fully loaded (22.5 ton). When the test continued, the welded components failed after 1200 km of service. Beyond cracking at the weld joints, these brackets flexed so heavily that the negative camber induced uneven tire wear. To ensure accuracy, a second test was performed with the weldment, and failure was reached at 4000 km.

The suspension component was redesigned to a single-piece ductile iron casting austempered to grade 2 ADI. The castings were produced at Steele and Lincoln Foundry, Dandenong, Australia. Each cast independent suspension bracket was rated at 6 ton (Fig. 1).

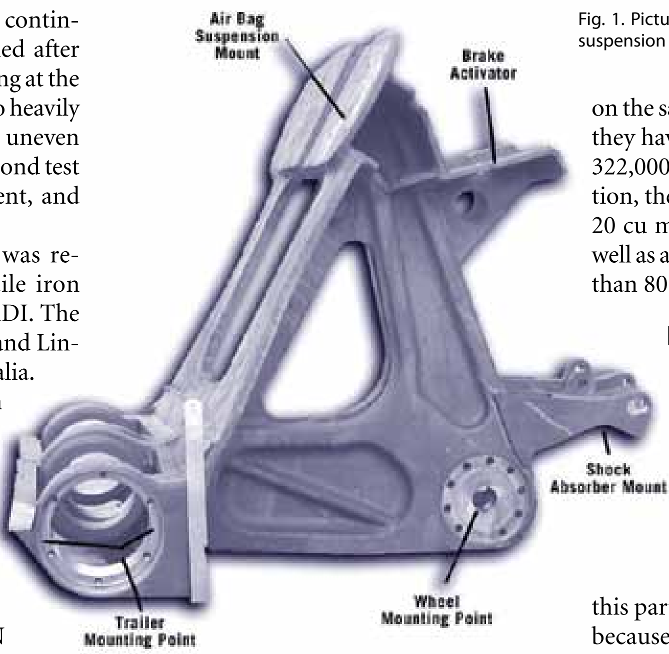


Fig. 1. Pictured is the cast ADI independent track trailer suspension bracket.

ADI was considered the material of choice for this application due to its high strength. The minimum properties of grade 2 ADI are 165 ksi tensile strength, 130 ksi yield strength, 10% elongation and 340 BHN hardness. By casting the component in ductile iron and then heat treating it, the bracket is made nearer to net shape in comparison to the fabrication, and welding was eliminated.

The ADI bracket is 900 mm long and 1200 mm high with a weight of 105 kg. While it has an advantage over steel in yield strength, tensile strength and hardness, the material's lower stiffness had to be addressed in the design. However, the failure of the steel components at the weld joints (the heat affected zones) is no longer an issue with a one-piece casting.

The ADI brackets were put into service on the same Perth-Sydney trip (Fig. 2) and they have successfully traveled more than 322,000 km without a problem. In addition, the brackets allowed the addition of 20 cu m of storage space to the trailer as well as an increased tire service life of more than 80,000 km.

Lower Control Arm

Another example of a component with conversion to casting opportunities was the lower control arm for the 2003 Dodge Ram pickup truck. Designed as a stamped steel weldment (Fig. 3), a redesign to casting showed cost and weight savings. While this part ultimately remained a weldment because the initial design and testing of the stamped part were well underway before the casting design was considered, the information lays a future foundation for ADI control arms.

In the initial control arm component design, designers believed the loads involved would require too heavy of section sizes for a casting to be competitive. During the development of the stamping

Fig. 2. Pictured is the cast ADI bracket installed on the truck trailer as well as the truck and trailer in action.

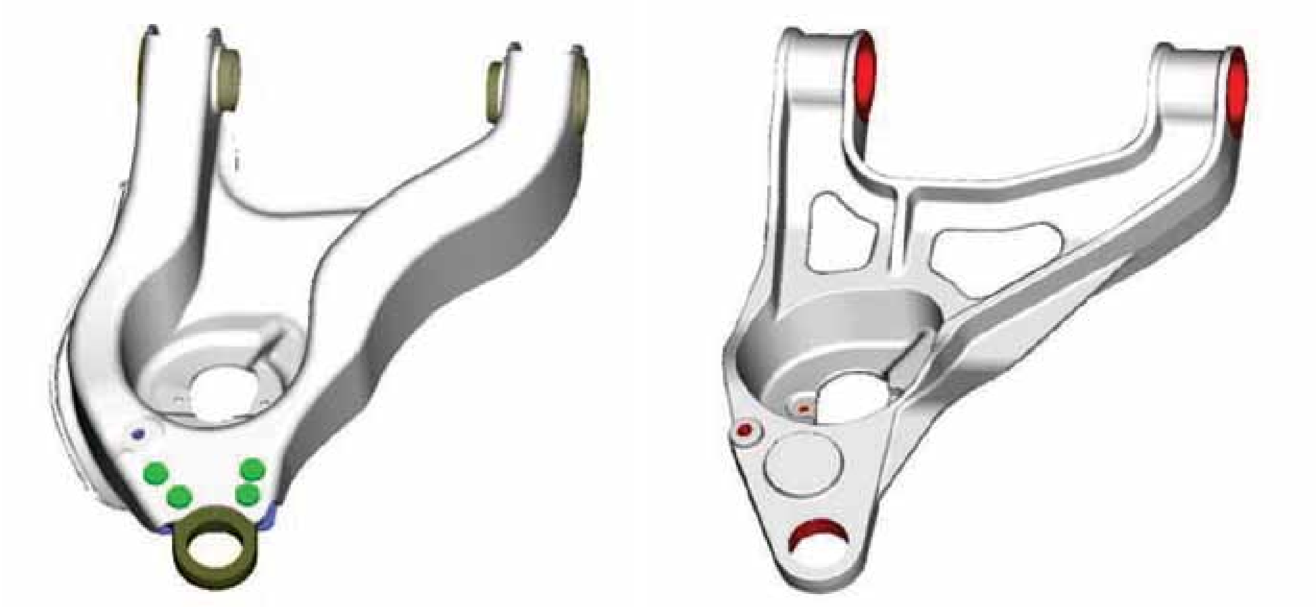


Fig. 3. Pictured is the stamped steel control arm design (l) and the initial cast ADI design (r).

design, however, it became necessary to use heavier gage steel to meet the performance requirements. A casting supplier, Citation Corp., Birmingham, Alabama, recognized an opportunity. By casting this component, a cost and weight savings would be realized compared to the stamped design.

Citation's analysis showed that a conventional D4512 iron would require sections that resulted in the part not meeting the weight requirements (Fig. 3). At this point, the foundry approached DaimlerChrysler Cast Metals Engineering & Prototyping to discuss the feasibility of an ADI design. It was decided that DaimlerChrysler would build a pattern to the metalcaster's supplied design and prototype parts would be cast by DaimlerChrysler Cast Metals. Citation would then austemper, machine and test the components.

Until recently, there has been little interest in the application of ADI to automotive and light truck suspension components. Two relatively recent low-volume applications include the upper control arm of the independent rear suspension of the Ford Mustang Cobra and the Cadillac limousine.

For high volume applications the emphasis has been on converting ductile iron components to aluminum for weight savings at higher cost. But with the current cost reduction climate, ADI has 3 times

Table 1. ASTM Minimal Mechanical Properties for the Stamped and Cast Materials

Property	ASTM D4512 (stamped)	ASTM A897 (cast)
Tensile (ksi)	65	125
Yield (ksi)	45	80
Elongation (%)	12	10

Table 2. Comparison of the Control Arm Steel Stamping and ADI Casting

	Stamping	ADI Casting
Weight (lb)	33	31
Weight/Vehicle (lb)	66	62
Durability	Pass	Pass
Cost per Assembly	—	2% Less
Tooling	—	54% Less

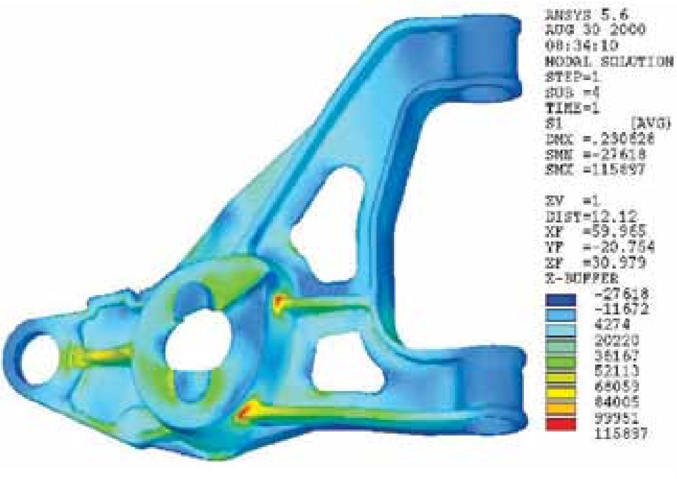


Fig. 4. Shown is the analysis using the 4G load on the cast design that helped identify the hot spots.

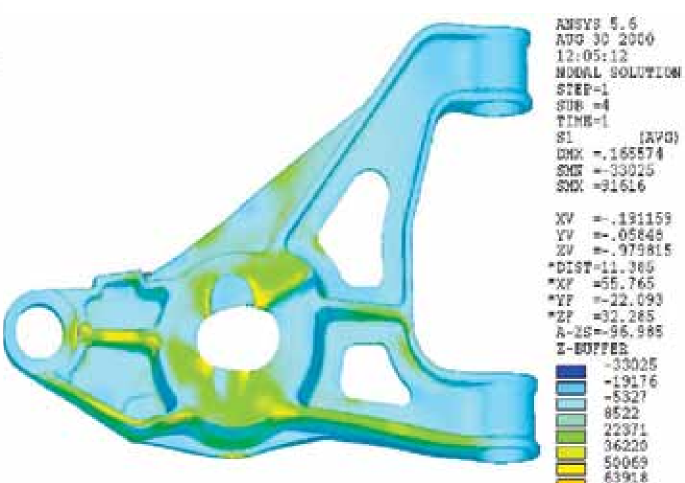


Fig. 5. Pictured is the final cast ADI control arm design during structural analysis.

the strength and 2.3 times the stiffness of aluminum and may be a cost-effective and weight-competitive alternative.

The initial design criteria of the lower control arm included a 33-lb weight, load requirements of 3G vertical and 2G brake, and a cost of less than $45 assembled. The basic steps the metalcaster follows in a development program such as this include:

- design for manufacturing and assembly;
- optimization for cost, weight and performance;
- structural analysis and component validation;
- process simulation for optimal quality and productivity;
- project management to ensure seamless planning and execution.

The initial design concept and analysis (Table 1) showed the cast part would meet the finite element analysis criteria for the load conditions. In addition, the assembled weight of the initial design was 28 lb.

Citation also carried out process simulation of the prototype design to understand the soundness of the cast component from a manufacturing perspective. The simulation results indicated no significant shrinkage or porosity took place in the casting. Areas of minor porosity might exist as would be expected from any cast component.

Radiographic inspection performed on the prototype castings at DaimlerChrysler confirmed the simulation results. Some minor porosity (Level 1 or 2) was found at the predicted locations in cast component. This minor porosity was deemed acceptable to the function of the part.

Once a design had been developed and analyzed, the next step was to produce prototype castings. The foundry worked with the DaimlerChrysler Woodshop and Cast Metals Engineering & Prototyping to build the prototype pattern and cast the parts. After austempering, the casting's mechanical properties were 302 HB hardness, 115 ksi tensile strength, 88 ksi yield strength and 11% elongation. The next step was the physical testing.

In the case of the control arm, an assembled component was tested on a half-car simulator and it failed prematurely.

Tips to Machining ADI

Tips to Machining ADI

An austempered ductile iron (ADI) casting can be machined using all normal machining techniques. As long as the component doesn't contain extensive metallurgical or casting defects, and most any machining operation can be carried out except the tapping of small diameter holes less than M6.

However, the choice of machining method for ADI is critical. The various options available do not respond equally when cutting the metal due to the hardening phenomenon of the heat treatment process.

The following is a look at the basic relationship between ADI and machining along with some tips on how to best approach the machining of ADI cast components.

Turning—A short broken chip is produced when turning ADI. This is an advantage when compared to steel, which requires chip breakers. During turning, hard metal tool insets are used with tool angles of: 5-6 degrees for tool clearance angles; 0-6 degrees for rake angles; and 60-90 degrees for cutting edge angles. The availability of fine-grained, high-density hard metal tool inserts has made a good surface finish a requirement of ADI components.

Drilling—Drilling tools are normally made of high-speed tool steel with a critical temperature of 500C. When drilling is performed without coolant, chips must be produced to remove the generated heat. In addition, the drilling speed must be kept low. During the process, if the tool meets hard particles such as cementite or martensite, its cutting edges will be ruined. To protect against this defect, the tool steel will require a hardness of 1700 Hv, which is twice that of martensite. Also, hard metal can tolerate temperatures up to 1000C and this type of drill is available with three cutting edges for a reduction in cutting forces.

Milling—In terms of chip formation, milling is the most difficult machining method. While different types of high speed tool steel and hard metal tools are available, the tool costs per working hour are considerably higher than turning.

Chip formation and a homogenous material are the most important factors in milling ADI. These factors are followed by a determination of the work hardened area of the casting to determine an unhardened area to begin cutting. Ductile iron with a hardness of 280-330 HB can be hobbed in sizes up to 10 m under the following conditions:

1. The casting is metallurgically and technically correct.
2. The hobber is made of high speed tool steel with a titanium nitride coating.
3. Cutting speed is 30% less than with steel using a correspondingly greater feed because a smoother surface is achieved when compared to steel.
4. Lubricant must be used generously.
5. Both the rough and final hobbing cuts should be made clockwise and between cuts a transverse adjustment of the hobber should be made when necessary.

With larger castings, an optimal solution would be to rough mill the castings prior to the austempered heat treatment. Subsequently, the root of the components should be shot peened and the sides of the castings can be hobbed with a tool steel.

Another option is to use boron nitride tools that tolerate up to 1400C. With these tools, the cutting speed is increased to a level where the material is melted in front of the cutting edge, reducing the required cutting forces to a fraction of normal. While no lubrication is used, a coolant is required to dampen the temperature of the chips. One limit in using these tools is that no more than 4-5% ferrite or austenite must be present in the casting or adhesion will occur.

Tapping—The tapping of ADI is possible with diameters greater than M6. Tapping holes that go completely through a wall is usually easy because the chips are removed from below. If dead-end holes are tapped, a strongly rising chip removal tap is required (however, it still will be difficult). One way out of the dilemma is to leave sufficient space to hold the chips at the bottom of the hole.

Today, titanium nitride taps are available to make this operation more efficient. When using a chip removal tap, the tool should be conical so the tap doesn't become jammed and destroyed due to adhesion. A properly used tap increases the working time between sharpening operations, improves the surface finish and retains better dimensional precision. The recommended tapping speeds for ADI are 30-40% of the values for steel (2-6 m/min.).

Cutting Keyways—When cutting keyways, good results can be obtained by using a hard metal tool with improved results using a titanium nitride coated tool. The machining factors to use are: 0 degree rake angles; 5 degree tool clearance angles; 6-10 m/min. speeds; and 0.10-0.14 mm/stroke feeds.

Broaching—Gear wheels with interior teeth, wheels for planetary gearboxes and holes with several keyways are examples of items usually machined by broaching. A broach tool is made of high speed tool steel often with a titanium nitride coating. Broaching speeds for ADI must be kept low at 1-2 m/min., eliminating a temperature rise problem. During ADI broaching, a tool with a hardness of 280-300 HB will last longer than when broaching steel.

In broaching ADI, when the chip forming temperature exceeds a certain limit, then the work hardening effect becomes weaker. Similar results are obtained in broaching an austenitic stainless steel. Normally, the broaching speed is kept low (3 m/min.), but the feed value is high.

—Meehanite Metal Corp.

Circle No. 118 on Reader Action Card.

Analysis of the failure showed no unusual casting abnormalities and further investigation revealed the design loads were incorrect. The revised load for analysis was actually found to be a 4G vertical load and a new analysis was required.

The failure with the assignable cause of incorrect design loads led to the development of a new design. The gusset areas where the failure occurred was blended more completely into the hat section and the radii were increased. Analysis using the 4G loads showed the reduced stresses in the revised design (Fig. 4 and 5).

In order to validate the design, fatigue bench testing also was performed and confirmed the analysis. Then a Weibull analysis comparison of the original vs. the cast designs was performed (Table 2). Even with the added weight required with the revised design, the ADI lower control arm compared favorably to the stamped part.

The next step would have been further verification of the design in the half car simulator. However, the delay caused by the initial use of incorrect loads caused the program to miss the original test schedule. DaimlerChrysler does plan to complete the validation testing and confirm the feasibility of ADI as a material choice for suspension components.

Even though this cast control arm did not go into production, the analysis provided valuable information on the feasibility of ADI for automotive and light truck suspension components. This experience will aid in future applications of ADI and it's potential as an aluminum alternative offering improved properties at lower cost and competitive weight.

For More Information

"Austempered Ductile Iron Castings for Chassis Applications,"
R. Warrick, P. Althoff, A. Druschitz, J. Lemke, K. Zimmerman, P. Mani and M. Rackers, SAE Paper 2000-01-1290.

"Automotive Applications of Austempered Ductile Iron,"
J. Keough and K. Hayrynen, SAE Paper 2000-01-0764.

"Designing and Achieving Lightweight Vehicles,"
Society of Automotive Engineers (SP-1684), Dearborn, Michigan (2002).

"2002 World Conference on ADI,"
American Foundry Society, Inc., Des Plaines, Illinois (2002).

Circle No. 119 on Reader Action Card.