High Temperature Cast Iron Materials for Exhaust Components

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Abstract: Ductile iron (DI) is a cast ferrous alloy that can be used for engine components. Several DI grades were tested, including ASTM A439 D5S, SiMo 5-1, SiMo with Vanadium additions (SiMo+V), and SAE J2582. A SiMo 5-1 alloy was designed and cast in the SMART Foundry in Lambertus Hall. This study determined the oxidation resistance of various grades of DI through oxidation testing at 760°C and 850°C for 500 hours and observing the change using microscopy techniques. SiMo+V had the smallest oxide growth at 760°C and ranked second to ASTM A439 D5S at 850°C. At both temperatures, ASTM A439 D5S experienced significant spallation of the positive oxide layer.

This work is sponsored by Caterpillar, Lafayette, IN

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Background

Caterpillar Engines – Exhaust Systems
- Used in stationary systems and class 9 vehicles
- Sustained and cyclic high temperatures
- DI is common for high stress and therma exposure [1]

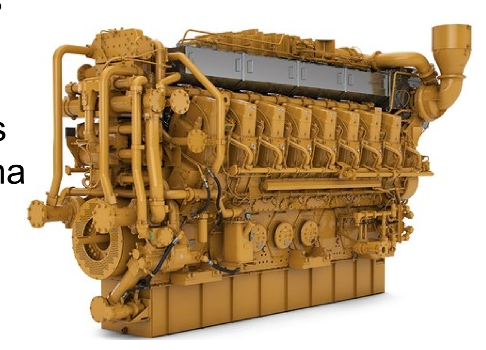

Figure 1. CAT G3600 Engine.

Ductile Iron
- Strong, ductile, unique microstructure
- Commonly have a ferritic or austenitic matrix
- Different grades of DI control oxidation through carbide production, eutectic adjustments, and matrix transition temperatures [2]
- Ni promotes an austenitic matrix
- Mo, Si, and V form carbides

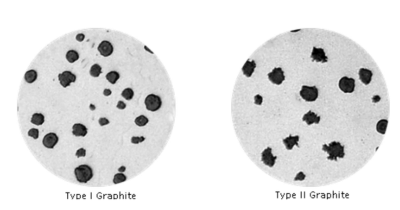

Figure 2. Graphite nodule morphology characteristic to DI. [3]

Oxidation
- Oxidation is expected to follow a logarithmic growth with active and passive layer formation over time [4]
- Layer growth is expected to level off with time - "protective oxide"
- Although most oxidation is expected in the first 500 hours, industry standard test for new material validation is 1,000 hours [4, 5]

Objectives
- Evaluation and characterization of four high temperature cast iron materials (ASTM A439 D5S, SiMo 5-1, SiMo+V, SAE J2582) to understand material properties and process impacts on castings for gas engine applications
- Compare oxidation resistance between as-cast and machined surfaces
- Design of a SiMo 5-1 alloy to be cast in the Caterpillar SMART Foundry in Lambertus Hall

Materials & Methods

Materials
- Materials studied include Ni-based ASTM A439 D5S, SiMo+V, SiMo 5-1, and SAE J2582

Table 2. Material composition of three of the materials studied, balanced with iron [6, 7, 8].

Grade	C (wt%)	Si (wt%)	Mn (wt%)	Mo (wt%)	V (wt%)	Cr (wt%)	Ni (wt%)
SiMo 5-1	-	4.80 - 5.20	-	0.80 - 1.10	-	-	-
SiMo+V	3.20 - 3.80	4.00 - 5.00	-	0.75 - 1.20	0.60 max	-	-
ASTM A439 D5S	2.00 Max	4.00 - 6.00	0.50 - 1.50	-	-	1.50 - 2.50	34.00 - 36.00
SAE J2582	3.00 - 3.80	3.50 - 4.50	0.10 - 0.50	0.51 - 0.70	-	-	-

Homogenization Treatment
- To reduce microsegregation in the castings, all bars were homogenized in Carbolite furnace

Table 3. Heat treatment schedules, cooled in air.

Type	Soak Time	Soak Temperature	Cooling Rate	Cool to
SiMo 5-1	1 hr	770 - 820°C	~102 minutes	650°C
SiMo+V	2 hr	771 - 820°C	~102 minutes	650°C
ASTM A439 D5S	1 hr	620 - 650°C	~102 minutes	310°C
SAE J2582	4 hr	790°C	~80 minutes	370°C

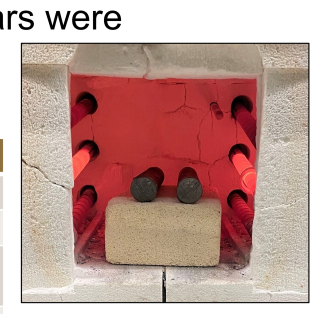

Figure 1. Homogenization Treatment of Bars.

Sectioning
- Bars were sectioned after heat treat to create samples for oxidation and tensile testing

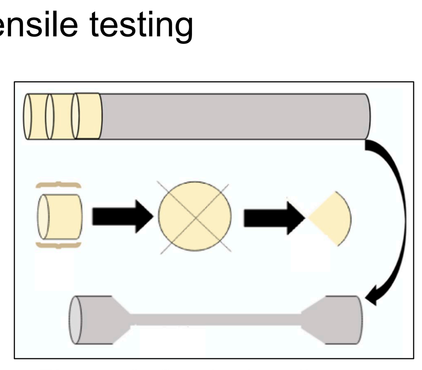

Figure 2. Sectioning diagram.

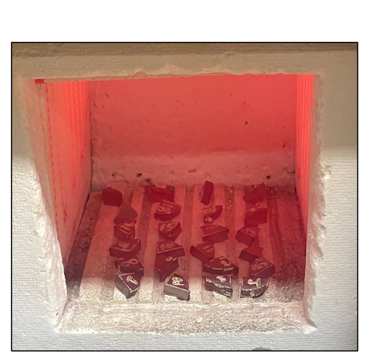

Figure 3. Oxidation Testing.

Oxidation Testing
- Oxidation formation was tested at 760°C and 850°C in air using a Thermo Scientific furnace
- Oxidation tests were conducted for about 500 hours each to capture the majority of oxidation growth
- Each sample was weighed and measured with calipers before and after oxidation testing

Scanning Electron Microscopy (SEM) & Elemental Analysis (EDX)
- Each sample was mounted in epoxy or Bakelite and polished using a Buehler Automet 250 autopolisher
- SEMs used: Apreo 2s at HARF and Whistler, and a Teneo Volumescope at Whistler
- Elemental analysis conducted on the Apreo 2s at Whistler. For EDX samples were sputter coated with a 10 nm layer of Platinum

Metallography
- Samples were repolished for optical imaging using a Leco polishing wheel and 3 µm diamond paste
- 2% Nital was used to etch for 10 seconds
- Images taken using an Olympus BX41M optical microscope

Discussion & Results

Oxidation Testing Results

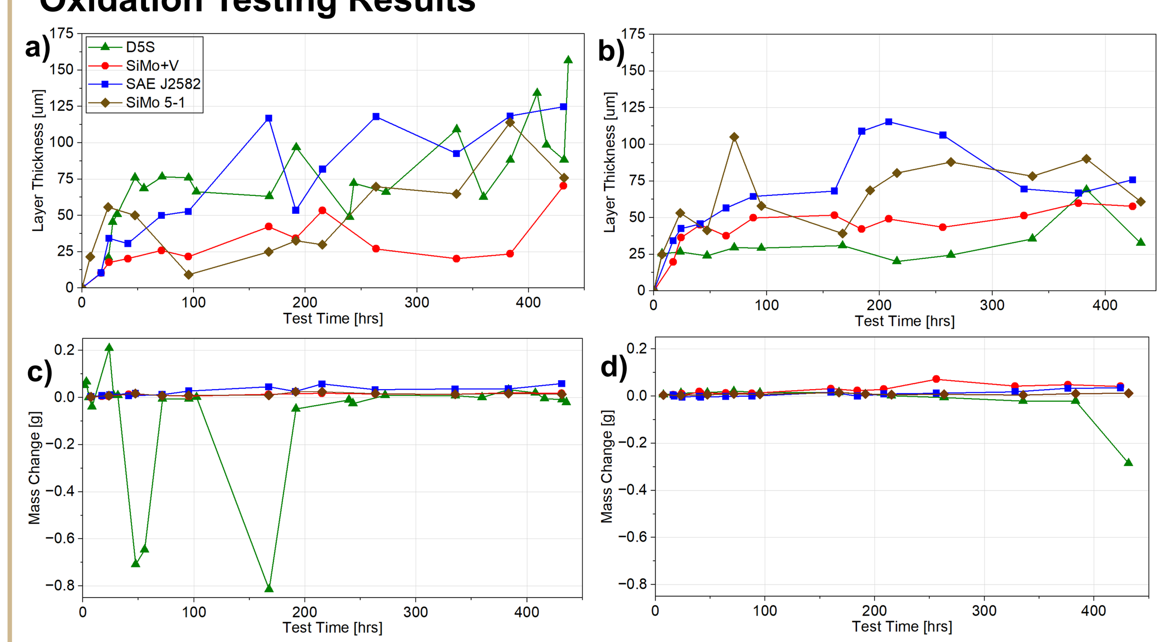

Figure 3. Oxidation testing results over time including negative layer thickness at a) 760°C and b) 850°C and mass change at c) 760°C and d) 850°C.

- Negative oxide layer growth over time for the cast surface of each alloy is graphed in Fig. 3. Using a T-test, there was no statistically significant difference in the oxide layer thickness between the cast and cut surface of ASTM A349 D5S at 760°C and J2582 and SiMo 5-1 at 850°C

Scanning Electron Microscopy

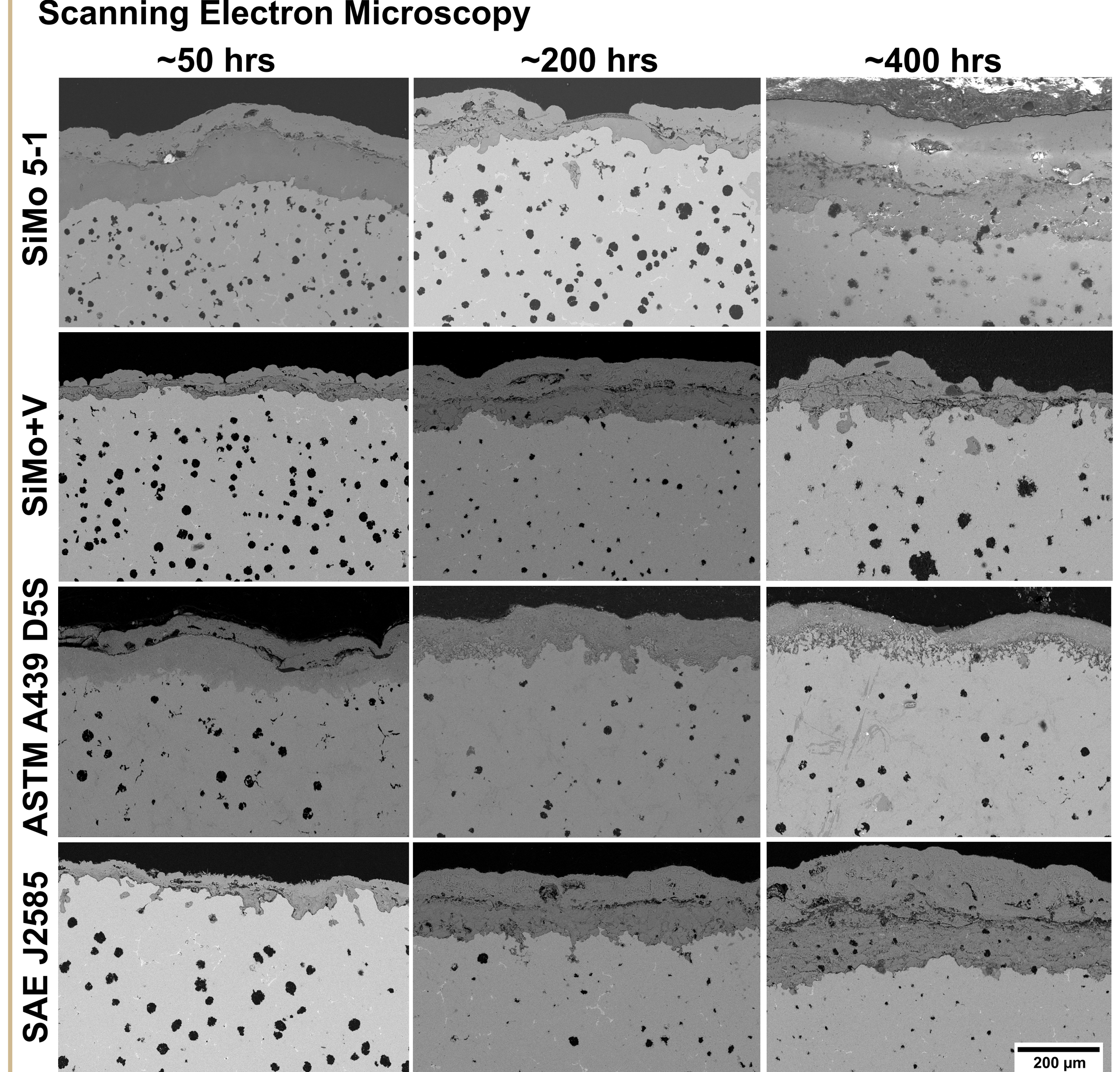

Figure 4. Oxide layers on the cast edge of SiMo 5-1, SiMo+V, ASTM A439 D5S and SAE J2582. Tested in air at 760°C. Spallation occurred on ASTM A439 D5S samples so only the negative layer is visible at ~200 hrs and ~400 hrs.

Elemental Analysis

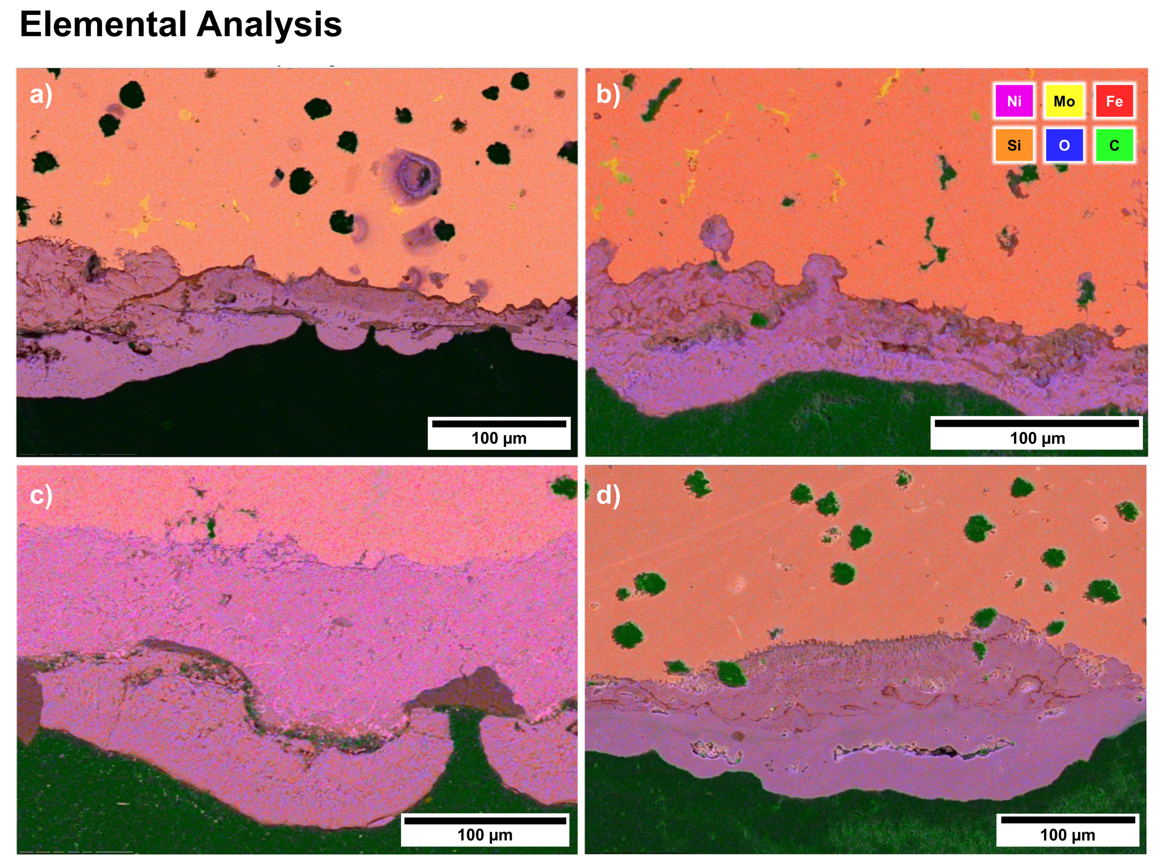

Figure 5. EDX maps of the cast surface oxide layers of a) SiMo 5-1, b) SiMo+V, c) ASTM A439 D5S and d) SAE J2582 at ~95 hrs in an oxidation test in air at 760°C.

Table 4. Composition of the negative oxide layer of the cast surface of four alloys after ~95 hrs at 760°C.

Element	SiMo 5-1	SiMo +V	D5S	SAE J2585
Fe	51.7%	55.1%	28.2%	65.3%
O	26.8%	21%	14.3%	17%
C	13.7%	-	16.9%	11.8%
Si	7.0%	12.1%	4.7%	5.4%
Ni	-	-	34%	-

Table 5. Composition of the positive oxide layer of the cast surface of four alloys after ~95 hrs at 760°C.

Element	SiMo 5-1	SiMo +V	D5S	SAE J2585
Fe	63.1%	71%	59.1%	70.5%
O	26.1%	19.7%	27.3%	18.7%
C	10.2%	-	12.9%	10.8%
Si	0.1%	0.3%	0.1%	-
Ni	-	-	0.6%	-

Discussion & Results, Cont.

Metallography

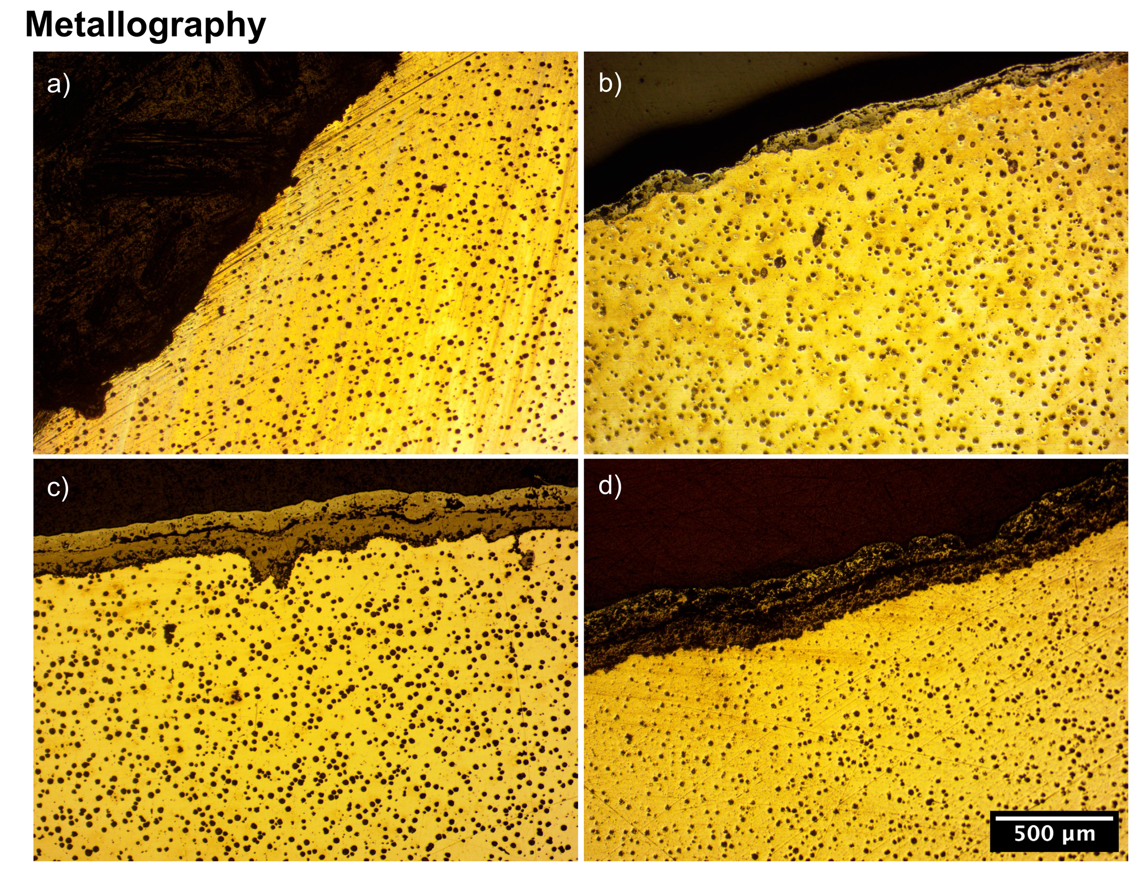

Figure 6. Oxidation Layer development on cast edge during testing at 760C in air after a) heat treat b) 23 hours c) 167 hours d) 383 hours. Etched with 2% Nital.

- The oxide layer appears to have a bilayer that progressively grew throughout the test (refer to Fig. 3 for layer growth measurements)
- The nodules present were rated as ASTM A247 Type I and II for all materials tested for the duration of the oxidation test

Future Work

Recommendations
- Understand differences between cut and cast oxide layer growth mechanism
- Continue working with the MET and Purdue SMART Foundry to cast SiMo 5-1 DI
- Characterize other austenitic ductile iron to determine whether spallation of oxide layer is a characteristic feature of austenitic grades

Future Work
- Continue casting SiMo 5-1 alloy in the Purdue SMART Foundry. Work was completed to design the alloy, initial charge, and mold. The expected range of the carbon equivalent is 4.3% - 5.2%

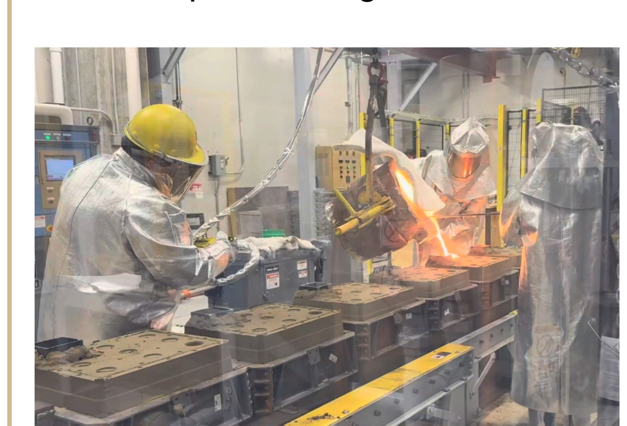

Figure 7. SiMo 5-1 DI pour in the SMART Foundry completed with MET.

Table 6. Designed chemistry of SiMo 5-1 alloy for casting.

Element	Targets
C	2.80% - 3.00%
Si	4.50% - 6.50%
Ni	<0.30%
Cr	<0.15%
Mo	0.75% - 1.25%
Cu	<0.30%
S	<0.01%
P	<0.05%

Acknowledgements

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