Considering its many positive properties, a strong argument can be made for converting to ductile iron, and many in the industry have already made the switch.

By Robert F. O’Rourke
Cast iron is generally thought of as a weak, dirty, cheap, brittle material that does not have a place in applications requiring high strength and defined engineering properties. While gray cast iron is relatively brittle by comparison with steel, ductile iron is not. In fact, ductile iron has strengths and toughness very similar to steel, and the machinability advantages make an attractive opportunity for significant cost reductions. Gray and ductile iron bar stock is commercially available and can be used as a direct replacement in gear and other applications using carbon steel bar.

Automotive gears, for example, are being converted to ductile iron for its damping capacity and cost reductions. Ductile iron bar stock conversions are also prevalent in many fluid power applications, including glands and rod guides, cylinders, hydrostatic transmission barrels, and in high-pressure manifolds. Both gray and ductile iron has been used for years in the machine tool industry because of their performance in sliding wear applications and vibration damping.

Understanding the metallurgical concepts of ductile iron is the key to understanding its potential use as an engineered metal and allows the design engineer to determine its suitability in specific applications and to intelligently select the best grade. Recent developments in understanding the variables that influence the machinability of gray and ductile iron grades have allowed the process engineer to quantify the expected cost savings when converting from carbon steel bars to continuously cast gray and ductile iron.

The following material includes a background on the development of continuous casting of gray and ductile iron, definitions of ductile irons, the metallurgical characteristics of the engineered grades, and some basic material properties. An update on recent studies in the machining characteristics of ductile iron is also presented.
discovered that what were normally flake graphite shapes were now spheroidal. Castings made with spheroidal rather than flake graphite had high strength and ductility, good fatigue life, and impact properties. Other properties such as vibration damping, machinability, and wear resistance have made ductile iron a suitable replacement for steel in gears and a number of other applications.

**Ductile Iron Defined**

Iron is a ferrous alloy consisting primarily of iron with carbon, silicon, manganese, and sulfur. Other elements are also present and controlled to produce the various grades and to influence other mechanical properties, machinability, and castability.

Carbon is added to iron in amounts that exceed the solubility limit, and during solidification, graphite precipitates into tiny spheres. Silicon and other alloys are used to control the morphology of the precipitated graphite and to control the amount of carbon that remains as a solid solution in the iron. Steel, by comparison, contains carbon in amounts that are completely soluble in iron; therefore, precipitated graphite nodules do not exist, and the entire structure consists of a metal matrix.

It is possible to produce the different grades of ductile iron by controlling the process variables to precipitate the desired amount of graphite particles and obtain the desired amount of combined carbon remaining in the matrix.

Steel grades are designated primarily by chemical composition, and the composition determines the mechanical properties. Ductile iron grades cannot be distinguished by chemistry because the properties are influenced by the graphite morphology and by the composition of the matrix, which is strongly influenced by other variables. The ductile grades are typically designated under ASTM A536 in the form of xx-xx-xx, representing the tensile and yield strength in ksi and the percent of elongation. As with steel, increased tensile and yield strength results from a higher amount of dissolved carbon in the matrix, creating a higher ratio of pearlite to ferrite. Higher strength results in decreased elongation, increased hardness and wear, and decreased machinability.

The photomicrographs in Figure 1 show the pearlite to ferrite ratios in three ductile iron grades at 100X magnification. As the percentage of pearlite (etched dark) increases, strength increases. The graphite nodules are also visible as round spheres, and the nodularity in each of the photos is similar.

The mechanical property requirements for each of the ductile iron grades listed in ASTM A536 are minimum values obtained from a separately cast test coupon. They can be used for design purposes as long as the data has been generated that correlates the strength in the casting to the strength in a separately-cast test coupon. Tensile test specimens are

<table>
<thead>
<tr>
<th>Grade</th>
<th>80-40-18</th>
<th>65-45-12</th>
<th>80-66-06</th>
<th>100-70-01</th>
<th>120-90-02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (min ksi)</td>
<td>60</td>
<td>65</td>
<td>80</td>
<td>100</td>
<td>120</td>
</tr>
<tr>
<td>Yield Strength (min ksi)</td>
<td>40</td>
<td>45</td>
<td>55</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>Elongation (min %)</td>
<td>18</td>
<td>12</td>
<td>06</td>
<td>03</td>
<td>02</td>
</tr>
</tbody>
</table>

**Table 1** — Mechanical property requirement for ductile iron as defined in ASTM A536

As more carbon is added to steel, strength and wear resistance increase, and machinability decreases. Low carbon steels such as 1018 and 1117 contain less than 0.20 percent carbon and have tensile strengths of approximately 67ksi. The higher strength grades such as 1040 and 1141 contain 0.40 percent carbon and will have tensile strengths on the order of 90 ksi. Machinability decreases as strength increases, and by comparison with 1212 steel, 1117 has a rating of 91 percent and 1141 has a rating of 81 percent (source: ASM Handbook).

In the case of ductile iron, the amount of carbon that remains in solid solution depends on the rate of solidification and cooling, on the inoculation practice, and on other elements that are added to either promote graphitization or to promote the formation of pearlite. Similar to steel, ductile iron with less carbon in the matrix (low-combined carbon) will be lower in strength, higher in ductility, and will have better machinability than ductile iron with high amounts of combined carbon.

<table>
<thead>
<tr>
<th>Test Grade</th>
<th>Number of Pieces Machined per Insert</th>
<th>Tool Life Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 30 Gray Iron</td>
<td>210</td>
<td>100%</td>
</tr>
<tr>
<td>Class 40 Gray Iron</td>
<td>180</td>
<td>86%</td>
</tr>
<tr>
<td>65-45-12 Ductile Iron</td>
<td>435</td>
<td>207%</td>
</tr>
<tr>
<td>80-55-06 Ductile Iron</td>
<td>235</td>
<td>112%</td>
</tr>
<tr>
<td>100-70-02 Ductile Iron</td>
<td>37</td>
<td>17%</td>
</tr>
</tbody>
</table>

**Table 2** — Machinability ratings, gray and ductile iron
easily obtained from continuously cast ductile iron, and the mechanical properties in parts machined from bar stock directly correspond to the properties in ASTM A536. Selecting the best grade of ductile iron for any application involves the same consideration as selecting the best grade of steel or other metals, determining the property requirements and finding materials that meet them. Ductile iron can be a suitable replacement for most of the plain carbon steels because the mechanical properties are similar with similar matrix structures. The primary advantage in making conversions from steel bar stock to ductile iron bar stock is lower processing cost through improved machinability.

**Ductile Iron Advantages**

Since its development in the mid-1940s, ductile iron casting production has grown dramatically. Ductile iron has engineering properties similar to steel, and near-net shaped castings are replacing forgings, weldments, and steel castings in a variety of applications. Ductile iron is also available in continuously cast bar stock and can be a direct replacement for carbon steel bars in a number of gears in the automotive, hydraulic, machine tool, and other industries.

Machinability advantages of continuously cast ductile iron bars over carbon steel bars are the primary reason for its growth during the past 40 years. Improved tool life and faster cycle times mean more parts produced per hour and less cost for consumable items such as machine tool inserts. Ductile iron contains precipitated graphite nodules acting as natural...
chip-breakers, causing less friction of the chip on the insert and allowing for a larger depth of cut because of the reduced forces required during machining.

The presence of graphite nodules offers additional benefits. Noise and vibration is reduced because of the damping properties of graphite—a key consideration in gear applications—and wear resistance is also improved.

Ductile iron is less dense than steel, and the same parts made from ductile iron will weigh 10 percent less than if they were made of steel.

### The Continuous Casting Process

Ductile iron bar stock is produced by a continuous casting process. Continuous casting of ductile iron bar stock involves mounting a water-cooled graphite die to the bottom of a bar machine crucible (Fig. 2). Molten iron flows by gravity into the die and a solid skin begins to form on the inside of the die, taking the shape of the bar. As the bar is continuously drawn out of the die, the outer skin is the only part that is solid. The core remains molten, and the outer shell is re-heated outside of the die by the core to a temperature of approximately 1,950 degrees F. In effect, the entire bar solidifies and cools in still air, producing a stabilized microstructure throughout the cross section.

The bar machine crucible acts as a riser feeding iron into the die as the bar is horizontally cast. Impurities that could cause hard spots and inclusions float to the top of the molten iron bath and are prevented from entering the graphite die. The ferro-static head pressure caused by the molten iron in the bar machine creates a very dense, fine-grained microstructure that allows surface finishes in machined parts to be similar to those in carbon steel bars.

Commercially produced ductile iron bars are readily available in diameters up to 20.0” in squares and rectangles to 18.5”x 22.0” as well as relatively complex shapes.
Machinability Data

The growth in the sale of continuously cast ductile iron bar stock comes primarily from the conversion of parts that were once made from carbon steel bars. A cost saving in machining is the single biggest benefit of the conversion.

Although machinability data on carbon steel is readily available, there is little information on ductile iron bar stock. A simple machinability test utilizing a Miyano JNC 60 turning center with bar feeding capabilities can be used to compare the tool life of a variety of ductile iron grades, and to compare those grades with common carbon steel bar stock.

The experimental procedure consists of turning a 1.250” length of a 2.375” diameter bar that has been cold finished to a size of +/- 0.0025”. The insert traveled along the workpiece at a constant speed of 450 surface feet per minute, indexing at a rate of 0.010” per revolution, taking a 0.125” depth of cut. The diameter was reduced by 0.250” each time the insert made one pass 1.250” long. The speed of the lathe was increased after each pass to maintain a constant surface footage.

The test utilized Perkin 5000EP coolant and Sandvik CNMA 432KR grade 3015 inserts. No special testing of the inserts was performed, and all were selected from random production lots. The original diameter of the bar was eventually reduced to 1.125”, constituting one part. The surface finish of the remaining section was read, recorded, and cut off with a separate insert. A facing operation readies the bar for the next part, and a counter kept track of the number of parts that were machined with each insert. Insert failure was determined through trial and error, and the best indication of when the insert failed was when either one of the following two factors was reached: the surface finish on the part exceeded 80 RMS on two consecutive part readings, or the...

“Ductile iron was invented somewhat by accident when a metallurgist was trying to find a replacement for chrome in wear-resistant gray iron castings. Properties such as vibration damping, machinability, and wear resistance have made ductile iron a suitable replacement for steel in gears and a number of other applications.”

Figure 3 — Test fixture to measure fatigue strength in spur gears
load meter reading on the lathe was greater than 60 percent of capacity during the machining pass.

Table 2 shows the average number of parts machined per insert on standard grades of continuous cast ductile and gray iron bars using the described procedure. Each trial was repeated three times using bars produced from a typical production run. No special process controls were used in the manufacture of the test material.

The data shows the machinability ratings for a typical production run of each of the standard grades of continuous cast gray and ductile iron being commercially produced. Class 30 gray iron was arbitrarily set as the standard, with a rating of 100 percent. All other grades, including steel, were compared with the Class 30 standard.

The purpose of the machinability study was to provide some guidelines that do not currently exist on the machining properties of gray and ductile iron. It is difficult to compare those ratings with available data on steel bar stock, but a similar test was conducted to make some initial comparisons.

Four grades of carbon steel were selected and machined according to the procedures previously described for continuous cast gray and ductile iron bar stock. The procedures had to be modified slightly because it was not possible to machine at 0.125" depth-of-cut at a rate of 450 surface feet per minute without exceeding the 60 percent maximum load in the initial pass. The surface footage was reduced to 400 with a depth of cut of 0.040".

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum Load (no failure)</th>
<th>Relative Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>8620 Carburized &amp; Hardened</td>
<td>7000</td>
<td>100%</td>
</tr>
<tr>
<td>80-55-06 Induction Hardened</td>
<td>6300</td>
<td>90%</td>
</tr>
<tr>
<td>65-45-12 Austempered ASTM A897 Grade 5</td>
<td>6500</td>
<td>93%</td>
</tr>
</tbody>
</table>

*Table 4 — Fatigue strength (lbs) of ductile iron compared to 8620 steel*

Tool life index is used to give a comparison of materials being machined under similar conditions and helps to predict the conditions under which a part can be machined economically. In most production environments, turning speeds well in excess of 450sfm are commonly used, and as the speed increases, tool life decreases.

It is important to note that the tool life index for all grades of gray and ductile iron—with the exception of a fully pearlitic
Ductile Iron Properties

Ductile iron grades are characterized by their tensile strength, yield strength, and elongation, but those properties are not always useful in determining the suitability of its use in a specific application. Tensile properties do not provide any information about wear resistance, vibration damping, or fatigue strength, which are important properties when selecting materials for a specific application.

Wear Resistance: Ductile iron can be surface hardened to 60 HRC using conventional heat-treating methods. The wear properties after heat treatment are similar to those of 8620 carburized and hardened steel. Tests reveal that the abrasion resistance of ductile iron as measured by volume loss is less than 8620 steel when it has been quench and tempered to a final hardness of at least 30HRC. The volume loss of austempered ductile iron (ADI) is even less, and does not appear to be influenced by the final hardness. Improved wear resistance results from the presence of graphite nodules, which improves heat transfer and helps to lubricate the sliding wear surfaces.

Noise Reduction: The presence of precipitated graphite in both gray and ductile iron helps dampen vibration in gears, machine tool parts, and hydraulic components. The relative damping capacity of gray iron is as much as 100 times that of steel. Ductile iron has approximately 10 times the damping characteristics of steel.

Noise reduction in automotive balance shaft gears has been reported to be as much as 20 decibels when the same gear machined from gray iron was tested against steel. Ductile iron gears have shown noise reductions to be as much as eight decibels.

Currently, ductile iron is being considered to replace 8620 steel in hydraulic gear pumps in order to lower machining cost and decrease noise.

Fatigue Strength: The fatigue strength of ductile iron using a reverse bending variable speed plate testing machine will be in the range of 30-40 ksi, depending on the exact nature of the test and the grade of ductile iron being tested.

Additional testing recently performed at the University of Dayton Material Testing Lab shows the relative strength of quench and tempered ductile iron and austempered ductile iron compared to 8620 steel. A spur test gear was machined and set in a fixture that simulates the contact points on the gear tooth. The gears were loaded in a tension-tension test to determine the maximum load to failure at 10-million cycles. Test results show that heat-treated ductile iron gears have approximately 90 percent of the fatigue strength of 8620 carburized and hardened gears. Austempered ductile iron gears have as much as 93 percent of the fatigue strength by comparison.
Conclusion
While ductile iron bar stock cannot be used as a direct replacement for steel bar in all applications, it should be considered as an alternative to steel in gear and other applications where wear resistance, vibration damping, and machinability are important. Understanding the physical property requirements for a particular application and the ability to quantify the cost advantages by converting to ductile iron bar stock gives the design engineer a powerful tool in selecting the best material to be used for any application.

Machinability of ductile iron offers cost reduction opportunities for more parts machined per hour and lower tooling expenses. The excellent wear resistance, its ability to dampen noise and vibrations, and strengths that are similar to steel make it an attractive engineering material.

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