SAE International™ **SURFACE VEHICLE STANDARD**

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Automotive Compacted Graphite Iron Castings

1. Scope

1.1 This SAE Standard covers the mechanical and physical requirements for Compacted Graphite Iron (CGI) castings used in automotive and allied industries. Requirements in this document include:

a. Tensile Strength
b. Yield Strength
c. Elongation
d. Graphite Morphology

1.2 Appendix A provides general information on application of this material along with additional data on mechanical and physical properties not specified but useful as a design reference. Appendix B provides a Compacted Graphite Iron Percent Nodularity Rating Chart not specified but useful as a visual reference.

2. References

2.1 Applicable Publications—The following publications form a part of this specification to the extent specified herein.

2.1.1 ASTM PUBLICATIONS—Available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

ASTM A 247—Test Method for Evaluating the Microstructure of Graphite in Iron Castings
ASTM E 8M—Test Methods for Tension Testing of Metallic Materials (Metric)
ASTM E 9—Test Methods of Compression Testing of Metallic Materials at Room Temperature
ASTM E 10—Test Method for Brinell Hardness of Metallic Materials
ASTM E 21—Test Methods for Elevated Temperature Tension Tests of Metallic Materials
ASTM E 132—Standard Test Method for Poisson's Ratio at Room Temperature

2.2 Related Publications—The following publications are provided for information purposes only and are not a required part of this specification.

2.2.1 SAE PUBLICATIONS—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

I.C.H. Hughes and J. Powell, "Compacted Graphite Irons – High Quality Engineering Materials in the Cast Iron Family," SAE Paper 840772, 1984.

S. Dawson, I. Hollinger, M. Robbins, J. Daeth, U. Reuter and H. Schultz, "The Effect of Metallurgical Variables on the Machinability of Compacted graphite Iron," SAE Technical Paper Series 2001-01-0409, March 2001.

2.2.2 OTHER

E. Nechtelberger, H. Puhr, J.B. van Nesselrode and A. Nakayasu, "Cast Iron with Vermicular/Compacted Graphite – State of the Art," International Foundry Congress, Chicago, Illinois, April 1983.

D.M. Stefanescu and C.R. Loper, "Recent Progress in the Compacted/Vermicular Graphite Cast Iron Field," Giesserei-Prax., No. 5.

S. Dawson, I. Hollinger and P. Smiles, "The Mechanical and Physical properties of Compacted Graphite Iron," Global Powertrain Congress, Detroit, October 1998

3. Grades

3.1 The specified grades, minimum mechanical properties and microstructure requirements, are shown in Table 1.

TABLE 1—MINIMUM MECHANICAL PROPERTIES AND MICROSTRUCTURE FOR COMPACTED GRAPHITE IRON[1]

Grade[2]	Typical Hardness Range	Minimum Tensile Strength MPa	Minimum Tensile Strength ksi	Minimum 0.2% Yield Strength MPa	Minimum 0.2% Yield Strength ksi	Minimum % Elongation	Typical Matrix Microstructure	Graphite Morphology % Nodularity[3]
C250	121-179 HB	250	36.3	175	25.4	3.0	Ferritic	<20
C300HN	131-189 HB	300	43.5	175	25.4	3.0	Ferritic	20-50
C300	143-207 HB	300	43.5	210	30.5	2.5	Ferritic / Pearlitic	<20
C350	163-229 HB	350	50.8	245	35.5	2.0	Ferritic / Pearlitic	<20
C400	197-255 HB	400	58.0	280	40.6	1.5	Pearlitic / Ferritic	<20
C450	207-269 HB	450	65.3	315	45.7	1.0	Pearlitic	<20
C500HN	207-269 HB	500	72.5	315	45.7	1.5	Pearlitic	20-50

1. Refer to 7.1
2. "HN" denotes "High Nodularity". These grades are characterized by having 20 to 50% nodularity while conventional CGI is characterized by having less than 20% nodularity.
3. Refer to 6.1

4. Hardness

4.1 The hardness ranges provided in Table 1 are guidelines only.

4.2 The area or areas on the casting where hardness may be checked should be established by agreement between the manufacturer and the purchaser.

4.3 Brinell hardness shall be determined according to ASTM E 10, Test for Brinell Hardness of Metallic Materials, after sufficient material has been removed from the casting to ensure representative hardness readings. A 10 mm ball, 3000 kg load and 10 second delay time shall be used unless otherwise agreed upon.

5. *Heat Treatment*

5.1 Appropriate heat treatment to obtain minimum mechanical properties, remove residual stresses, or improve machinability may only be performed by agreement between the manufacturer and the purchaser.

6. *Microstructure*

6.1 The metallographic examination of Graphite Morphology shall be performed in the specified critical region of the casting, test lug from the casting or separately cast test coupon or cast test bar as agreed between the manufacturer and the purchaser.

6.2 Compacted graphite iron shall be examined metallographically for the specified graphite morphology. The microstructure shall contain the specified percentage of graphite nodules, Types I and II (reference Plate 1, Graphite Form Types of ASTM A 247). The percentage of nodular graphite can be determined by manual particle count, semiautomatic or automatic image analysis or chart comparison techniques as agreed between the manufacturer and the purchaser. The remaining graphite particles shall be in the compacted graphite shape, Type IV. Flake graphite, Type VII is not permitted.

6.3 The matrix microstructure shall consist of ferrite, pearlite or a combination of these and be substantially free of primary cementite.

7. *Quality Assurance*

7.1 It is the responsibility of the manufacturer to demonstrate process capability. The specimen(s) used to do so shall be of a configuration and from a location agreed upon between the manufacturer and the purchaser.

7.2 Sampling plans shall be agreed between the manufacturer and the purchaser. The manufacturer shall employ adequate controls to ensure that parts conform to the agreed upon requirements.

7.3 Non-destructive methods may be utilized to assess graphite morphology when correlation to microstructure has been established and agreed between the manufacturer and the purchaser.

8. *General*

8.1 Castings furnished to this document shall be representative of good foundry practice and shall conform to the dimensions and tolerances specified on the casting drawing.

8.2 Minor imperfections usually not associated with the structural functioning may occur in castings. These imperfections are often repairable, however, repairs should be made only in areas and by methods approved by the purchaser.

8.3 The manufacturer and the purchaser may agree upon additional casting requirements, such as manufacturer identification, other casting information and special testing. These should appear as additional product requirements on the casting drawing.

PREPARED BY THE SAE METALS TECHNICAL COMMITTEE—DIVISION 9—
AUTOMOTIVE IRON AND STEEL CASTINGS

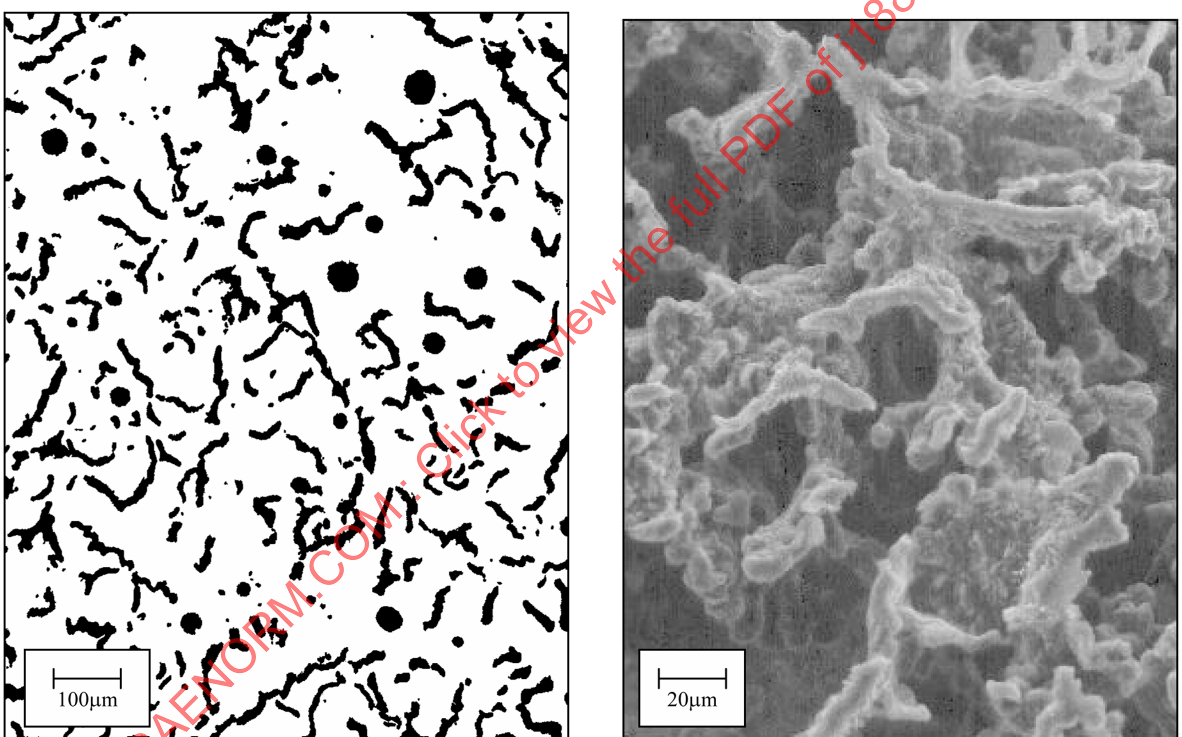
REAFFIRMED BY THE SAE AUTOMOTIVE IRON AND STEEL CASTINGS COMMITTEE

APPENDIX A

COMPACTED GRAPHITE IRON
(MATERIAL DESCRIPTION NOT A PART OF THE STANDARD REQUIREMENTS)

A.1 Material Description

A.1.1 The graphite particles in Compacted Graphite Iron (Figure A1) appear as individual 'worm-shaped' or vermicular particles. The particles are elongated and randomly oriented as in gray iron, however they are shorter and thicker, and have rounded edges. While the compacted graphite particles appear vermicular when viewed in two dimensions, deep-etched SEM micrographs show that the individual 'worms' are connected to their nearest neighbors within the eutectic cell. This complex coral-like graphite morphology, together with the rounded edges and irregular bumpy surfaces, results in strong adhesion between the graphite and the matrix. The compacted graphite morphology inhibits the initiation and growth of cracks and is the source of the improved mechanical properties relative to gray iron.



(a) (b)

FIGURE A1—COMPACTED GRAPHITE IRON VIEWED (A) ON A TWO-DIMENSIONAL PLANE-OF-POLISH (10% NODULARITY CGI) AND (B) WITH A SCANNING ELECTRON MICROSCOPE AFTER DEEP-ETCHING.

A.2 Commercial Production Methods

A.2.1 The compacted graphite morphology is achieved by the addition of certain modifying elements to a low sulfur base iron prior to casting. Similar to ductile iron, most commercial compacted graphite iron is produced by the addition of magnesium, alone or in combination with rare earth elements such as cerium, that have a similar modifying effect on the graphite. Conventional CGI (<20% nodularity) is stable over a range of approximately 0.008% magnesium. Process control is most critical at the low end of this range. CGI is separated from gray iron by an abrupt transition of only about 0.001% magnesium. If the magnesium content is insufficient, flake-type graphite will form causing an immediate 20-30% decrease in mechanical properties. Magnesium contents above the stable range promote higher percent nodularity. Higher percent nodularity (20-50%) provides modest increases in mechanical properties with simultaneous reductions in the thermal conductivity, castability and machinability of CGI.

A.2.2 Control of the compacted graphite structure within the conventional nodularity range can be achieved by the addition of titanium, which inhibits graphite nodule formation. The addition of titanium allows higher magnesium contents to be used thus safely avoiding flake-type graphite formation while restricting the natural tendency to higher percent nodularity. Titanium additions, however, may reduce the machinability of CGI (See A.5.4.)

A.2.3 The compacted graphite structure has also been achieved without the aid of titanium by close control of the modifying elements as defined above and/or thermal analysis measurements of the iron prior to casting. Thermal analysis methods accurately assess the solidification characteristics of a small sample of iron that are then applied to the bulk iron to insure it is cast within the desired nodularity range. The titanium-free production processes are better suited for high volume castings that require extensive machining.

A.3 Material Properties Summary

A.3.1 The material properties of compacted graphite iron are intermediate to those of gray and ductile iron. CGI has better strength and stiffness than gray iron and better castability, machinability and thermal conductivity than ductile iron, making it ideal for components with simultaneous mechanical and thermal loading. The relative properties of gray, compacted graphite and ductile iron are provided in Table A1.

TABLE A1—RELATIVE PROPERTIES OF PEARLITIC GRAY, COMPACTED, AND DUCTILE IRONS

Property	Gray Iron	CGI	Ductile Iron
Tensile Strength	55	100	155
0.2% Yield Strength	—	100	155
Elastic Modulus	75	100	110
Elongation	0	100	200
R-B Fatigue	55	100	125
Hardness	85	100	115
Thermal Conductivity	130	100	75
Damping Capacity	285	100	65

An overview of the mechanical and physical properties of CGI is provided in Table A2.

TABLE A2—MECHANICAL AND PHYSICAL PROPERTIES OF CGI

Property	Test Method	Temp. (°C)	70% Pearlite	100% Pearlite
Ultimate Tensile Strength (MPa)	ASTM E 8M (25 °C) ASTM E 21 (100 °C and 300 °C)	25	420	450
		100	415	430
		300	375	410
0.2% Yield Strength (MPa)	ASTM E 8M and E 21 ASTM E 21 (100 °C and 300 °C)	25	315	370
		100	295	335
		300	284	320
Elastic Modulus (GPa)	ASTM E 8M and E 21 ASTM E 21 (100 °C and 300 °C)	25	145	145
		100	140	140
		300	130	130
Elongation (%)	ASTM E 8M and E 21 ASTM E 21 (100 °C and 300 °C)	25	1.5	1.0
		100	1.5	1.0
		300	1.0	1.0
Unnotched Fatigue Limit (MPa)	Rotating-Bending, 3000 rpm	25	195	210
		100	185	190
		300	165	175
Endurance Ratio	Fatigue Limit/UTS	25	0.46	0.44
		100	0.45	0.44
		300	0.44	0.43
Thermal Conductivity (W/m-°C)	Comparative axial heat flow Electrolytic iron reference	25	37	36
		100	37	36
		300	36	35
Thermal Expansion Coefficient (µm/m-°C)	Pushrod dilatometry Platinum reference	25	11.0	11.0
		100	11.5	11.5
		300	12.0	12.0
Poisson's Ratio	ASTM E 132	25	0.26	0.26
		100	0.26	0.26
		300	0.27	0.27
0.2% Compressive Yield (MPa)	ASTM E 9 (medium length)	25	400	430
		400	300	370
Density (g/cc)	Displacement (750x25x25) mm	25	7.0-7.1	7.0-7.1
Brinell Hardness (BHN)	10mm diameter ball, 3000 kg load	25	183-235	192-255

A.4 Factors Influencing Material Properties

A.4.1 Graphite Morphology—Compacted graphite irons rarely consist of only compacted graphite particles. CGI typically contains a specified amount of nodular graphite. Within the range of 0 to 50% nodularity, increasing nodularity has a positive influence on the mechanical properties. However, as percent nodularity increases, the material's physical and operational properties, such as its castability, thermal conductivity, damping capacity and machinability, can be significantly reduced. Appendix B provides CGI microstructures rated by percent nodularity for comparative evaluations.

Flake-type graphite morphologies cannot be tolerated in CGI specified areas. Flake-type 'patches' may form in CGI due to under-treatment or fading of magnesium and result in significant reductions in the mechanical properties. The influence of graphite morphology on the tensile and yield strengths of pearlitic CGI is shown in Figure A2.

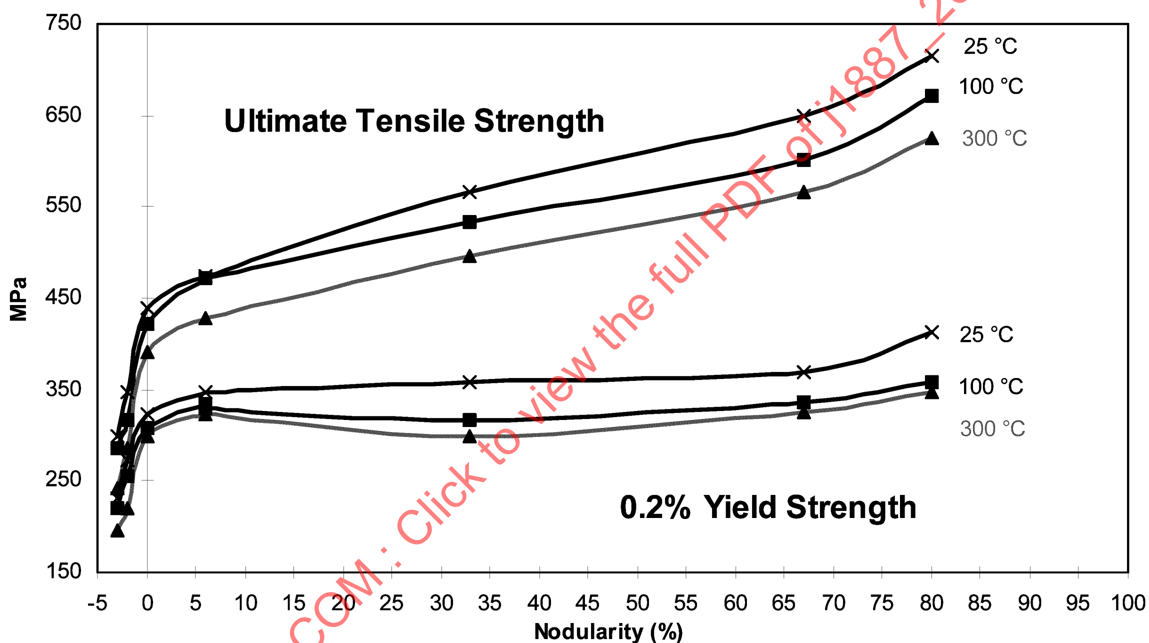


FIGURE A2—ULTIMATE TENSILE STRENGTH AND 0.2% YIELD STRENGTH OF 85 TO 100% PEARLITIC CAST IRONS AS A FUNCTION OF NODULARITY AND TEMPERATURE

NOTE— Negative % nodularity refers to the percent of the microstructure containing flake graphite wherein –5% represents a fully flake structure.

A.4.2 Matrix Structure—CGI solidifies with a ferritizing tendency similar to ductile irons. Pearlitic matrix structures can readily be obtained by alloying with conventional stabilizers such as copper and tin, although antimony, arsenic, chromium, manganese, molybdenum and vanadium have also been used. The influence of percent pearlite on the tensile and yield strengths of CGI is provided in Figure A3.

The use of pearlite stabilizers in compacted graphite iron results in 10 to 15% higher hardness (Brinell) than for gray irons with similar matrix structures. Thus, a 70% pearlitic CGI has approximately the same hardness as fully pearlitic gray iron.

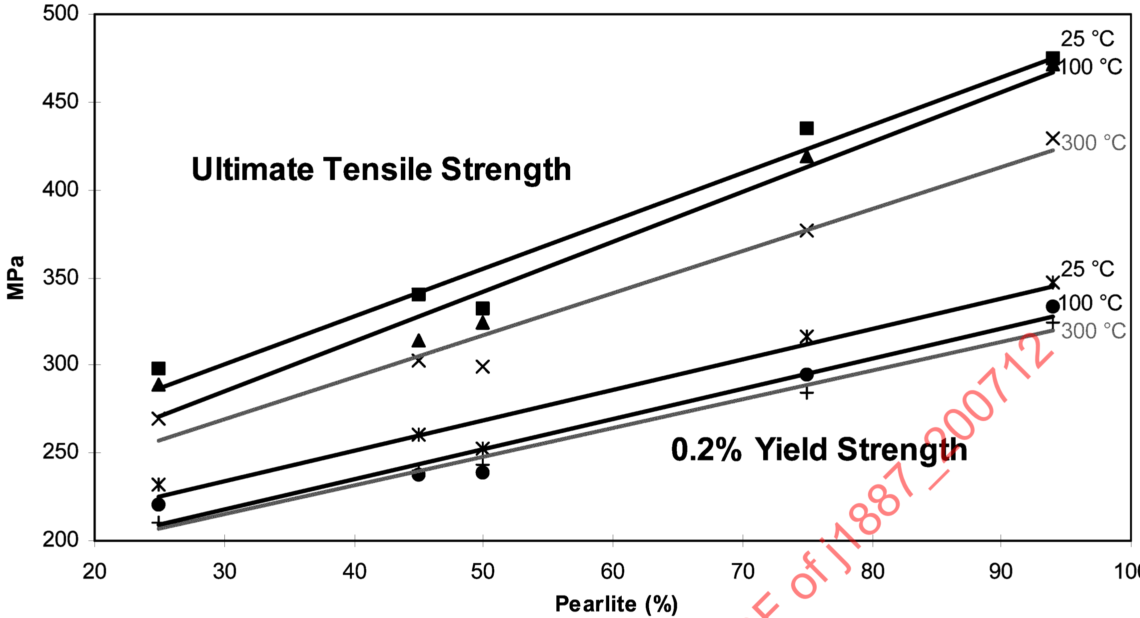


FIGURE A3—ULTIMATE TENSILE STRENGTH AND 0.2% YIELD STRENGTH OF 0 TO 10% NODULARITY CGI AS A FUNCTION OF PEARLITE CONTENT AND TEMPERATURE

A.4.3 CGI Composition—The carbon content and thus carbon equivalent (CE) of cast irons influences the size, shape and number of graphite particles. As such, CE is an important factor in determining mechanical and physical properties. In order to optimize castability it is generally beneficial to increase the carbon equivalent toward eutectic solidification. The strength of CGI decreases only slightly with increasing carbon equivalent. The relative loss of strength in CGI is more similar to ductile iron and significantly less than that of gray iron. A typical CGI composition is provided in Table A3.

TABLE A3—TYPICAL CGI COMPOSITION

Carbon Equivalent	Carbon	Silicon	Sulfur	Manganese	Phosphorus
4.20-4.60%	3.5-3.8%	2.0-2.6%	<0.025%	0.20-0.50%	<0.050%

Similar to gray and ductile irons, compacted graphite irons can be alloyed with a wide range of elements to optimize properties for a given application. Specific examples include Cr-Mo alloying for heavy-duty diesel engine cylinder heads, Si-Mo alloying for exhaust manifolds and P-B alloying for cylinder liners.

A.4.4 Section Sensitivity—The CGI microstructure is sensitive to changes in section thickness or, more specifically, to changes in solidification cooling rates. The solidification and cooling rates of CGI castings are primarily governed by section thickness, however, the local casting modulus (surface area-to-volume ratio) and the preheating of sand caused by flow-through of molten metal must also be considered. Within a casting, higher cooling rates promote the formation of smaller and more nodular graphite particles and finer pearlite. For example, depending on the production process, CGI containing 10% percent nodularity in thick sections (≥6mm) may simultaneously contain 30 to 60% nodularity in thin walls (≤4mm). The changes that can occur in the microstructure influence the mechanical and physical properties. Table A4 summarizes the typical increase in mechanical and physical properties of pearlitic CGI (at 25 °C) as a function of percent nodularity.

TABLE A4—MECHANICAL AND PHYSICAL PROPERTIES OF PEARLITIC CAST IRONS

Material Property	Percent Nodularity 10	Percent Nodularity 30	Percent Nodularity 50	Percent Nodularity 70	Percent Nodularity 90
Tensile Strength (MPa)	450	520	590	640	700
0.2% Yield Strength (MPa)	370	390	410	440	490
Fatigue Limit (MPa)	210	220	230	240	255
Elastic Modulus (GPa)	145	150	155	155	160
Elongation (%)	1-2	1-3	2-4	2-5	3-6
Thermal Expansion (µm/m-°C)	11.0	11.0	11.0	11.5	12.0
Thermal Conductivity (W/m-°C)	37	33	31	30	28

Section sensitivity can be reduced with changes in the iron chemistry, such as the addition of titanium. Although such actions can be taken to reduce the section sensitivity, in many cases the differential cooling rates can be advantageous. In engine blocks, for example, the higher percent nodularity in thin-wall areas such as the water jacket and crankcase housings and ribs provide increased strength and stiffness to the benefit of the product.

A.5 Machinability—The machinability of CGI is intermediate between that of gray iron and ductile iron. Specific machining results depend on the microstructure, the machining operation and the machining parameters (cutting speed, feed rate, insert material and insert geometry).

A.5.1 Effects of Graphite Shape—As the graphite changes from a flake to compacted morphology the increase in strength and the change from a brittle to a ductile fracture mode predominate in the reduced machinability of CGI. These effects dilute and/or mask the potential contribution of other factors. Relative to gray iron, tool life reductions of 50% in carbide tooling operations to >80% in PCBN turning operations have been observed. The inability to alter the compacted graphite shape without sacrificing the material properties limits the ability to improve the machinability of the CGI itself. For example, a CGI structure containing patches of flake graphite provides approximately 30% longer tool life than normal CGI, however the flake patch structure results in reduced mechanical properties.

Increasing percent nodularity from conventional CGI to the typical ductile iron ranges also results in further reduced machinability. In operations utilizing carbide tooling, low nodularity CGI has up to 2 times longer tool life. In PCBN turning studies, a 5% nodularity CGI had 40% longer tool life than a 50% nodularity iron and 3.5 times longer life than a 85% nodularity iron.

Given that CGI is inherently more difficult to machine than gray iron, every effort to reduce percent nodularity will contribute to the CGI tool life. For components requiring extensive machining, a conventional grade of CGI (0 to 20% nodularity) should be selected.

A.5.2 Effects of Pearlite—The machinability of iron castings decreases as the Fe_3C (cementite) content increases (pearlite spacing decreases). This factor may predominate in explaining foundry-to-foundry variations in CGI machinability.

Changes in pearlite content do not provide a quantum step toward making CGI machinability equal to gray iron. Depending on cutting tool materials and machining conditions (feed and speed) milling may improve with increasing pearlite while turning and/or boring become more difficult. The decision of optimal pearlite content will ultimately vary depending on the insert materials, cutting speeds and the need to alleviate specific machining bottlenecks.

A.5.3 Effects of Alloying Elements—Copper and tin are the preferred alloys for pearlite stabilization up to >95%. Further alloying with manganese, chromium or antimony to achieve a 100% pearlitic microstructure may reduce tool life by up to 50%, likely due to increases in the Fe_3C content of the pearlite that results from increasing these elements.

A.5.4 Elemental Effects—Titanium levels in cast irons are determined either by the raw materials or intentional alloying. Small amounts of titanium may be added to form hard, titanium carbonitride inclusions to improve the wear resistance of CGI. Larger amounts of titanium are sometimes used to assist in the control of the graphite morphology and/or section sensitivity. The presence of titanium can reduce machining tool life, compared to titanium-free CGI. This can be particularly important in the production of high volume castings that require extensive machining such as cylinder blocks and heads. In these applications titanium should be kept as low as possible to preserve CGI machinability. The titanium content may be less critical in low volume or lesser-machined castings such as exhaust manifolds that may require titanium for microstructure control.

Chromium is a potent pearlite stabilizer and carbide promoter in CGI. It should be restricted to trace levels for the optimal machining of CGI.