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Mixed graphite cast iron for automotive exhaust component applications

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Abstract: Both spheroidal graphite iron and compacted graphite iron are used in the automotive industry. A recently proposed mixed graphite iron exhibits a microstructure between the conventional spheroidal graphite iron and compacted graphite iron. Evaluation results clearly indicate the suitability and benefits of mixed graphite iron for exhaust component applications with respect to casting, machining, mechanical, thermophysical, oxidation, and thermal fatigue properties. A new ASTM standard specification (A1095) has been created for compacted, mixed, and spheroidal graphite silicon-molybdenum iron castings. This paper attempts to outline the latest progress in mixed graphite iron published.

Key words: SiMo iron; spheroidal graphite; compacted graphite; mixed graphite; exhaust components; brittleness at medium temperature; thermal fatigue cycles

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1 Introduction

Four groups of ferrous alloys are currently used for cast exhaust components [1,2]: Group 1 – ferritic high-silicon cast iron, Group 2 – austenitic high nickel iron (commonly referred to as Ni-resist), Group 3 – ferritic stainless steel, and Group 4 – austenitic stainless steel. Of the four groups, ferritic high-silicon molybdenum cast iron (SiMo) has the lowest cost of raw materials and manufacturing, and largest production volumes. SiMo iron typically contains 3.8wt.% to 4.8wt.% Si and 0.5wt.% to 1.5wt.% Mo. The microstructure of SiMo mainly comprises graphite, ferritic matrix and some Mo-rich precipitates. Conventional spheroidal graphite (SG) and compacted graphite (CG) SiMo irons are utilized by OEM's in Asia, Europe, and North America. A natural question arises: can cast iron with a microstructure between CG and SG bring an improvement in production and material properties? This type of microstructure is referred to as mixed graphite [3], but also has been known as low-vermicularity iron [4], or half SG iron or half CG iron [5].

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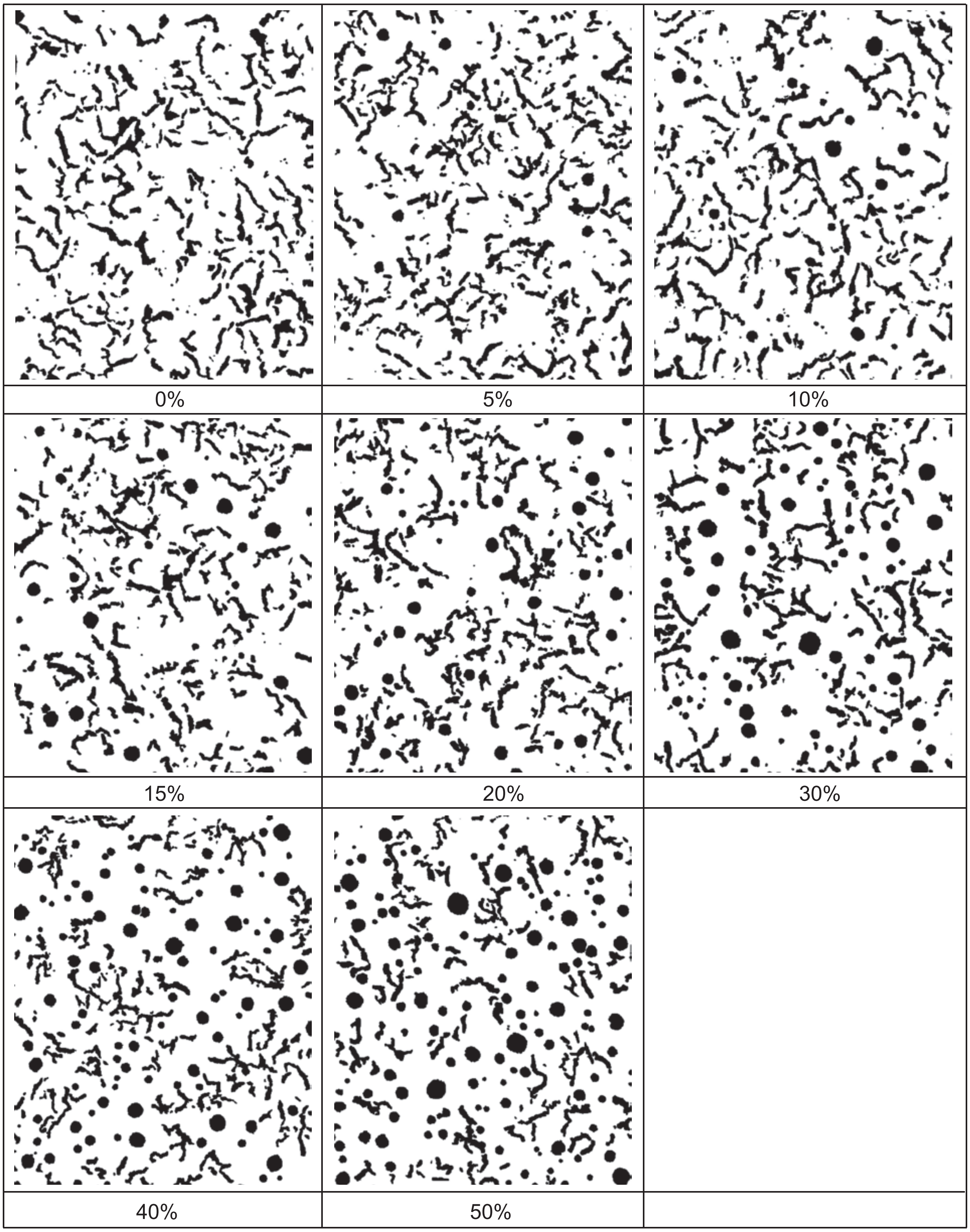
2 Microstructure of MG iron and misconceptions

Table 1 briefly lists some specifications of nodularity and vermicularity associated with the graphite morphologies, though the critical nodularity values can be slightly different among the documents. Figure 1 illustrates the full spectrum of graphite shapes from 0% nodularity (entirely CG) to 100% nodularity (entirely SG) [6,7]. The graphite rating chart of Fig. 1 was adapted from SAE document (from 0 to 50% nodularity) [6] and AFS book (from 50% to 100% nodularity) [7], respectively. The graphs from the two references [6, 7] appear to have different magnifications, graphite size or graphite count. Mixed graphite in the medium range of nodularity, i.e., from 40% to 70%, is not dominated by either compacted graphite or spheroidal graphite shape, as shown in Table 1 and Fig. 1. Assuming the sum of nodularity and vermicularity approaches to 100%, it is substantially free of flake graphite in microstructure. The microstructure borderline is not always distinct between CG and MG, and between MG and SG cast irons. Historically, there were misconceptions about MG iron such as scrap iron, degenerated graphite and incapable foundry process. MG iron can be defined in a similar way of CG and SG iron castings. It is a mixture of SG and CG in a certain ratio and has its graphite substantially in ASTM I, II, and IV, or ISO III, V, and VI forms, and is substantially free of deteriorated graphite

Table 1: Graphite nodularity and vermicularity specifications of CG, MG and SG iron

Specification	Nodularity (%)	Vermicularity (%)
General SG iron	> 80	-
General CG iron (ASTM A842 and China GBT/T 26655)	⩽ 20	⩾ 80
CG SiMo (ASTM A1095)	< 40	> 60
MG SiMo (ASTM A1095)	40 to 70	30 to 60
Low Vermicularity Cast Iron [4]	50 to 70	30 to 50



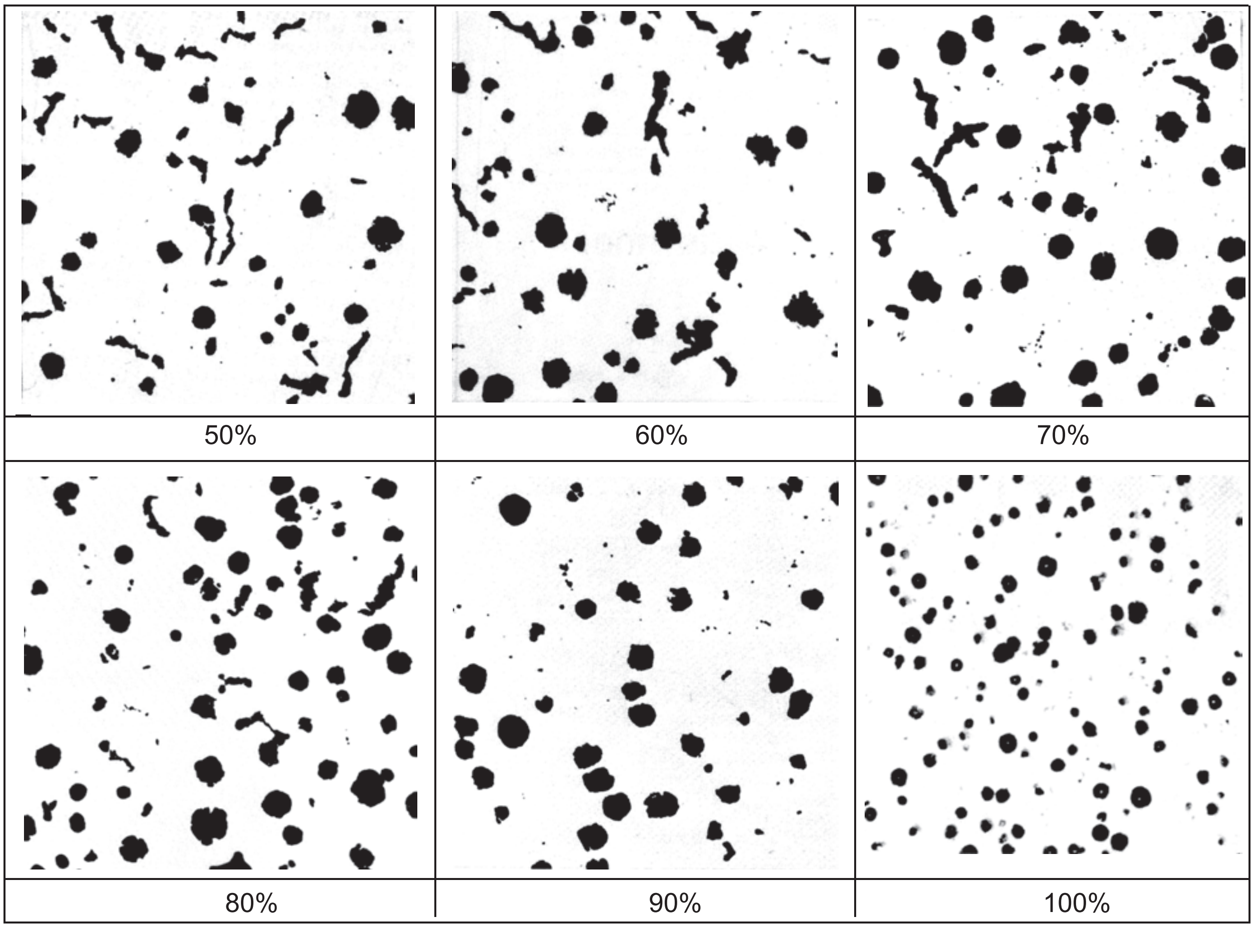


Fig. 1: Graphite shapes of cast iron with increasing nodularity from 0% to 100% [6,7]. ASTM A1095 for SiMo iron: CG with <40%, MG in a range of 40% to 70%, and SG with > 80%, nodularity.

shapes such as flake, exploded or crab graphite. The effect of graphite shape on SiMo iron has been extensively studied [3]. As such, a new ASTM standard A1095 has been developed for CG, MG, and SG SiMo iron castings.

3 Casting process of MG iron

Mixed graphite microstructure can be consistently achieved in a production environment by reducing the amounts of nodulizers or by the use of so-called vermicularizing reagents, as compared to SG or CG iron. Post inoculation practice was used by adding approximately 0.05% to 0.50% Fe-Si-based inoculant for SiMo iron castings. By contrast to conventional CG iron, MG iron does not require a high fraction of compacted graphite structure, which can eliminate the addition of anticompactizing elements such as Ti. As a result, there is a decreased tendency for inclusions, dross, Ti-induced defects, and machining issues. Zhao [4] and Jin [8] also observed that mixed graphite iron exhibited the optimum castability and mechanical properties for exhaust manifolds. Cooling curves of MG iron measured from 38-mm cube specimens are comparable with those of CG and SG samples. The liquidus temperatures measured (1,140 °C) are almost identical for CG, MG, and SG SiMo iron, mainly dependent on iron chemistry. As expected, MG occupies an intermediate position between CG and SG regarding the cooling curve recalescence, targeted carbon equivalent and section sensitivity of microstructure. Foundries having process capability for SG or CG iron should be capable of making MG iron castings.

4 Tensile properties

Table 2 presents some tensile testing results obtained by the present author. As expected, the elongation (E) at room temperature (RT) and 0.2% offset yield strength (YS) at RT and 425 °C increased with increasing the graphite nodularity. By contrast, the elongation at 425 °C displays a different trend (Table 2). Lower elongation was observed for SG and CG samples, while higher elongation for MG samples, tested at 425 °C. The minimum ductility at 425 °C for SG iron is referred to as the brittleness at medium temperature (BMT) which has long been known as a deleterious phenomenon [9]. One mechanism was suggested [9]: the BMT is caused by the grain boundary segregation of impurities, which can be the magnesium assisted sulfur segregation. Therefore, mixed graphite iron can be immune to BMT because of its moderate magnesium content. The BMT of SG iron can be alleviated by controlling

Table 2: Tensile testing results at RT and 425 °C of CG, MG, and SG SiMo iron samples

Nodularity(%)	E (%)		YS (MPa)	
	RT	425 °C	RT	425 °C
30 (CG)	3.0	3.0	450	360
50 (MG)	8.0	8.0	480	380
70 (MG)	10.0	6.0	500	390
90 (SG)	14.0	2.0	510	395

the residuals of sulfur and magnesium with a certain level of phosphorous [10]. For CG iron, however, the low elongation at both RT and 425 °C is not caused by the impurities of sulfur and magnesium, but rather by low graphite nodularity.

5 Thermophysical properties

Thermophysical properties, especially thermal conductivity, coefficient of thermal expansion (CTE), and Ac1 temperature (the onset of phase transformation from ferrite to austenite upon heating) of cast iron are critical to exhaust component applications. There are a few methods of measuring thermal conductivity of cast iron. In this work, thermal diffusivity (α) was measured using the laser flash technique (ASTM E1461). Bulk density (d) values were calculated from the sample's geometry and mass. Specific heat (C_p) was measured using differential scanning calorimeters. Thermal conductivity (λ) values were calculated as a product of these quantities, i.e., $\lambda = \alpha d C_p$. Figure 2 illustrates the thermal conductivity of SiMo samples measured in this work. SG SiMo data of standard SAE J2515 [11] are included in Fig. 2. The thermal conductivity data of SiMo iron agree between this work and SAE standard. Figure 3 is plotted from Ref. [4] of approximately 2.5% Si iron in which the measurement method could be also different from the above-mentioned laser flash technique. There are variations in the thermal conductivity in the published documents. Figures 2 and 3 are presented to illustrate the trend of thermal conductivity as a function of temperature and graphite shape, instead of the absolute values of thermal conductivity. When temperature is below 500 °C, the thermal conductivity is increased with lowering the graphite nodularity. When temperature exceeds 500 °C, the thermal conductivity is comparable among CG, MG, and SG iron samples (Fig. 3).

The coefficient of thermal expansion was measured using a dilatometer. The measured CTE of CG, MG, and SG SiMo samples is presented as a function of temperature in Fig. 4. As is known, CTE is mainly influenced by the matrix structure, not by the percentage of graphite nodularity or vermicularity. The phase transformation temperature, Ac1, of cast iron is mainly dependent on the chemistry, instead of graphite morphology. The Ac1 temperature greatly increases with increasing silicon, chromium, and aluminum contents in cast iron.

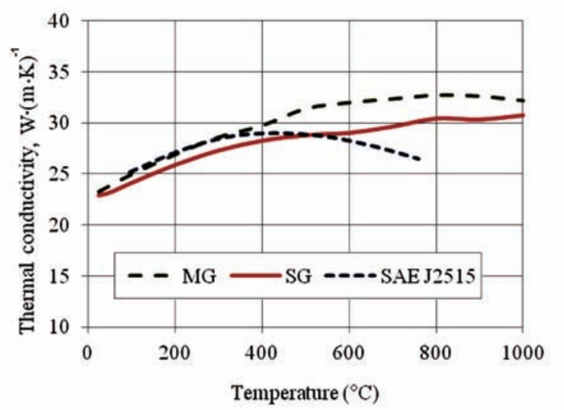


Fig. 2: Thermal conductivity of SiMo iron as a function of temperature

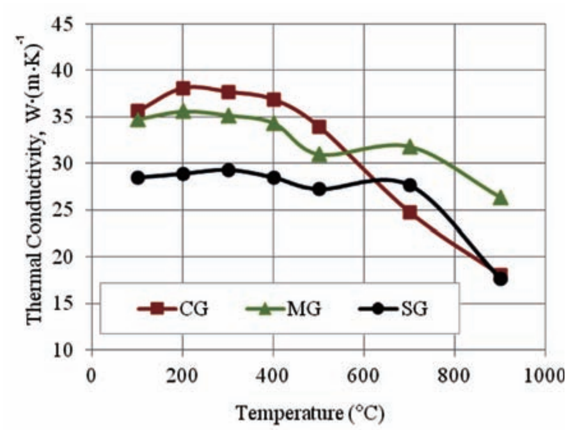


Fig. 3: Thermal conductivity of cast iron plotted from Ref [4]

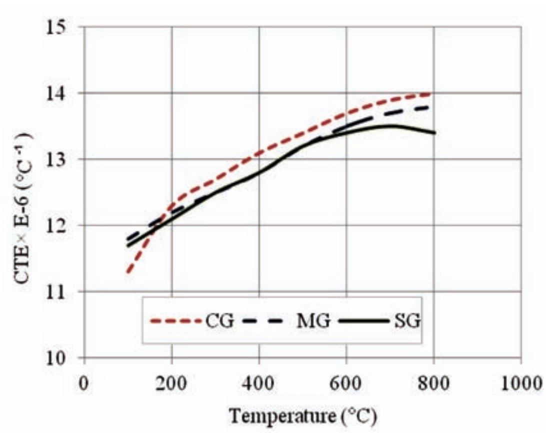


Fig. 4: Coefficient of thermal expansion (CTE) of CG, MG, and SG SiMo samples

6 Oxidation resistance

High temperature oxidation of SiMo iron has been tested in an earlier study [3]. Table 3 briefly characterizes the oxidation behaviors of CG, MG, and SG SiMo iron samples through both static and cyclic oxidation testing performed over the past few years. More weight changes were observed for CG samples than SG samples. There was severe internal oxidation for CG samples because of the interconnected graphite structure, but less external oxide scale formation. For the SG samples, an opposite trend was observed: thicker external oxide scales built up, but much less weight change and internal oxidation damage occurred. The MG samples exhibited hot oxidation behavior intermediate between that of CG and SG irons.

Table 3: Brief summary of hot oxidation behaviors of CG, MG and SG SiMo samples

Iron type	Weight change	External scale	Internal oxidation	Scale adherence
CG	More	Thinner	More	Stronger
SG	Less	Thicker	Less	Weaker
MG	Intermediate between CG and SG			

7 Thermal fatigue life

Two types of cyclic thermal fatigue testing can be performed using products such as exhaust manifolds or turbo housings, and cylindrical or disc specimens. For the former, engine exhaust simulator (EES) testing has been developed at Wescast Industries Inc. for evaluating the thermal durability of exhaust components, as shown in Fig. 5. EES testing makes use of natural gas burners and positive displacement blowers. The thermal cycling profiles in EES testing include heating/cooling rates, peak/valley temperatures and holding time. The cycles to failure determined from EES testing were expressed as the manifold durability. Like other thermal fatigue testing, EES testing was subject to some scatter even under the same testing conditions. However, results to date show MG iron parts demonstrated equal or better EES performance than CG and

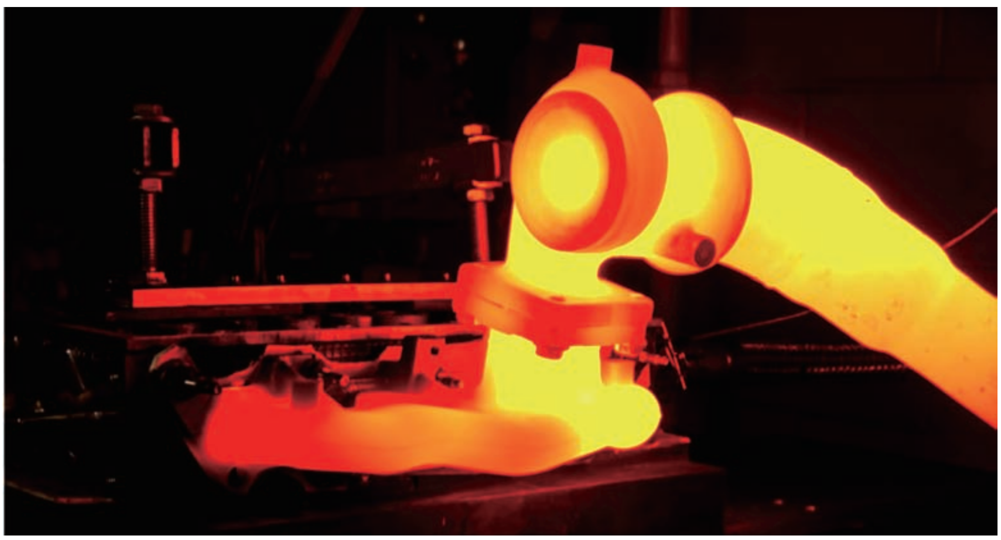


Fig. 5: Engine exhaust simulator (EES) testing taken from www.wescast.com

Table 4: Results of EES testing on SiMo iron exhaust manifolds

Product type	Maximum EGT[a]	EES thermal cycles to failure		
		CG	MG	SG
A	950 °C	150	270	190
B	950 °C	250	330	265
C	900 °C	1,140	1,575	-
D	900 °C	945	1,335	-
E	880 °C	-	2,017	1,800
F	880 °C	-	2,900	2,287

[a]EGT denotes exhaust gas temperature

SG iron parts, as presented in Table 4. The thermal fatigue resistance of SG iron was lowered with increasing magnesium content [10]. This may explain why MG SiMo had higher EES cycles than SG SiMo. MG iron had similar levels of magnesium residuals but improved ductility and strength, as compared with CG iron. As a result, MG SiMo outperformed CG SiMo iron in EES and other testing. It should be pointed out that CG, MG, and SG irons may have a different application scope in terms of product geometries and engine requirements.

Table 5 lists some data of thermal fatigue testing using cylindrical or disc specimens [4,5,8]. Figure 6 is plotted from Table 5. Again, MG samples show comparable or better thermal fatigue life than conventional CG and SG samples. In addition to exhaust component applications, MG iron can provide an opportunity to produce cast iron engine cylinder blocks, head, liners, and brakes, with cost saving and performance improvements. There is large-scale production of mixed graphite SiMo iron castings [4,8].

Table 5: Thermal cycles to cracks of cast iron specimens [4,5,8]

Testing conditions	Thermal cycles to cracks		
	CG	MG	SG
250 – 700 °C	1,200	1,250	1,100
	1,300	1,900	1,400
	1,650	1,800	1,800
250 – 900 °C	460	680	620
	640	660	550
	450	640	640

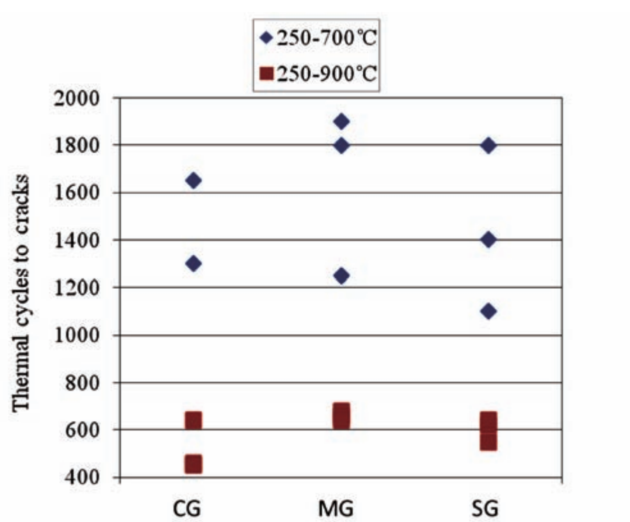


Fig. 6: Thermal cycles to cracks of CG, MG, and SG iron samples plotted from Table 5

8 Summary

Comparative evaluations of compacted graphite, mixed graphite and spheroidal graphite irons have been extensively performed. MG iron has shown marked improvements over conventional SG iron and especially CG iron with titanium additions, in the aspects of casting process, machinability, ductility at medium temperature, oxidation resistance, and thermal fatigue property. A new ASTM standard A1095 has been created for CG, MG, and SG SiMo iron castings.

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