While austempered ductile iron (ADI) was conceived fewer than 20 years ago, it is a rapidly growing material finding its way into a host of end products. This heat treated ductile iron can increase foundries' bottom line while creating a bigger casting "pie" by drawing conversions from forgings.

According to Stratocasts, Inc., the ADI casting market is expected to double to 80,000 tons by 1998. The material's growth rate has been estimated at 16% per year.

ADI's microstructure consists of acicular ferrite in a high carbon austenite matrix called ausferrite. This microstructure is shown in Fig. 1.

While some captive foundries that examined the process in the late 1970s experienced only limited success, today's technology--and market conditions--are propelling wider use of the material. Heat treating technology has matured, and foundries have advanced considerably in producing high quality ductile iron (itself an infant material by casting standards). There is no opportunity for ADI without quality ductile iron.

**Austempering**

The heat treatment procedure for ductile iron castings in producing ADI consists of three steps:
- austenitize in the temperature range of 1550-1750°F (840-950°C) for a time sufficient to produce a fully austenitic matrix that is saturated with carbon;
- rapidly cool the entire part to an austempering temperature in the range of 450-750°F (230-400°C) without forming pearlite or allowing the formation of ausferrite to begin;
- isothermally treat at the austempering temperature to produce ausferrite with an austenite carbon content in the range of 1.8-2.2%.

Producing ADI

The production of ADI requires a partnership between the foundry and the heat treater. It is important for both parties to actively communicate to ensure the production of the desired end product.

**Foundries**—Ductile iron foundries must produce high quality ductile iron to produce ADI castings. Austempering can't cure poor quality iron. Rather, the effects of the slightest defects (shrinkage, slag stringers, poor microstructural features, etc.) on the mechanical properties of ductile iron become magnified as a result of austempering.

In terms of austempering, high quality ductile iron can be defined as that which has:
- uniform nodule distribution with a nodule count minimum of 100 nodules/mm²;
- nodularity in excess of 80%;
- maximum level of 0.5% carbides+nonmetallic inclusions;
- maximum allowable volume of 1% porosity and/or microshrinkage.

In addition, chemical composition specifications must be established in conjunction with the heat treater that depend on casting section size and the hardenability needed for austempering. Once chemical composition specifications have been established, it is critical to produce ductile iron consistently within the established ranges. Wide variations in chemical composition require adjustments to the heat treatment cycle, therefore, foundries must provide castings with a consistent composition.

**Heat Treaters**—An austempering process is designed by the heat treater to produce the desired mechanical properties specified by the customer. To accomplish this, the heat treater should be involved before, during and after austempering for several reasons:
1. Before an austempering process can be designed, the chemical composition, part geometry (section size) and desired mechanical properties are needed. Heat treaters advise ductile iron foundries whether the chemical composition is sufficient to produce the de-

<table>
<thead>
<tr>
<th>Grade</th>
<th>Tensile Strength (KSI)*</th>
<th>Yield Strength (KSI)*</th>
<th>Elongation (%)*</th>
<th>Impact Energy (FT-Lb)**</th>
<th>Typical Hardness (BHN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>125</td>
<td>80</td>
<td>10</td>
<td>75</td>
<td>269-321</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>100</td>
<td>4</td>
<td>60</td>
<td>302-363</td>
</tr>
<tr>
<td>3</td>
<td>175</td>
<td>125</td>
<td>4</td>
<td>45</td>
<td>341-444</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>155</td>
<td>1</td>
<td>25</td>
<td>388-477</td>
</tr>
<tr>
<td>5</td>
<td>230</td>
<td>185</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
sired end product. Foundries receive ranges to follow for carbon equivalent (carbon and silicon), manganese, molybdenum, copper and nickel.

2. Once an austempering process has been developed, it is the responsibility of the heat treater to ensure each processing step is carefully controlled and completed.

3. After heat treatment, testing of samples must be completed to verify the austempering process has produced the desired end product. The actual testing requirements are specified by the customer. Testing can be completed by the heat treater or specimens can be supplied for independent verification.

**ADI Properties**

A wide range of mechanical properties for ADI is available depending upon the choice of heat treatment parameters. Austempering at higher temperatures produces ADI with lower strength and hardness and higher ductility and toughness compared to lower austempering temperatures. The property combinations available for ADI are documented in Table 1, which lists the five ASTM standard grades of ADI. These specifications give the minimum tensile and impact levels along with typical Brinell hardness values. Typical properties of ADI produced in industry as a function of Brinell hardness are given in Fig. 2.

For a given level of ductility, ADI provides twice the strength of conventional ductile iron. The strength of ADI is comparable to a variety of steels. The modulus of ADI, however, is about 20% less than that of steel and must be accommodated for in the early design stages.

Component weight reductions of greater than 10% can be realized by using ADI in place of steel forgings. This can often be a significant savings in terms of fuel consumption. If relative weight per unit of yield strength is considered, ADI performs remarkably well. This is illustrated in Fig. 3, which shows the relative weight per unit of yield strength for a variety of materials. (For this analysis, forged steel has been normalized to 1.) In most instances, aluminum, which is perceived as a lightweight engineering material, is unable to match the weight per unit of yield strength of ADI.

ADI rotating bending fatigue strengths at 10⁷ cycles for grades 1, 2 and 3 are listed in Table 2. ADI has been documented to exhibit fatigue strengths that are equal to or greater than forged steel. ADI also responds favorably to surface treatments such as shot peening, which can result in significant increases in fatigue strength. ADI doesn't exhibit a true fatigue or endurance limit as a slight decrease in fatigue strength at high cycles (>10⁷) occurs. This decrease in fatigue strength at high cycles, however, isn't as significant as that reported for fcc matrix materials such as aluminum and can be accounted for in early design stages.

ADI offers excellent abrasion resistance. The austenite within the ausferrite can undergo a strain-induced transformation to martensite, resulting in an increase in flow stress and hardness. Figure 4 illustrates the results of pin abrasion wear for austempered steel, Q & T steel, Q & T ductile iron and ADI. As shown in this figure, ADI can provide an equivalent level of abrasion resistance to both austempered and Q & T steel at a lower hardness level.

Examination of the hardness levels of ADI (Table 1 and Fig. 2) might cause machinability concerns. In practice, however, ADI can offer machining savings. Grades 1 and 2 are easier to machine than steels of an equivalent hardness due to the presence of graphite in the microstructure. Machining requirements for the higher grades can be completed prior to austempering because the part growth relationships during heat treatment are predictable (0.0005-0.0003 in./in.), with more growth for ferritic than pearlitic grades.

The damping capacity of ductile cast iron is better than that of steel due to the presence of graphite within the microstructure. The unique microstructure of ADI further enhances internal damping, especially in grades 4 and 5 with finer austemirite. Studies completed on Kyremenite ADI gears in Finland have shown that vibrations are damped 40% faster in ADI than in steel components.

**Table 2. Rotating Bending Fatigue Strengths (Allowable Stress at 10⁷ Cycles)**

<table>
<thead>
<tr>
<th>Grade</th>
<th>ksi/MPa</th>
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<tbody>
<tr>
<td>1</td>
<td>65/450</td>
</tr>
<tr>
<td>2</td>
<td>70/485</td>
</tr>
<tr>
<td>3</td>
<td>60/415</td>
</tr>
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Applications

Because a wide range of properties of ADI are available based on the selection of heat treat parameters, the potential for use of ADI is unlimited. Currently, ADI parts are found in numerous automotive, truck, agricultural, industrial, railroad, construction and military applications.

Auto and truck applications use the lower density (compared to steel), high strength, high damping capacity and lower manufacturing cost ADI offers. Typical applications include: suspension components, camshafts, ring and pinion gears, timing gears, CV joints, engine mounts, differential housings and wheel hubs.

Agricultural and construction applications make use of the excellent wear resistance of ADI in combination with impact energy. ADI parts have especially performed well in contact with soil. Typical applications include: digger teeth, plow points, grader blades, pavement breakers and fertilizer knives.

There are numerous miscellaneous industrial applications that require a combination of wear resistance and strength in addition to high impact energy. Examples of these applications include: conveyor components, pump components, dies, wear plates and housings.

Railroad applications require good wear resistance along with high static and fatigue strength. ADI can provide this as well as the possibility for lighter design. Railroad applications include: top caps, wear shoes, nipper hooks, shock absorbers and engine parts. Until recently, maintenance car wheels were the only type of ADI railroad wheels produced. This is rapidly changing in Finland with the completion of a 10-year laboratory and field testing plan on Kymenite ADI passenger coach wheels. In addition to superior performance, life cycle costs were 30% lower than steel wheels.

Military applications of ADI include projectiles, armor, rocket bodies, track shoes, track guides, engine rotors and struts. Currently, military applications comprise the smallest market for ADI. Recognizing the potential for military applications, the U.S. government has authorized funding for the investigation of ADI applications in suspension systems, track components and weapons. Such applications can result in a reduction in weight and cost without sacrificing mechanical performance.

Economic Factors

Figure 5 illustrates a typical example of a material costing for ductile iron, ADI and forged steel. The manufacturing cost for forged steel is significantly larger than that of ductile iron and ADI. The commission available to technical sales personnel as well as the profits for ductile iron foundries are given for both ductile iron and ADI. There is a considerable value added to ductile iron by austempering. This results in larger commissions for technical sales and larger profits for ductile iron foundries by using ADI.

Another means of examining the economics of using ADI is to do a comparison of relative cost per unit of yield strength. This is shown in Fig. 6, which contains the relative cost per unit of yield strength for aluminum, steel, ductile iron and ADI. Ratios are based on steel forgings normalized to 1. In most instances, ADI is the best buy per unit of yield strength.

With the advent of ADI, ductile iron foundries in partnership with heat treaters have the ability to compete in the market of high performance materials. ADI has a high strength to weight ratio, excellent abrasion resistance, good machinability as well as superior damping capacity in comparison to steel.

There is considerable value added to the product by austempering, resulting in higher profits for both technical sales and ductile iron foundries—all of which can occur at a lower total manufacturing cost to the consumer.