Compacted Graphite Iron: A Viable Alternative

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Based on a paper published in Engineered Casting Solutions AFS Spring 2000

SinterCast

Introduction

March 20, 1948 is well-known to cast iron foundrymen as the date on which K. D. Mills, A. P. Gagnebin and N. B. Pilling filed the first patent application for the production of ductile iron. The patent was granted on October 25, 1949 and the world-wide production of ductile iron has since grown to approximately 13 million tons per year. In October 1998, the world foundry industry gathered at the Ductile Iron Society/AFS World Symposium to celebrate the Golden Anniversary of ductile iron and all of the good progress that had been made. Relatively few of the delegates knew that Millis, Gagnebin and Pilling filed, and received, a patent for compacted graphite iron (CGI) on the same dates in 1948 and 1949.

It is logical that the development efforts initially focused on ductile iron. It is approximately twice as strong as CGI and its stable production range is approximately five times larger. Although stronger and easier to produce, the choice between gray and ductile iron forced designers to select from either end of the cast iron spectrum: gray iron with good castability, machinability, damping capacity and thermal conductivity; or, ductile iron with good strength and stiffness. Most decisions required compromise.

With the recent advances in electronics, measurement and foundry process control technology, compacted graphite iron has become a viable production material. With better strength and stiffness than gray iron, and better castability, machinability and thermal conductivity than ductile iron, it is ideal for components with simultaneous mechanical and thermal loading, such as cylinder blocks and heads.

What is CGI?

Cast irons are differentiated by the shape of the graphite particles. As shown in Figure 1, gray cast iron is characterized by randomly oriented graphite flakes, while the graphite in ductile iron exists as individual spheres. The graphite particles in CGI are randomly oriented and elongated as in gray iron, but they are shorter, thicker, and have rounded edges.

The difference between the three types of graphite is more striking in the three-dimensional deep-etch scanning electron micrographs shown in Figure 2. In contrast to either gray or ductile iron, the entangled compacted graphite 'clusters' interlock themselves into the iron matrix to provide a strong adhesion between the iron and the graphite. The rounded edges of the CGI particles suppress the crack initiation that would otherwise occur at the sharp flake edges, while the complex shape of the clusters and the good iron/graphite adhesion impairs crack propagation. Together, these factors account for the increase in strength relative to gray iron and the improved thermal conductivity relative to ductile iron. The relative properties of the three cast irons are summarized in Table I.

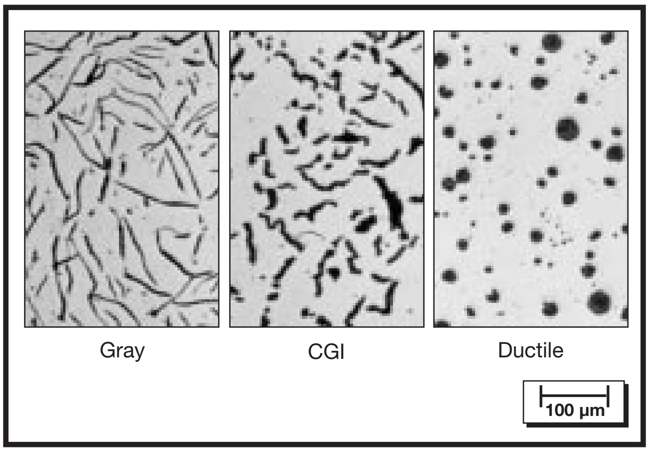

Figure 1: Gray iron, compacted graphite iron, and ductile iron are differentiated by the shape of the graphite particles

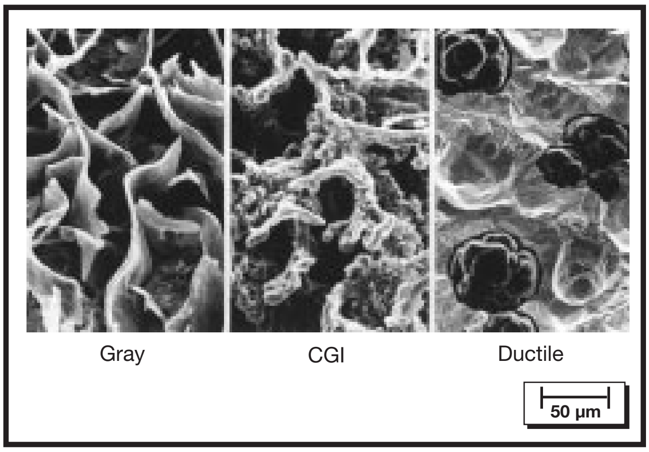

Figure 2: Deep-etched scanning electron micrographs show the three-dimensional shape of the graphite

Table I: Typical properties of pearlitic gray, compacted and ductile cast irons

Property	Gray	CGI	Ductile
Tensile Strength (MPa)	250	450	750
Elastic Modulus (GPa)	105	145	160
Elongation (%)	0	1.5	5
Thermal Conductivity (W/mK)	48	37	28
Relative Damping Capacity	1	0.35	0.22
Hardness (BHN 10/3000)	179–202	217–241	217–255
R-B Fatigue (MPa)	110	200	250

Compacted Graphite Iron is intermediate to gray and ductile iron in its microstructure, its properties and its production in the foundry. As such, CGI invariably contains some spheroidal graphite, referred to as % nodularity. For optimal castability, machinability and thermal conductivity, the % nodularity should be kept as low as possible (0-10%) in performance-critical sections.

As a cast iron, CGI can be produced with either a ferritic or a pearlitic matrix and can be alloyed with a variety of elements to alter its strength, hardness or elevated temperature behavior. The as-cast matrix can be heat treated by any conventional cast iron technique, including surface hardening and austempering.

Foundry Production

Similar to ductile iron, compacted graphite iron is produced by adding magnesium to a desulfurized base iron. As shown in Figure 3, CGI is stable over a range of approximately 0.008% magnesium (Mg), which is approximately five times smaller than the commercially used Mg-range for ductile iron. At the low end of the stable range, CGI is separated from gray iron by an abrupt transition of 0.001% Mg. This represents the greatest challenge in the production of CGI. If the magnesium addition is insufficient, or if the magnesium content of the iron decreases due to fading, flake-type graphite can appear in the casting causing an immediate 20-30% decrease in strength and stiffness. The Mg-fading (evaporation of 0.001% Mg every five minutes) phenomenon discourages foundries from working too close to the far left side of the CGI range. However, operating at the high-Mg side of the stable range can promote high nodularity in the faster cooling portions of the casting. While the higher nodularity provides increased strength and stiffness, it simultaneously impairs thermal conductivity and machinability, and most importantly, can exacerbate shrinkage problems.

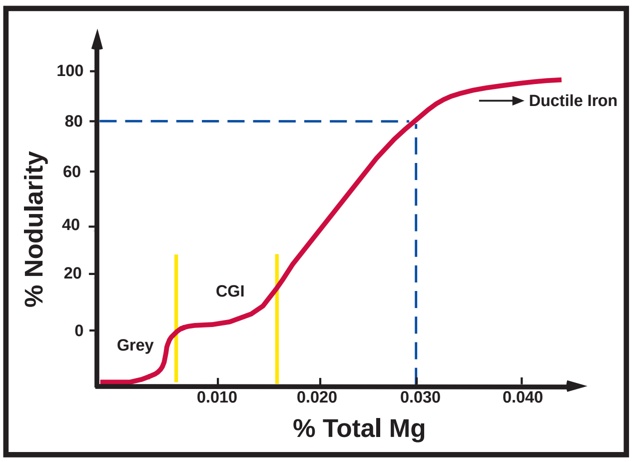

Figure 3: Compacted graphite iron is stable over a narrow range of magnesium. The stable range is separated from gray iron by an abrupt transition of 0.001% Mg

Compacted Graphite Iron has been routinely produced in components of relatively simple geometry for more than 25 years, particularly those that can tolerate higher nodularities. However, it is only in the last 2-3 years that process control technology has evolved to the point where foundries are willing to quote on jobs for complex components with narrow microstructure specifications.

CGI Properties

The mechanical and physical properties of CGI are determined by the graphite shape and the pearlite/ferrite ratio. As shown in Figure 4, the tensile strength and elastic modulus of CGI gradually increase with increasing nodularity, but decrease precipitously with the onset of flake graphite formation. As such, flake graphite is inadmissible in CGI. The nodularity axis in Figure 4 is compressed in the flake zone to replicate the rapid transition from CGI to flake graphite as a function of magnesium. A nodularity rating of –5% thus represents a fully A-type gray iron.

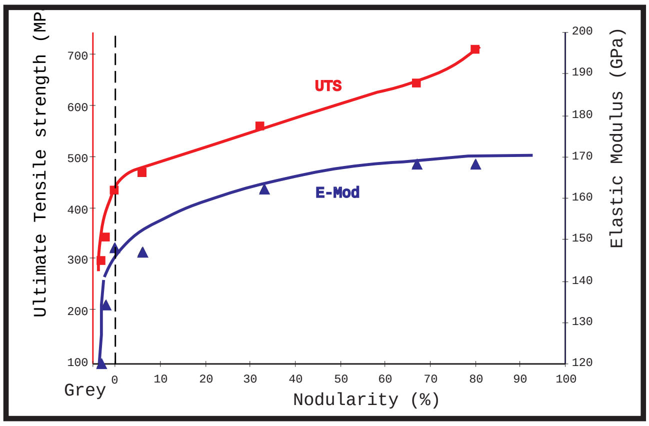

Figure 4: The strength and stiffness of CGI (>85% pearlitic) increase with increasing nodularity and decrease precipitously with the onset of flake graphite

One of the most important design considerations of CGI is the effect of applied stress on the elastic modulus. In gray cast irons, the elastic modulus decreases linearly in the presence of an applied load. However, because of the ductility of CGI, the elastic modulus remains constant until a certain temperature-dependent stress limit is reached. The modulus then begins to decrease in a linear manner. The practical significance of this is that the elastic modulus of dynamically loaded CGI components may be 50-75% higher (rather than 35-40% in the unloaded state) than identically designed and loaded gray iron castings. Design simulations must therefore input the proper stiffness values for both gray iron and CGI, as a function of loading, to accurately identify weight reduction opportunities and performance limitations.

As shown in Figure 5, the mechanical properties of CGI increase linearly with pearlite content. The linear behavior allows designers to select the preferred pearlite content to suit property, hardness and machinability requirements. A 20% pearlite range is typical (ie, target 70% +/-10%), or alternatively a fully pearlitic (>95%) structure can be specified.

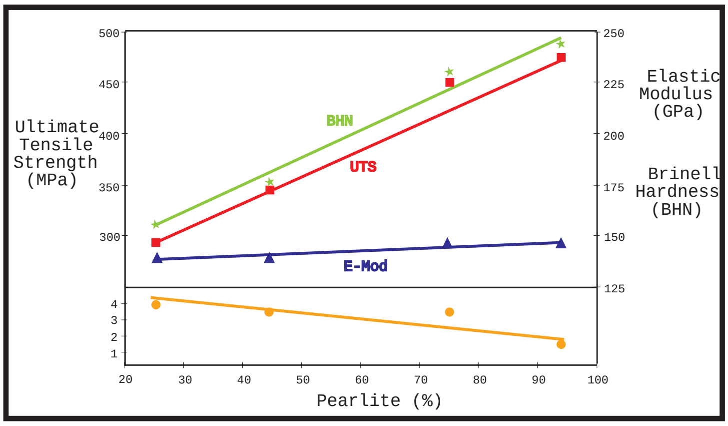

Figure 5: The mechanical properties of CGI (0–10% nodularity) increase linearly with increasing pearlite content

Design Opportunities

As an intermediate material between gray iron and ductile iron, the most obvious use of CGI is in applications where the mechanical properties of gray iron are insufficient, and/or those of ductile iron are overkill. This type of approach was used in an early application of CGI for high speed train brake disks where gray iron experienced surface cracking (crazing) failures while the high elastic modulus and low thermal conductivity of ductile iron led to excessive warpage. As shown in Figure 6, CGI provided a good intermediate balance between crazing, cracking and distortion, and was successfully applied to the brake disk application.

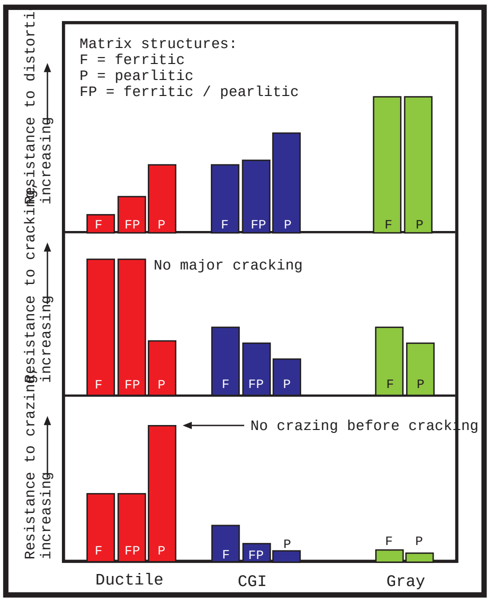

Figure 6: Intermediate properties make CGI an ideal material for many applications with simultaneous thermal and mechanical loading

Relative to conventional gray cast iron, CGI provides opportunities for:

- Reduced wall thicknesses at current operating loads
- Increased operating loads at current component design
- Reduced safety factors due to less relative variation in as-cast properties
- Reduced brittle failure in handling, assembly and service due to higher ductility
- Achieving higher strength without resorting to alloying
- Shorter thread engagement depth and therefore shorter bolts

Relative to ductile iron, CGI can provide:

- Improved castability for more complex/intricate components
- Up to 20% improved mold yield due to better feeding
- Less accumulated stress due to higher thermal conductivity and lower elastic modulus
- Improved heat transfer
- Improved machinability

Although CGI is often specified in simple housing and bracket applications where the strength of ductile iron is ‘overkill’, the real future for CGI is in demanding applications that simultaneously require strength, castability, thermal conductivity and extensive machining. This is true of cylinder blocks and heads, particularly for heavily loaded diesel engines.

A Case History

Engine design is governed by performance objectives and constrained by packaging, durability and fuel economy/emissions requirements. In diesel engines, these conflicting demands can only be satisfied by increasing the peak firing pressure in the cylinder bores (Pmax). This increased combustion load is transferred via the connecting rod to the crankshaft and ultimately applies a fatigue load to the main bearing region of the block. As Pmax in state-of-art passenger car applications has been increasing from approximately 135 bar in 1997 to 160 bar in 2000, and is forecast to increase to 180-200 bar by 2005 to satisfy emissions legislation, conventional materials require larger cross-sections to withstand the fatigue loading. This, however, contradicts packaging and weight criteria.

Rotating-bending, 3-point bending and tension-compression testing all show that the fatigue strength of CGI is approximately double that of conventional gray iron. These results, obtained from polished specimens, have recently been validated in bench tests on four cylinder passenger car diesel blocks fitted with dummy crankshafts, pistons and connecting rods. This room temperature bench test caused fatigue failure in the gray iron block at approximately 200 bar while the CGI block withstood testing at up to 380 bar. This result indicates that cast components, with different geometry and surface conditions, also provide the improved fatigue properties observed in polished specimens. CGI allows for increased loading, often at reduced risk of service failure, without increasing component size or weight.

A recent design analysis conducted by the engine design firm AVL List GmbH of Austria (‘Further Reading’) has evaluated downsizing opportunities for a 1.8 litre diesel engine cylinder block upon conversion from gray iron to CGI. This analysis showed that Pmax could be increased from 135 bar in gray iron to 180 bar in CGI, and that the displacement could simultaneously be reduced from 1.8 liters to 1.3 liters while providing the same performance. In consideration of required add-ons to the CGI engine to increase the performance, such as turbocharger, larger water pump and exhaust manifold, the net CGI downsizing benefits for two different design options included:

- 9% reduction in overall weight of the finished engine
- 22% reduction in weight of machined cylinder block
- 15% reduction in overall length of the finished engine
- 5% reduction in both the height and width of the finished engine

Conventional Wisdoms

When specifying gray or ductile iron, designers know that uniformity of graphite shape is critical to maintaining mechanical properties. In gray iron, the presence of degenerate graphite forms such as undercooled (Type D) graphite or large kish (Type C) graphite can reduce strength and stiffness by 20-25%. Similarly, ‘crab-shaped’ graphite and exploded nodules can reduce the strength and stiffness of ductile iron. Based on these experiences, designers may be inclined to specify a uniform graphite structure in CGI. However, although low-nodularity (0-10%) CGI structures are required in performance-critical sections such as cylinder bores to optimize castability, thermal conductivity and machinability, higher nodularities can actually benefit the structural regions of a casting. The natural tendency of CGI to solidify with higher nodularity in the faster cooling sections may result in the thin outer walls (less than 4 mm) having 20-50%

nodularity while thicker as-cast walls contain 0-10% nodularity. In many cases, where the thin sections are not thermally loaded and do not require extensive machining, the higher nodularity only serves to increase the strength, stiffness and ductility of the castings. CGI microstructure specifications should therefore focus on performance-critical sections and tolerate/benefit from shifted nodularity in thin wall areas.

Thermal fatigue failures in gray iron are typically rectified by adding material to increase cross-sectional areas thus reinforcing strength and stiffness. However, CGI has higher strength and lower thermal conductivity than gray iron, which can cause thermally loaded CGI components to operate at higher temperatures. Therefore, if a CGI component experiences thermal fatigue, particularly in material substitution applications for existing gray iron designs, the solution may lie in reducing the wall thickness to improve heat transfer. Today's bench tests for thermal fatigue invariably rely on a severe thermal cycle to minimize the test duration. However, rapid heating and cooling rates favor materials with high thermal conductivity while higher absolute temperatures emphasize mechanical strength. The design of bench scale thermal fatigue tests may therefore favor gray iron while the actual service duty-cycles would favor CGI. Re-designed CGI components have confirmed this premise. Care must therefore be taken to ensure that the short bench test does not wrongly condemn a CGI design.

Wall thicknesses in as-cast components are determined either by strength or mold-making limitations. Unfortunately, very few cast walls arrive at these two limits at the same time. Although CGI may have a higher shrinkage tendency than gray iron, both materials effectively have the same fluidity and thus mold-filling capabilities. The higher strength of CGI allows designers to reduce weight by focusing on the relatively thick load-carrying regions of a casting that are not yet limited by molding considerations. Although every kg is important in a casting, and thick and thin sections must both be attacked, the easiest and most effective changes are those made to the thick sections. Castability and molding may determine the minimum wall thickness, but they do not necessarily define the minimum weight.

Machinability

With 75% higher tensile strength and 30-40% higher stiffness, it is intuitively evident that CGI will be more difficult to machine than gray iron. As shown in Figure 7, low speed cutting (100-200 m/min) with conventional carbide tools provides approximately 50% of the tool life of gray iron in both milling and turning operations. Similarly, high speed (400-800 m/min) milling operations provides approximately 50% of the gray iron tool life when using polycrystalline cubic boron nitride (PCBN) or ceramic inserts. However, the machining of CGI is most severe when using PCBN or ceramic inserts in high speed continuous cutting operations, such as turning or cylinder boring.

For the particular case of cylinder boring, for which modern engine block transfer lines require a maximum cutting time of 8-14 seconds (20-22 second cycle time), a number of novel cutting techniques are currently being developed, Figure 8 ('Further Reading'). These techniques generally revert to the superior wear resistance of carbides but rely on multiple cutting inserts. Although cutting at lower speeds, these concepts satisfy cycle time requirements by compensating

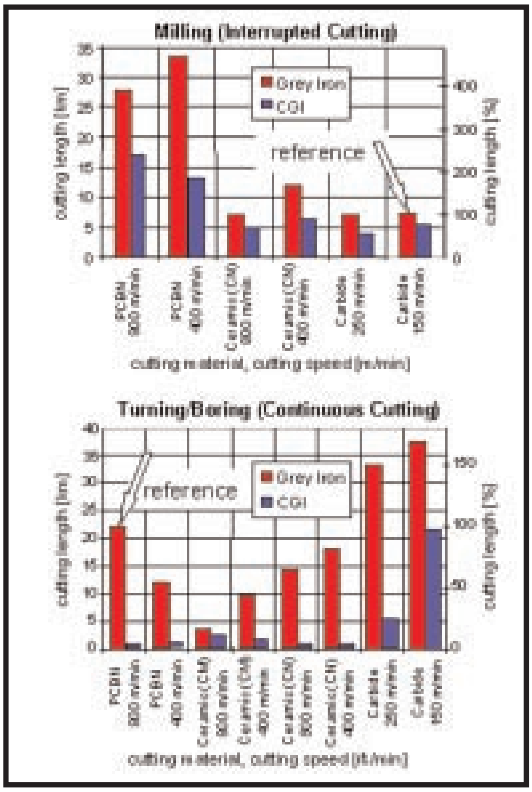

Figure 7: Comparative tool life for different tool materials in interrupted (milling) and continuous (turning/boring) cutting of pearlitic CGI and Gray Iron

for the reduced cutting speed (from 800 to 100 m/min) with an increased feed rate and sharing the total cutting load among the many inserts. These concepts have demonstrated the ability to provide at least one full production shift during laboratory testing, while satisfying tool wear, dimensional and surface roughness criteria.

Figure 8 also shows the so-called ‘rotary’ tooling concept where the cutting insert rotates as the tool spirals down the cylinder bore. Rotation of the insert (at approximately 2000 rpm for 800 m/min continuous cutting) prevents any fixed point from carrying the entire cutting load. This novel concept has resulted in twenty times longer cutting lives for CGI than even gray iron with conventional fixed insert cutting. The rotary concept can also be used in milling and turning applications.

It is well known that the very narrow stable range for CGI production can be extended toward higher magnesium levels by alloying with 0.1-0.25% titanium. While the titanium increases the stable range, and thus allows foundries to stay safely away from the low magnesium risk of flake graphite, it simultaneously results in the formation of titanium carbide and carbonitride inclusions. As shown in Figure 9, these inclusions, which are harder than many tool materials, significantly increase the abrasive wear. Even the improved tooling concepts introduced in Figure 8 are unable to successfully machine cylinder bores when the titanium content exceeds 0.10%. Titanium additions must be avoided in the production of CGI castings requiring significant machining.

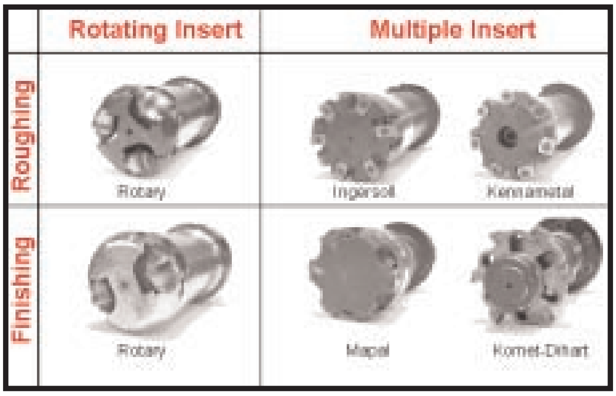

Figure 8: Multiple insert and ‘rotary’ cutting tooling concepts for CGI cylinder boring

CGI Standards

CGI material specifications are typically based on a set of minimum mechanical properties including tensile strength, 0.2% yield strength and elongation. To ensure that the expected physical properties are achieved, the CGI microstructure must also be specified. Numerous internal OEM standards have been developed for CGI in specific applications, however relatively few independent standards exist. The most widely accepted of the independent standards, ASTM A-842, was issued in 1985 and is currently under review. This standard offers five grades of CGI, denoted by minimum tensile strengths of 250, 300, 350, 400 and 450 Mpa. The ASTM A-842 specification limits percent nodularity in all grades to 20% maximum, with no flake graphite.

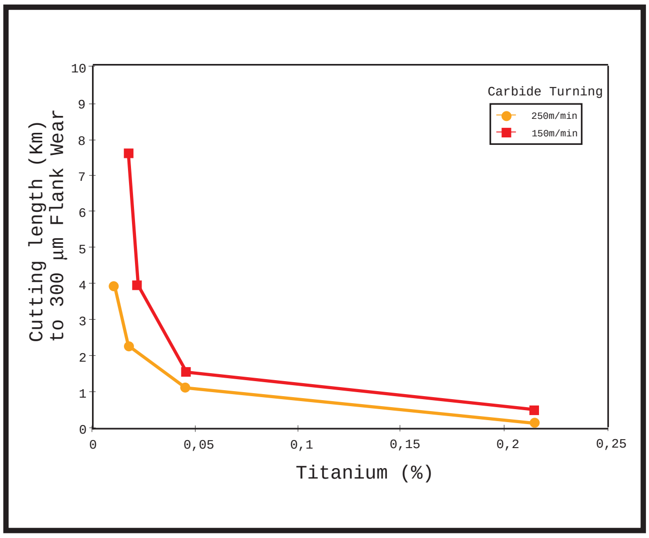

Figure 9: The effect of up to 0.22% titanium on tool life during continuous carbide cutting (turning) of pearlitic CGI

A new CGI specification is currently under development by the Society of Automotive Engineers (SAE) that specifies grades of conventional (20% maximum nodularity) CGI and also introduces grades of higher (20-50%) nodularity CGI that have recently been applied in production.

Conclusions

Considerable progress has been made in the development of compacted graphite iron over the past ten years. Foundry process control has evolved to allow for high volume production of complex CGI castings and machining solutions have been presented. In parallel with these developments, design principles have been established and production references exist. Both Audi A8 and BMW 7 series flagship cars have recently incorporated new V8 CGI diesel engines. Compacted graphite iron has become a viable alternative.

Further Reading

S. Dawson: Compacted Graphite Iron: Mechanical and Physical Properties for Engine Design, Materials in Powertrain Conference (Werkstoff und Automobilantrieb), VDI, Dresden, Germany, 28-29 October 1999.

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J.Schmid: Honing Technology for Optimal Cast Iron Cylinder Faces, Engine Technology International, Issue 1/99, February 1999, pp. 108-109.

S. Dawson and I. Hollinger, M. Robbins and J. Daeth, U. Reuter and H. Schultz: The Effect of Metallurgical Variables on the Machinability of Compacted Graphite Iron.

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