Cast Iron: A Solid Choice for Reducing Gear Noise

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Material selection can play an important role in the constant battle to reduce gear noise. Specifying tighter dimensional tolerances or redesigning the gear are the most common approaches design engineers take to minimize noise, but either approach can add cost to the finished part and strain the relationship between the machine shop and the end user. A third, but often overlooked, alternative is to use a material that has high noise damping capabilities. One such material is cast iron.

Cast iron is well known for being highly machinable, but it is often neglected as an engineering material because of the misconception that it is weak and brittle. While it's true that the gray irons are relatively brittle, ductile iron is not. Gray iron contains graphite in the form of flakes, while ductile iron contains graphite in the form of small, rounded nodules in a metal matrix. Ductile iron's mechanical properties are similar to those of carbon steels with a similar matrix:

	80-55-006 Ductile Iron 1141	Carbon Steel
Tensile Strength (psi)	80,000 (min.)	98,000 (typical)
Yield Strength (psi)	55,000	52,000
Elongation	6%	22%

NOTE:

- Ductile iron properties are minimum as specified in ASTM A536, grade 80-55-06.
- Carbon steel values are typical and not to be used for design purposes.
- Source for carbon steel values: *ASM Metals Reference Book.*

Cast iron's lack of use could also be attributed to the fact that many designers do not recognize the complex nature of the material or the wide number of applications for which it can be suitable. It is important to note that cast iron is not one material but a family of grades, each with its own characteristics. For example, tensile strengths range from 20,000 psi in the ferritic gray irons to 230,000 psi in the austempered ductile irons. Tensile strengths in steel gears typically will be higher than those found in cast iron. For comparison purposes, carbon steel has tensile strengths ranging from 100,000 psi to 250,000 psi, depending on the type of heat treat.

Cast iron's matrix structure resembles that of steel—the most commonly used gear material. Both are ferrous materials that are alloyed with carbon. Carbon combines with iron to form pearlite, which consists of alternating plates of hard iron carbide and soft ferrite. The carbon content controls the pearlite content in steel. High carbon steels contain more pearlite than low carbon steels. The pearlite content in cast iron is controlled by the cooling rate of the casting and the addition of pearlite stabilizing alloys. The balance of the matrix is pure iron ferrite. The pearlite-to-ferrite ratio influences strength, hardness and machinability in cast irons and steels.

Cast iron is a composite metal consisting of precipitated graphite in a metal matrix. The size and shape of the graphite particles influence most of the mechanical properties in a cast iron part. Ductile iron has spherical graphite and therefore has higher tensile strengths than gray irons that are made of flake graphite (Fig. 1). Graphite's ability to act as a natural chip breaker gives cast iron its desirable free machining characteristics.

Ductile and Gray Iron

Ductile and gray iron are the two types of cast iron most suitable for gear manufacturing. Ductile iron with a ferritic matrix has machining characteristics similar to 12L14 steel. Increasing the amount of pearlite improves wear resistance. A fully pearlitic ductile iron has optimal cast tensile strength (up to 100,000 psi) with a hardness of 302 BHN. Heat treating will increase strength to 120,000 psi when quenched and tempered, and up to 230,000 psi when austempered.

All types of cast iron—from gray to ductile—reduce noise because of the inherent sound

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damping properties of the metal. This is due to the graphite content of cast iron, which gives it optimal noise reduction capacity. Precipitated graphite particles absorb noise vibration; therefore, the relative damping capacity of ductile iron is twice that of steel. Gray cast iron has twice the damping capacity of ductile iron. The relative damping capacities of steel, ductile and gray iron are illustrated in Figure 2.

Ultimately, material selection for gears depends on what the application requires—the amount of damping desired and the required mechanical properties in the gear tooth. One example where cast iron was the best material choice involved the balance shaft in an automobile manufacturer's four-cylinder engine. Significant noise reduction was achieved after the gear material was changed from steel to ductile iron. No alterations to either the gear's design or dimensional tolerances were necessary to obtain these results. The switch to ductile iron also yielded a significantly lower machining cost.

Converting to ductile iron is not recommended in cases where added strength is required because of fatigue failures. Also, gears that are subject to high impact forces may not be suitable for ductile iron. It is important to understand the forces acting on the gear as well as the required safety factors before making a switch to ductile iron.

Despite its desirable noise reduction capabilities, the historic use of iron in gear manufacture goes back less than 30 years. Austempered ductile irons (ADI) began to be used as a material for gears in the 1970s when Kymi Kymmene Metall, a Finnish company, achieved excellent results after replacing forged steel with ADI. In 1977, General Motors converted a forged and case-hardened steel ring gear and pinion to ADI for its line of Pontiac rear-drive cars and station wagons. Another significant gain for iron came in 1983, when Cummins Engine Co. began using ADI for timing gears produced to AGMA Class 8 standards (Ref. 1).

ADI paved the way for steel conversions, but gray iron has been used for years in automotive applications. Distributor gears, oil pump gears and camshaft gears are made out of alloyed gray cast iron primarily because it is easy to heat treat and offers excellent wear resistance.

Cast iron, both gray and ductile, is easily heat treated because of the level of carbon present. Low carbon steels, such as 8620, must first be carburized, then quenched and tempered.

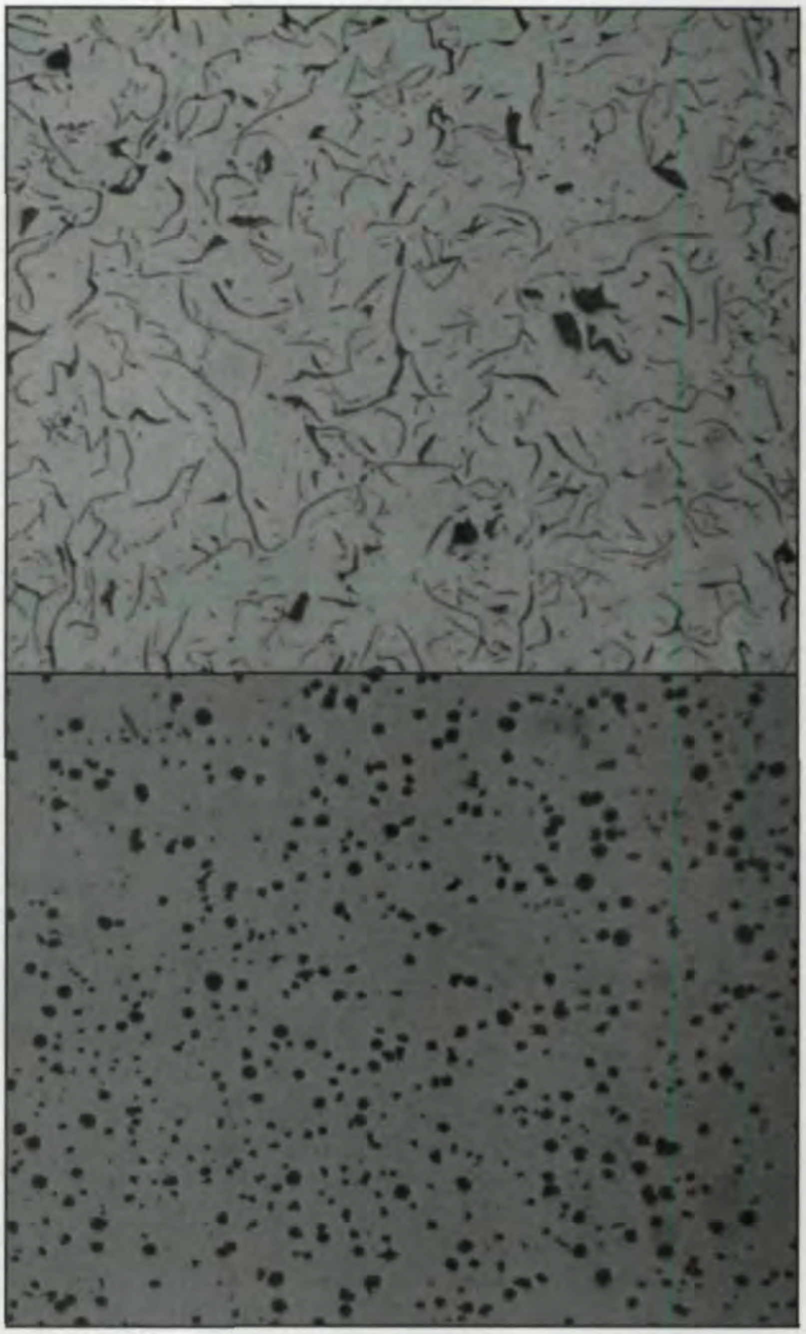

Fig. 1 — Flake (top) versus nodules (bottom) graphite cross sections.

EFFECT OF GRAPHITE SHAPE ON MECHANICAL PROPERTIES		
	Flake Graphite	**Nodular Graphite**
Tensile Strength (ksi)	20-50	60-230
Yield Strength (ksi)	n/a	40-185
Elongation (%)	n/a	2-18 (minimum)
Torsional Strength	50% of tensile strength	90% of tensile strength
Shear Strength	150% of tensile strength	90% of tensile strength
Impact Strength (ft-lbs)	1-5	10-25
Fatigue Strength (ksi)	20	40
Modulus of Elasticity (psi)	18 million	25 million
Vibration Damping (relative to carbon steel)	60 times	10 times

Source: *Iron Castings Handbook*

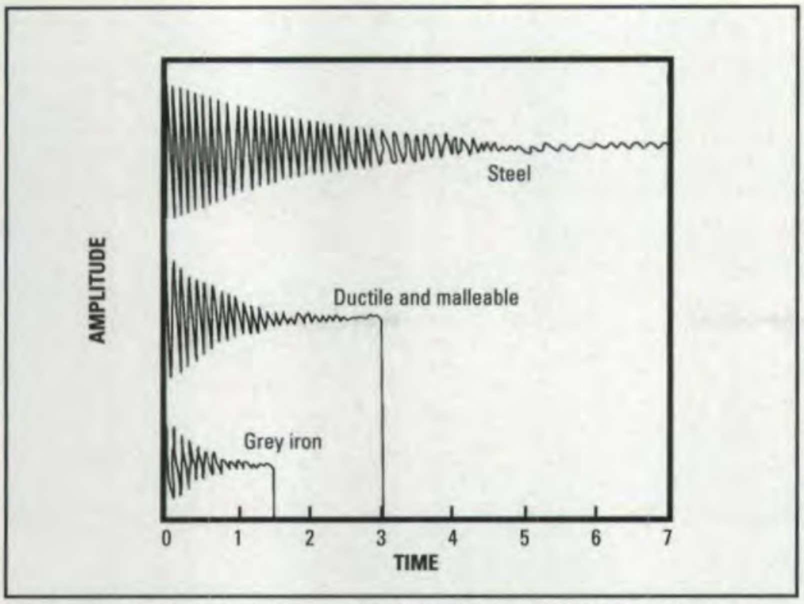

Fig. 2 — Relative damping behaviors of steel, ductile & malleable irons and grey iron.

MECHANICAL PROPERTY COMPARISON Steel v. Continuous Cast Iron				
Steel Grade	**Tensile (psi)**	**Yield (psi)**	**Elongation (%)**	**Machinability Rating (based on 1212 = 100%)**
1018	61,000	47,000	37	70%
1045	85,500	54,300	28	60%
1141	99,000	61,000	25	67%
12L14	78,000	60,000	17	180%
Dura-Bar Grade				
65-45-12	65,000	45,000	12	150%
80-55-06	80,000	55,000	6	100%
100-77-02	100,000	70,000	2	80%

Reference only, not typical or minimums Source: *ASM Metals Reference Book*

Fig. 3 — Mechanical Property Comparison, steel versus continuous cast iron.

Fig. 4 — Continuous cast iron production.

Cast iron has plenty of carbon available and is easy to heat treat.

In metallurgical terms, "heat treat" means the matrix must be transformed to austenite prior to quenching in order to achieve the required hardness. The solubility of carbon in austenite is 2%. The higher the carbon in austenite, the higher the hardness when quenched.

Since carbon makes up only 0.20% of 8620 steel, there is not nearly enough to maximize the quench hardness. Additional carbon is introduced into the matrix by a diffusion process called carburizing. The carburized depth determines the hardness depth after heat treating. The rule of thumb is that it costs about $0.01 per 0.001" depth of hardness, and you haven't paid for the heat treat yet.

So, to heat treat to 0.100" depth, carburizing would cost $1.00, and quenching and tempering would cost the same as it does in iron. Cast iron—both gray and ductile—does not have to be carburized prior to heat treating because it is made up of at least 2.5% carbon.

However, cast iron is still not widely accepted as a suitable material by many gear manufacturers. Manufacturers who are set up to machine steel bar stock may be reluctant to change to cast iron for several reasons. The initial pattern cost is one reason. Castings are made in sand molds, and patterns are required to produce the shape of the mold cavity. Iron is poured into the cavity to make the part. Patterns can cost up to $20,000 each to produce. In addition, manufacturers set up to machine bars have bar feeders and machining centers designed to handle bars, not cast slugs. Therefore, switching to iron castings means having to retool the machining center. Manufacturers may also be reluctant to switch because of typical quality problems associated with statically cast iron blanks, such as sand and slag inclusions, hard spots, shrinkage and porosity. Cast iron can also be dirty to machine because of its graphite content.

Continuous Cast Iron

There is an alternative to sand-cast iron blanks that overcomes many of these obstacles. Cast iron also can be produced through continuous casting, a unique process that produces a material that is almost perfectly suited for gear manufacturing. Figure 3 compares the properties of continuous cast iron with those of steel.

Continuous cast bar stock eliminates issues associated with pattern and retooling expenses. Manufacturing this highly machinable material involves a water-cooled graphite die mounted on the base of a refractory lined crucible. Molten iron enters the die and a solid skin begins to form around the perimeter of the bar. As the bar is pulled through the die, the solid skin becomes thick enough to support the molten iron core. The only part of the bar that is solid immediately outside of the die is the rim.

Heat from the molten iron core re-heats the rim above the critical temperature, and the entire bar cools in still air, eventually to room temperature (Fig. 4). The reheating of the rim and uniform cooling create a homogenous, consistent structure throughout the cross section. This eliminates the cracking and porosity problems commonly encountered with sand casting.

The die/cooler system is mounted on the bottom of the bar machine. Slag, dross and tool wearing inclusions float to the top of the crucible, well away from the entrance end of the die. The ferrostatic head from the molten metal in the bar machine crucible feeds iron under pressure into the die and eliminates microshrinkage that can have a detrimental effect on fatigue properties in the gear teeth. The clean, fine grain microstructure makes continuous cast iron an excellent starting material for gears, as it shares the same optimal noise damping capabilities as other types of cast iron.

Although machining continuous cast iron is still "dirty" because of the presence of graphite, which turns into fine dust during machining, any machine shop with good dust collection and coolant management will not have a dirt problem. Machining cast iron is no more dirty or hazardous than machining leaded steels or any other free machining grade that has solid, precipitated particles introduced as chip breakers. Graphite is black, which makes it appear dirtier, but it is not nearly as hazardous as lead.

Final Considerations

Cast iron may not be a viable substitute for steel in all gear applications. For example, high-speed gear sets will benefit from the damping properties of iron more than low-speed gears. However, both high and low speed gears can take advantage of the growth consistency in austempered ductile iron.

Heat treat distortion occurs in carburized gears because of the inconsistency in the depth of the diffusion layer attained during carburizing. Also, the matrix in rolled carbon steel is not homogenized, and residual stresses are present as a result of the rolling process.

Continuous cast iron is stress free because it is not rolled and does not require carburizing. In other words, there is no heat treat distortion, and its growth consistency is uniform throughout the material. Iron and steel grow when heat treated because of the volume change in the atomic structure. However, growth is predictable; it's the distortion that causes problems.

Heat treat distortion should also be taken into consideration in gear material selection because it is one of the largest contributors to noise and early fatigue failure in steel gears. Less heat treat distortion means quieter gears and, possibly, longer life.

The cost of continuous cast iron bar stock is typically 5–15% higher than rolled carbon steel. It can also be 5–15% cheaper than forgings. Usually, material cost is higher when continuous cast iron is used for gears less than 4" in diameter and lower when used for gears greater than 4".

Overall, cast iron can be an economical solution for problems created by noise and vibration, especially in applications where a slight decrease in strength is a workable tradeoff. The free machining characteristics of cast iron offer an environmentally friendly alternative to leaded steels, and its wide range of properties allows the design engineer to select the best-suited grade for an application. ○

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