

Preliminary Evaluation of a Low-Cost Cast Iron for Exhaust Manifold and Turbocharger Applications

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ABSTRACT

Exhaust manifolds and turbocharger housings require good elevated temperature strength, good resistance to thermal fatigue and a stable microstructure. High silicon ductile iron, high silicon-molybdenum ductile iron and Ni-resist (a high nickel ductile iron) are the cast materials of choice. Unfortunately, molybdenum and nickel are expensive. In this study, a lower cost, high silicon-titanium, compacted graphite iron was developed and compared to high silicon ductile iron and higher cost, high silicon-molybdenum ductile iron. Room and elevated temperature strength data is presented.

INTRODUCTION

Increasing the fuel economy of automobiles continues to be an important concern for the auto industry in order to both reduce CO₂ emissions and also reduce the cost of vehicle operation. One way to increase engine efficiency is to raise the maximum operating temperature of the automobile's engine. For internal combustion engines to function properly at elevated temperatures, special materials must be selected that can withstand the rigorous environment. High silicon-molybdenum ductile iron is one material currently used in high temperature automotive applications including turbocharger housings and exhaust manifolds. For low alloy ductile irons, the mechanical properties begin to decrease rapidly when temperature exceeds about 300-350°C. A plot of tensile strength versus temperature is shown in Figure 1. Alloying a cast iron with 4% or more silicon and 0.5-1.0% molybdenum can raise the use temperature to as high as 850°C [1]. The drop in mechanical properties in low alloy cast iron is primarily due to four factors: creep, thermal fatigue, oxidation and microstructural instability.

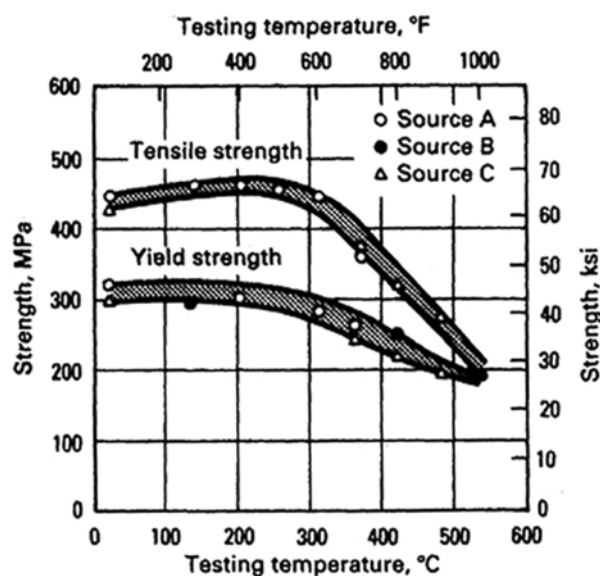


Figure 1. Plot showing the strength of cast iron as a function of temperature. Strength remains relatively constant up to 300-350°C and then decreases rapidly with increasing temperature. Used with permission from ASM [2].

Alloying a cast iron with 4 wt% or more silicon has been shown to greatly improve resistance to thermal fatigue [1]. Since iron is prone to oxidation at elevated temperatures, silicon is added to form a Si rich layer at the surface, which significantly reduces the oxidation rate [1,2]. The microstructural stability of cast iron is also improved with additions of Si. Two microstructural features can affect the performance of cast iron; pearlite decomposition and the α to γ phase transformation. Pearlite can decompose at temperatures below the α to γ phase transformation if held for a long enough time and may decompose and reform when cycled through the α to γ phase transformation.

Decomposition and reformation cause volume expansions and contractions, which are undesirable for a part in service. Silicon suppresses the formation of pearlite and promotes the formation of ferrite. A detailed discussion of the microstructural stability in high Si and high Si-Mo ductile irons was published in 2002 [3]. Also, unalloyed cast iron undergoes the α to γ phase transformation at approximately 727°C. This phase transformation produces a significant volume contraction upon heating and a significant volume expansion upon cooling, which are undesirable for a part to experience in service. The addition of Si raises the transformation temperature. At 4-5wt% Si, the transformation temperature is increased to 800-950°C [2]. The effect of Si content on the transformation temperature of cast iron is shown in Figure 2. Although alloying with Si helps prevent three of the four factors that reduce the high temperature properties of cast iron, Si does not have a significant effect on creep resistance.

<figure 2 here>

Creep is an elevated temperature phenomenon in which materials experience time dependent strain when being held at stresses below the yield strength of the material. The movement of dislocations plays a crucial role in creep and, at elevated temperatures ($> 0.5 T_m$), the thermal energy is high enough to allow dislocation motion to occur at reasonably high rates. Therefore, creep becomes an important design consideration for material selection at elevated service temperatures [4]. Adding small amounts of molybdenum (1-2wt%) to cast iron results in the formation of small carbides at the grain boundaries, Figure 3. These carbides act to slow the movement of dislocations and pin grain boundaries, thus reducing the effects of creep phenomena such as diffusional creep and grain boundary sliding, thus improving elevated temperature strength. Although, Mo is effective in increasing the creep resistance of cast iron, it is also expensive (approximately \$36.00 per lb). There are many elements that could be substituted for Mo, but each has unique problems. One of these elements is titanium.

<figure 3 here>

Titanium is a very strong carbide former. Since carbides can improve creep resistance and titanium costs about 90% less than molybdenum (approximately \$3.85 per lb), substituting an equal amount of Ti for Mo could reduce casting cost by more than 0.16 to 0.33 \$ per lb. However, Ti prevents the formation of graphite nodules [5]. The effect Ti has on the ability to form nodular graphite can be seen in Figure 4. A comparison of the microstructures of high Si-Mo ductile iron with a high percent nodularity and a cast iron with Ti in place of Mo with a low percent nodularity (high Si-Ti compacted graphite iron) is shown in Figure 5.

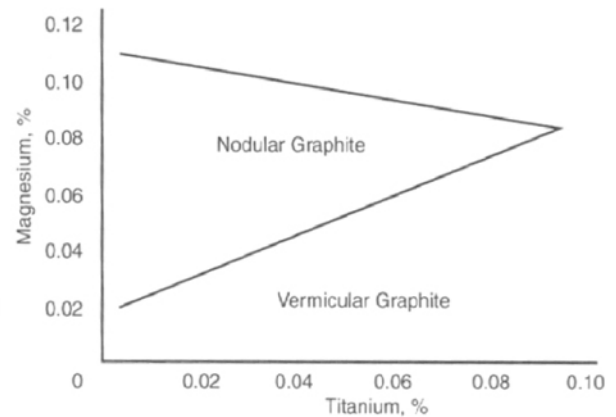


Figure 4. Plot showing the effects of Ti and Mg additions on the formation of nodular graphite. Used with permission from Rio Tinto [5].

One drawback of high nodularity ductile irons is that they have relatively low thermal conductivity, which may lead to localized hot spots. By adding Ti and reducing the nodularity, a compacted graphite iron (CGI) is formed. The vermicular graphite morphology present in CGI results in higher thermal conductivity and the effect of localized hot spots will be reduced. The thermal properties of various grades of cast iron are shown in Table 1.

Table 1. Thermal Conductivity of Gray Iron and Compacted Graphite Iron [6].

Cast Iron Thermal Conductivity [W/(m*K)]	
Gray Iron	45-52
CGI (100% pearlite)	35-40
CGI (70% pearlite)	37-43

Due to the difference in the graphite morphology, titanium has never been considered as a viable replacement for Mo in ductile irons. However, in recent years, high Si-Mo compacted graphite iron has become a specified alternative to high Si-Mo ductile iron in Europe (Volkswagen AG, specification VW 50021). Therefore, the use of titanium in place of molybdenum is now a possibility.

<figure 5 here>

The purpose of this investigation was to examine the possibility of using titanium additions in place of molybdenum in cast iron to obtain the necessary high temperature properties. If successful, the resulting material, high Si-Ti compacted graphite iron, could become a less expensive alternative to the high Si-Mo cast irons currently used in turbocharger housing and exhaust manifolds.

EXPERIMENTAL METHODS

To determine if high Si-Ti compacted graphite iron is a viable alternative to high Si-Mo ductile iron, the mechanical properties of five experimental chemistries with Ti contents ranging from 0.28-0.63 wt% were evaluated. Seven 32 kg (70 lb) heats were prepared for this study using low carbon steel punchings, graphite and 99% SiC. No returns or pig iron were used. With the exception of Heat No. 5, titanium in the form of 70% ferro-titanium was added to the furnace during melting. In Heat No. 5, the titanium addition was made during treatment in order to observe the effects of late addition on the formation of titanium carbide particles. In addition to these high Si-Ti castings, a 4.5 wt% Si ductile iron and 4.4 wt% Si-0.84 wt% Mo ductile iron were also cast and evaluated. For the molybdenum containing iron, 60% ferro-molybdenum was added to the furnace. The carbon and silicon contents of the base iron were determined using an Electro-Nite QuiK Cup containing tellurium. The irons were treated using the sandwich treatment method with a 1.5% addition of 5% Mg-Fe-Si covered with a 1% addition of foundry grade 75% FeSi containing 0.8% Ca and 1.0% Al, a 0.5% addition of Barinoc and 1 kg (2 lbs) of cover steel. Tap temperatures were 1510-1540°C (2750-2800°F). Pin and chilled disk samples for chemical analysis were taken from the furnace before adding the Ti additions, after the titanium additions and from the pouring ladle after Mg treatment. Carbon and sulfur content were determined using a Leco C/S analyzer and the other alloying elements were determined using an optical arc-spark spectrometer. The actual chemistries for the seven experimental heats are listed in [Table 2](#). Y-blocks were poured at 1370-1425°C (2500-2600°F) for all seven of the experimental heats. Shake-out time was one hour.

<table 2 here>

After casting, samples were heat treated in the following manner to produce a fully ferritic, low residual stress condition:

1. Heat to 900-950°C at a rate of 300°C per hour maximum. The slow heating rate avoids creating residual stress and part distortion.
2. Soak at 900-950°C for 1-3 hours.
3. Cool to 760-630°C at a rate of 175°C per hour maximum.
4. Soak at 760-630°C for a minimum of 2 hours. This precipitates molybdenum carbide at the grain boundaries to improve creep strength and reduces the percentage of pearlite in the microstructure to <5%.
5. Cool to 630-570°C at a rate of 60°C per hour maximum.
6. Cool to 290-230°C at a rate of 200°C per hour maximum.
7. Air cool to room temperature. Maximum cooling rate was 200°C per hour to avoid creating residual stresses.

This heat treatment cycle took 24 hours to complete. A thermocouple was attached to one of the cast samples to track the actual time-temperature profile during heat treatment. The actual time-temperature profile for the castings evaluated in this study is shown in [Figure 6](#).

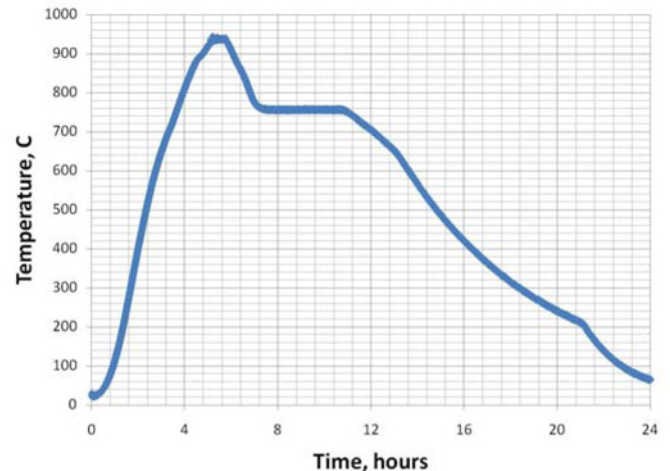


Figure 6. Actual time-temperature data for the heat treatment of the high Si-Ti, high Si, and high Si-Mo cast irons evaluated in this study.

Mechanical testing included Brinell hardness testing (3000 kg load), room temperature tensile testing and elevated temperature tensile testing performed at 425°C, 550°C and 625°C. The elevated temperature tensile testing was performed at Westmoreland Mechanical Testing & Research, Inc. The microstructures of these castings were examined using an optical light microscope to determine the percentage of ferrite & pearlite, graphite morphology & nodularity and the amount of carbides present. Nodularity by area was determined using sphericity as the critical shape factor. Twenty-five fields of views were used to determine nodularity and a sphericity of greater than or equal to 0.55 was used to classify a graphite particle as a good nodule.

RESULTS AND DISCUSSION

The high Si-Ti CG irons produced in this study met the requirements of the Volkswagen AG 50021 specification for high Si-Mo compacted graphite iron but did not meet the required mechanical properties of the high Si-Mo ductile iron specifications. The results of the mechanical testing are presented in [Tables 3 & 5](#).

<table 3 here>

The room temperature tensile strength of the high Si-Ti CG irons poured in this study typically met the minimum tensile and yield strength requirements of the high Si-Mo ductile iron specifications and well exceeded the minimum requirements for high Si-Mo compacted graphite iron. The

limited elongation resulting from the vermicular graphite morphology prevented the high Si-Ti CG iron from meeting the minimum elongation requirements for high Si-Mo ductile iron. The microstructure of the high Si-Ti CGI castings are shown in [Figure 7](#). A higher than expected amount of nodular graphite (42%) was present in the 0.28 wt% Ti material (the lowest titanium addition). This level of nodularity was unexpected because the literature suggested that nodularity should be extremely low when the titanium level exceeded 0.1 wt% [5]. Due to the high nodularity, the 4.3 wt% Si-0.28 wt% Ti CG iron had an elongation of 5.1% and fully met the Volkswagen AG 50021 specification for high Si-Mo ductile iron. As the titanium contents increased the nodularity decreased as expected with the exception of the 4.6 wt% Si-0.41 wt% Ti CGI, which had a “late” titanium addition (titanium added to the iron during treatment). The late addition of Ti in the 4.6 wt% Si-0.41 wt% Ti CGI resulted in a higher nodularity of 64%. The 4.7wt% Si-0.63 wt% Ti CG iron (the highest titanium addition) had a graphite morphology that was predominantly vermicular, with a nodularity of only 22%, which reduced the elongation to 3.2%. The microstructure of the high Si iron (4.5 wt% Si and 4.4) and high Si-Mo iron (4.4wt% Si-0.84 wt% Mo) were also examined and are shown in [Figure 8](#). Both the high Si and high Si-Mo irons had greater than 80% nodularity and could therefore be classified as ductile irons. The nodularity of the high Si ductile iron was significantly less (80%) than the nodularity of the high Si-Mo ductile iron (93%). The high Si ductile iron was poured directly after the high Si-Ti heats and had a slightly higher amount of Ti (0.02 wt%) than the high Si-Mo ductile iron (0.01wt%). The lower nodularity of the high Si ductile iron could partially be attributed to a higher Ti content. Due to the high nodularity of the high Si and high Si-Mo ductile irons, they possessed significantly higher room temperature tensile elongations than the compacted graphite iron castings. The measured nodularity for all seven heats is listed in [Table 4](#).

<[figure 7](#) here>

<[figure 8](#) here>

Table 4. Measured nodularity for all seven experimental heats.

	Nodularity (Percent)
4.3% Si-0.28% Ti	42
4.3% Si-0.37% Ti	37
4.6% Si-0.41% Ti	64
4.4% Si-0.50% Ti	27
4.7% Si-0.63% Ti	22
4.5% Si	80
4.4% Si-0.84% Mo	93

<[table 5](#) here>

The elevated temperature strength of the high Si-Ti CG iron castings were slightly lower compared to high Si ductile iron and significantly lower compared to high Si-Mo ductile iron, [Table 5](#). Compacted graphite irons are expected to have lower strength and lower tensile ductility compared to ductile irons of the same hardness due the graphite morphology (shape). In this study, it was determined that the elevated temperature tensile strength of the high Si-Ti CG irons were only 1-9 MPa (1-9%) lower than high Si ductile iron and 23-31 MPa (20-26%) lower than high Si-Mo ductile iron at 650°C. The high Si-Ti CG irons had surprising close elevated temperature strength compared to high Si ductile iron, which indicated that the titanium carbide particles were contributing to improve high temperature strength. However, the high Si-Ti CG iron was well below the properties of the high Si-Mo ductile iron, which indicated that the titanium carbide particles did not contribute as much to elevated temperature strength as the molybdenum carbide particles. This is most likely due to the size, distribution and location of the titanium carbide particles; large, faceted, titanium carbide particles were apparent in the microstructure, [Figure 9](#).

<[figure 9](#) here>

A late titanium addition (ferro-titanium added to the treatment ladle) did not significantly decrease the size or increase the number of titanium carbide particles. Two similar iron chemistries were prepared (4.3 wt% Si- 0.37 wt% Ti and 4.6 wt% Si-0.41 wt% Ti) and titanium was added to the melting furnace for one and in the treatment ladle for the second. It was postulated that a “late” titanium addition may result in smaller and more numerous carbide particles. Whereas there was a difference, the difference did not appear to be significant. The microstructures of the 4.3 wt% Si- 0.37 wt% Ti CG iron and the 4.6 wt% Si-0.41 wt% Ti CG iron with titanium added to the treatment ladle are shown in [Figures 9](#) and [10](#), respectively.

The addition of titanium produced similar elevated temperature tensile strength compared to high silicon ductile iron. In general, compacted graphite irons have lower tensile strengths compared to ductile irons due to the difference in graphite morphology. This finding is significant since a compacted graphite iron should have higher thermal conductivity compared to a nodular iron. Almost no data for the elevated temperature tensile properties of high silicon, compacted graphite iron could be found in the literature.

<[figure 10](#) here>