Off-Highway Applications of Austempered Materials

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ABSTRACT
Austempering is a high performance heat treat process that, when applied to ferrous materials, produces components that have properties superior to those processed by conventional means. Austempered materials include: Austempered Ductile Iron (ADI), Austempered Steels, Carbo-Austempered™ Steels, Carbide Austempered Ductile Iron (CADI). Off-Highway applications of each of these materials will be discussed.

INTRODUCTION
Austempering is an isothermal heat treat process that can be applied to ferrous materials to increase strength and toughness. Figure 1 shows an isothermal (I-T) diagram for steels with both the Austempering (green line) and the quench and tempering (red line) processes outlined. Austempering consists of Austenitizing followed by rapidly quenching to a temperature where the material is then transformed isothermally to form either Ausferrite, (acicular ferrite and carbon stabilized austenite), in cast iron, or Bainite, (acicular ferrite and carbide), in steel. The quench & temper process consists of Austenitizing and then rapidly quenching below the Martensite start line. The Martensite that forms is very hard and brittle; and subsequently must undergo a tempering step to acquire the desired combination of strength and toughness.

Because Austempering is an isothermal process, it offers advantages versus quench & tempering. Since the formation of Bainite or Ausferrite occurs over minutes or hours at a single temperature, distortion is minimized and cracking does not occur. Meanwhile, the formation of Martensite occurs immediately as the metal temperature drops below the Martensite start temperature. Because cooling is achieved at different rates in various sections, this is a non-uniform transformation, which can result in significant distortion and/or cracking.

Carbo-Austempering™ is a heat treat process used on certain steels where the surface of the part is carburized, followed by an isothermal quench at a temperature that produces a high carbon, bainitic case. When this process is applied to low carbon steels, it results in the formation of a bainitic case and a low carbon, tempered Martensite core. For medium carbon steels, Bainite is formed throughout the cross-section of the part.

Carbidic Austempered Ductile Iron (CADI) is a ductile cast iron containing carbides, (that are either thermally or mechanically induced) that is subsequently Austempered to produce an Ausferritic matrix with an engineered amount of carbides. This process creates components that have high wear resistance characteristics.
AUSTEMPERED DUCTILE IRON

Austempering can be applied to ductile iron castings to yield Austempered Ductile Iron (ADI) with better strength, and wear resistance than either as-cast irons or other competitive materials. As seen in Figure 2, the tensile and yield strength of ADI increases with increased Brinell hardness. The different grades of ADI, (achieved through a variation in the Austempering temperature and time), can create a range of properties in ADI as seen in Table 1.

Table 1: ASTM 897 Property table for ADI

<table>
<thead>
<tr>
<th>Grade</th>
<th>Tensile Strength (MPa/Ksi)</th>
<th>Yield Strength (MPa/Ksi)</th>
<th>Elong. (%)</th>
<th>Impact Energy (J/ft-lb)</th>
<th>Typical Hardness (HBW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>850 / 125</td>
<td>550 / 80</td>
<td>10</td>
<td>100 / 75</td>
<td>269 – 321</td>
</tr>
<tr>
<td>2</td>
<td>1050 / 150</td>
<td>700 / 100</td>
<td>7</td>
<td>80 / 60</td>
<td>302 – 363</td>
</tr>
<tr>
<td>3</td>
<td>1200 / 175</td>
<td>850 / 125</td>
<td>4</td>
<td>60 / 45</td>
<td>341 – 444</td>
</tr>
<tr>
<td>4</td>
<td>1400 / 200</td>
<td>1100 / 155</td>
<td>1</td>
<td>35 / 25</td>
<td>366 – 477</td>
</tr>
<tr>
<td>5</td>
<td>1600 / 230</td>
<td>1300 / 185</td>
<td>N/A</td>
<td>N/A</td>
<td>444 – 555</td>
</tr>
</tbody>
</table>

CONTACT FATIGUE - Austempered Ductile Iron has increased contact fatigue strength and wear resistance than comparable materials. Figure 3 compares the allowable contact stress behavior of ASTM Grades 2 and 5, (ASTM 1050-700-07 and 1600-1300-00).

Figure 3: Contact Fatigue (90% Confidence Limits) From the ASME Gear Research Institute

Figure 4 demonstrates that the contact fatigue properties of various grades of ADI are comparable to gas nitrided steels and competitive with carburized and hardened steel.

Figure 4: Comparison of Contact Fatigue Strengths of ADI with Those of Conventional Irons and Steels.

Figure 5 illustrates that ADI has improved abrasion resistance when compared to other materials. ADI experiences less volume loss at similar hardness levels,
resulting in a component with improved wear characteristics.

MANUFACTURABILITY – ADI offers an opportunity for increased manufacturability since rough machining can be done prior to heat treatment. In the as-cast condition, the material is much easier to machine, resulting in a cost reduction. Though many applications can be heat treated after final machining, finish machining after heat treatment increases the strength characteristics of ADI, giving it superior fatigue strength than prior to finish machining. Figure 6 compares the relative machinability of several ferrous materials. Note that ductile iron in a ferritic or pearlitic condition is easier to machine than 4140 steel or ADI. If ductile iron is machined prior to heat treatment, one can gain the advantage of better machinability. Furthermore, machining of ductile iron and ADI results in a compact, discontinuous chip that is easily handled and is fully recyclable.

OFF-HIGHWAY APPLICATIONS OF ADI

Figure 7: ADI Grade 1 Axle Hub Ring Gears.

Figure 8: ADI Hay Baler Knotter Gear

Figure 9: ADI Gear and Axle for Commercial Lawnmowers.
AUSTEMPERED STEELS

Medium and high carbon steels can be successfully Austempered along with powdered metal mixes that have sufficient hardenability and nearly full density. The Bainitic microstructure produced by Austempering steel is more wear resistant than tempered Martensite. In addition, Bainitic steels are more resistant to hydrogen embrittlement and stress corrosion cracking.
Table 2: Grossman and Bain Comparative Data for 0.74% C Steel Parts

<table>
<thead>
<tr>
<th></th>
<th>Quench &amp; Tempered</th>
<th>Austempered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rc Hardness</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>UTS (MPa / ksi)</td>
<td>1701 / 246.7</td>
<td>1949 / 282.7</td>
</tr>
<tr>
<td>Yield Strength (MPa / ksi)</td>
<td>839 / 121.7</td>
<td>1043 / 151.3</td>
</tr>
<tr>
<td>Elongation (% in 6 inches)</td>
<td>0.3</td>
<td>1.9</td>
</tr>
<tr>
<td>%RA</td>
<td>0.7</td>
<td>34.5</td>
</tr>
<tr>
<td>Impact* (J / ft-lbs)</td>
<td>3.9 / 2.9</td>
<td>47.9 / 35.3</td>
</tr>
</tbody>
</table>

For given high hardness levels (Rc > 40), Austempered steel parts exhibit higher strength and toughness than comparable quench & tempered parts as shown in Table 2.

Above a certain hardness level, the fatigue strength of conventional quench & tempered steel drops significantly as illustrated in Figure 15. This does not occur in Austempered structures. In fact, the fatigue strength continues to increase up to the maximum Bainitic hardness.

Figure 15: Fatigue Strength of Bainite vs. Tempered Martensite

AUSTEMPERED STEEL APPLICATIONS

Figure 16: Austempered Steel Large Gear Segments

Figure 17: Austempered Steel Output Shafts

Figure 18: Large trenchless mole components
CARBO-AUSTEMPERED™ STEEL

Low to medium carbon steels are good candidates for Carbo-Austempering™. Typically a high carbon, bainitic case (Rc 50 to 60) is produced on a component with a lower carbon, tempered Martensite core (Rc < 40). In some instances, advantages have been realized in medium carbon alloy steels with a high carbon, bainitic case (45-55 Rc) on a medium carbon, bainitic core (45-50 Rc).

During Carbo-Austempering™, the transformation begins in the center or core of the part. This results in the formation of compressive stresses as the outside layer or case transforms last during the heat treat process. The residual compressive stresses on the surface of a Carbo-Austempered™ steel result in improved high load, low cycle fatigue properties versus conventional Carburized and Hardened steel. This is illustrated in Figure 20, which contains rotating bending fatigue curves for both Carbo-Austempered™ and conventionally Carburized and Hardened 8822 steel. Note the superior performance of the Carbo-Austempered™ steel in the low cycle regime (<10⁵ cycles).

Similar results were obtained with single tooth bending fatigue testing of Carbo-Austempered™ 8620 steel. This is illustrated in Figure 21, which contains single tooth gear fatigue curves for 8620 steel that has been both Carbo-Austempered™ and Carburized, Quench and Tempered. The Carbo-Austempered™ gears will carry loads up to 40% greater than their Carburized Q&T counterparts in the low cycle regime. Additionally, the Carbo-Austempered™ gears have an endurance limit that is 17% greater than the Carburized Q&T gears.

Carbo-Austempered steels also exhibit superior impact properties in comparison to conventional Carburized and Hardened steel. Figures 22 and 23 illustrate such a
comparison for both v-notched and unnotched impact specimens from 5120 steel, respectively. The notched impact energy of the Carbo-Austempered™ specimens is almost twice that of the Carburized and Hardened specimens in Figure 22. The difference in performance for the unnotched bars is significantly higher with the Carbo-Austempered™ impact energy being in excess of twenty-two times that of the Carburized and Hardened 5120 shown in Figure 23.

Figure 22: A Comparison of Fatigue Strength of V-notched Carbo-Austempered™ and Carburized and Hardened Steel of Similar Hardness.

Figure 23: A Comparison of Fatigue Strength of Unnotched Carbo-Austempered™ and Carburized and Hardened Steel of Similar Hardness.

CARBO-AUSTEMPERED STEEL APPLICATIONS

CARBIDIC AUSTEMPERED DUCTILE IRON

CADI is a ductile cast iron containing carbides, that is subsequently Austempered to produce an Ausferritic matrix with an engineered amount of carbides.

Methods of carbide introduction include:
- As-Cast Carbides
  - Internal (chemical or inverse) chill
  - Surface chill (limited depth, directional)
- Mechanically Introduced Carbides
  - Cast-in, crushed M,C_{x} carbides
  - Cast-in, engineered carbides (shapes)
- Welded
  - Hardface weldment
  - Weldment with M,C_{x} grains
Figure 26: CADI with 65% carbide and a 500F ADI matrix. (These carbides were produced as-cast).

Figure 26 shows a CADI sample with as-cast carbides that was Austempered at 500F with 65% carbides remaining.

Figure 27 shows the wear resistance of a typical CADI vs various grades of ADI, as-cast irons and steels.

Table 5 shows a table of typical unnotched Charpy impact values including CADI.

<table>
<thead>
<tr>
<th>Material</th>
<th>Charpy Impact Value (ft-Lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-45% Carbide 500 CADI</td>
<td>10</td>
</tr>
<tr>
<td>Carburized 8620 Steel</td>
<td>13</td>
</tr>
<tr>
<td>Pearlitic Malleable Iron</td>
<td>13</td>
</tr>
<tr>
<td>7003 Ductile Iron</td>
<td>38</td>
</tr>
<tr>
<td>Grade 5 ADI</td>
<td>40</td>
</tr>
<tr>
<td>5506 Ductile Iron</td>
<td>45</td>
</tr>
<tr>
<td>Grade 3 ADI</td>
<td>70</td>
</tr>
<tr>
<td>Grade 1 ADI</td>
<td>90</td>
</tr>
<tr>
<td>4512 Ductile Iron</td>
<td>95</td>
</tr>
</tbody>
</table>

POTENTIAL APPLICATIONS FOR CADI

Agricultural components have been produced in CADI with as-cast carbides since the early 1990s. Limited production quantities of CADI parts with cast-in, crushed carbides have been produced as well. Research into chill-carbide CADI camshafts is ongoing. However, the visibility of CADI has been greatly increased of late with the public launch of CADI in programs at John Deere.

Figure 28: John Deere’s new, high performance, rotary combine uses CADI in its critical thrashing elements. (Courtesy of SAE Off Highway Magazine)
CADI presents some intriguing product possibilities. Agricultural applications may include rippers, teeth, plow points, wear plates and harvester, picker and baler components. Possible railroad applications include contact suspension components and railcar/hopper car wear plates. In construction and mining potential applications include digger teeth and scarifiers, cutters, mill hammers, flails, guards, covers, chutes, plates, housings, transport tubes and elbows, rollers and crusher rollers.

**SUMMARY**

Austempered Ductile Iron (ADI) has an exceptionally high strength-to-weight ratio with good fatigue strength and fracture toughness. ADI is suitable for many off-highway applications in drivetrains, suspensions, hitches and other components.

Austempered Steels exhibit remarkable fatigue strength and toughness at hardnesses exceeding 38 Rc. They also resist hydrogen embrittlement during plating. High density, powdered metal parts do not crack during heat treatment. Austempered steel offers design solutions in output shafts, and gear components.

Carbo-Austempered™ Steels exhibit low cycle, high load fatigue performance that is 40 to 70% better than that of comparably carburized and hardened components. Carbo-Austempered™ Steels can demonstrate an order of magnitude greater impact strength than carburized and hardened steels. Carbo-Austempered™ Steels are beneficial in low cycle, high load applications, such as clutch components, gears, splines and shafts.

**ACKNOWLEDGMENTS**

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**REFERENCES**

3. “Austempered Materials and Their Applications to Drive Line and Suspension Components”, SAE 2000-01-2563, J. R. Keough

**ADDITIONAL RESOURCES**

+ Applied Process Inc. internal research
+ www.appliedprocess.com
+ www.ductile.org