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High-temperature mechanical- and fatigue properties of cast alloys intended for use in exhaust manifolds

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In the present work materials for use in exhaust manifolds of heavy-duty diesel engines were tested in air from 20 to 1000 °C with respect to mechanical properties. Two cast irons, SiMo51 and Ni-resist D5S, four austenitic cast steels, HF, A3N, HK30 and HK-Nb, and one ferritic cast steel, 1.4509 were studied. The experimental work included thermal conductivity, thermal expansion, uniaxial stress–strain testing, low-cycle fatigue testing up to 30,000 cycles and fractography. Below 500 °C, SiMo51 is superior. At higher temperatures, a transition from elastic to plastic strain dominance was observed for the cast irons, reducing their performance. Carbide-forming elements increase heat conductivity and result in a dendrite-like fracture surfaces during fatigue testing. The austenitic steels are superior only at higher temperatures.

1. Introduction

The exhaust regulations for heavy-duty trucks are continuously becoming more restricted in order to limit the environmental effects from exhaust gases and particles. By increasing the specific power output of diesel engines, the fuel efficiency is improved and emissions reduced. However, a drawback is that it leads to increased exhaust-gas temperatures putting higher demands on the materials for the exhaust manifolds. The gas temperature is expected to reach as high as 1000 °C in the near future making it impossible to use the ferritic ductile cast iron SiMo51, commonly found in turbo manifolds today, as its maximum operating temperature is limited to 750 °C. In gasoline engines, reaching higher exhaust gas temperatures, an austenitic ductile cast iron, named Ni-resist D5S, is found. For the most demanding conditions, found in high-power gasoline engines, 25Cr20Ni alloys, for example ACI HK30, are used.

The turbo manifold has a complex shape with a load bearing function making cast alloys the primary choice for this application. They must resist vibrations, oxidation and thermal low-cycle fatigue (LCF) from start-up and shutdown of the engine. The loading conditions are generally of multi-axial nature, which is more difficult to test. Itoh et al. [1] gives an example of a method of evaluating stress and strain ranges under non-proportional multiaxial loading. However, the design calculations of this type of component are traditionally based on LCF-data. The repeated compression and tension cycles in the LCF tests correspond to the stress state produced in the component from thermal expansion and contraction during start-up and shutdown of the engine.

Designing for fatigue resistance requires many aspects to be taken into consideration. The microstructure of a material affects the fatigue life and depends on several factors, such as alloy additions, casting temperature and cooling rate. Upon fatigue loading of a component, the material adjusts to the accumulated strain in different ways depending on its microstructure. For example, carbides strengthen cast irons and steels, as they are harder to deform than ferrite or austenite and provide particle hardening. However, dislocations tend to pile up at carbide/matrix interfaces resulting in crack initiation during deformation [2]. If cracks initiate along slip bands or at grain boundaries, the fatigue limit is proportional to the Vickers hardness. However, as discussed by Murakami [3], defects in the material, such as pores or inclusions, make the fatigue life harder to predict as crack initiation is strongly influenced by the shape and size of the defect. Suresh [4] also describes the influence of defects on fatigue life to be dependent on the relative strength of the matrix and the defects and the strength of the matrix/inclusion interface. In ductile irons, graphite nodules are generally considered as defects and affect the fatigue behavior as plastic deformation easily occurs at graphite/matrix interfaces [5,6]. Sjöberg and Svensson [7,8] have studied the effect of graphite morphology on the plastic deformation behavior of cast irons and observed that nodular-shaped graphite gave rise to a lower deformation rate compared to lamellar-shaped graphite (i.e. Gray iron). The influence of the

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microstructure of cast iron on fatigue behavior is also described by Čanžar [9], who observed a higher fatigue life corresponding to smaller and more regularly shaped nodules. Consequently, any factor that produces a localized stress concentration reduces the fatigue life. Hence, surface roughness and notches also play an important role in fatigue life prediction [10]. The notch effect during fatigue testing has been extensively studied by, for example, Sakane et al. [11] and Berto et al. [12–14]. However, investigation of notched specimens is not included in this study as LCF-data for smooth specimen is generally used for strength calculations of exhaust manifolds.

As the temperature is increased, atoms are thermally activated and the vacancy concentration is increased. This decreases the strength of the material as grain boundaries and grains become soft and dislocation movement is enhanced making the material easier to deform [15,16]. Hence, increasing the high-temperature strength by changing the microstructure, general approaches are to increase the strength of the matrix by solid solution hardening, precipitation hardening and grain boundary hardening. In the literature, work concerning fatigue of heat-resistant materials can be found. Hitachi Metals, has developed a 20Cr/10Ni austenitic cast alloy designated NSHR-A3N, which is proposed to replace SiMo51 in turbo manifolds. Shingledecker et al. [17,18] have tested a similar alloy; a 19Cr/10Ni cast alloy called CF8C-Plus, developed by Oak Ridge National Laboratory and Caterpillar, and is proposed to show improvements over SiMo51, Ni-resist D5S and A3N in both creep and thermal fatigue properties. The improved mechanical properties were explained to come from a fully austenitic matrix, strengthened by N- and Mn-additions and precipitations of fine, nano-scale NbC. Moreover, Kim et al. [19] have tested a 20Cr10Ni cast alloy (ACI HF30-type) for its high-temperature low-cycle fatigue resistance at 600 °C and 800 °C. The authors used the Coffin Manson parameters and a thermal activated dislocation glide model to compare fatigue parameters of the cast alloy with a wrought alloy of similar composition (AISI 304-type) and came to the conclusion that the fatigue resistance of HF30 was similar to 304. Similar experiments were performed for a ferritic 18Cr cast alloy of ACI-grade HB20 [20], demonstrating comparable low-cycle fatigue life to HF30. Another ferritic alloy, developed by Daido Steel Co, that is proposed to replace the expensive, austenitic cast iron Ni-resist D5S in turbine housing, is a ferritic cast stainless steel named StarCast DCR3. According to Takabayashi et al. [21], this alloy shows improvement over Ni-resist in thermal fatigue resistance at temperatures up to 950 °C. Moreover, Kim et al. [22] has tested a 25Cr20Ni cast alloy (ACI HK40-type) alloyed with Nb and different W-contents for its mechanical properties at room temperature, 400 °C, 600 °C and 800 °C and for its low-cycle fatigue life at 800 °C and the author observed an increased strength from W-addition but reduced ductility and suggested an optimum W-content of 2 wt%. The addition of Nb to heat-resistant alloys has also been studied by others, showing, for example, refinement of the as-cast microstructure of a 33Ni26Cr cast alloy (ACI HP-type) [23] and increased proof strength of an 18Cr10Ni stainless steel (AISI 304-type) [24]. The high-temperature mechanical properties of a HP-40 alloy containing 1 wt% Nb has been tested by Voicu [25] between 950 °C and 1000 °C. Voicu observed cracks at carbide/dendrite interfaces, which were suggested to be responsible for the fracture of the samples. Moreover, Kim et al. [26] studied the low-cycle fatigue behavior of a 24Cr ferritic stainless steel at room temperature, 600 °C and 700 °C and observed a higher fatigue life at 700 °C than at 600 °C, which was explained by a difference in dislocation structure at the higher temperature.

To conclude, many materials have been tested individually but the comparisons are few. As a result, the present paper addresses the commercial alloy SiMo51 with its most potential candidate materials for increased exhaust gas temperatures. The high-temperature mechanical properties are investigated and compared. The aim is to create guidelines for material selection at different temperatures. As LCF data traditionally is used for judging the resistance to temperature cycling, it is in focus in the present study.

2. Material and methods

2.1. Materials

The studied alloys were cast in 40 kg ingots, the stainless steels by Smålands Stålgjuteri AB, Eksjö, Sweden and the ductile cast irons by Castings P.L.C, West Midlands, England, respectively. The ingots were designed to avoid pore formation by letting a central plate of size $550 \times 150 \times 20$ mm^3 be connected by two cylinders of 550 mm length and 60 mm diameter. The cylinders and additionally 75 mm of each 550-side of the plate were removed producing a blank of size $400 \times 150 \times 20$ mm^3 for machining of test specimens. These were taken out in the 150 mm-direction, i.e. perpendicular to the removed cylinders.

The chemical compositions of the cast ductile irons and the cast stainless steels are given in Table 1 and 2, respectively. Both of the tested ductile cast irons, SiMo51 and Ni-resist D5S are commercially used in exhaust manifolds. The former is commonly found in diesel engines and the latter in gasoline engines, reaching higher exhaust-gas temperatures. As indicated in Table 2, four of the cast stainless steels are fully austenitic while one is fully ferritic in accordance with their Cr and Ni content. It should be pointed out that A3N is a modification of the HF alloy with additions of Nb, W and Co, and that HK-Nb is a modification of the HK30 alloy by additions of Nb. In addition, HK30 is a commercial alloy, commonly found in exhaust manifolds of high-power gasoline engines.

Table 1
Chemical composition of cast ductile iron alloys (wt%, Fe bal.).

Designation	Structure	C	Si	Mn	Cr	Ni	Mo	Mg
SiMo51	Ferritic	3.17	4.15	0.40	0.10	0.04	0.86	0.052
Ni-resist D5S	Austenitic	2.41	5.38	0.28	1.77	33.12	0.18	> 0.056

Table 2
Chemical composition of cast stainless steel alloys (wt%, Fe bal.).

Designation	Structure	C	Si	Mn	Cr	Ni	Nb	W	Co
HF	Austenitic	0.33	1.50	1.43	18.76	8.87	0.01	0.01	0.02
A3N	Austenitic	0.57	0.58	1.05	19.59	10.15	1.75	2.28	0.29
HK30	Austenitic	0.51	1.50	1.45	25.41	18.67	< 0.005	0.01	0.03
HK-Nb	Austenitic	0.37	1.29	0.96	25.38	22.40	1.39	0.02	0.03
1.4509	Ferritic	0.02	0.81	0.75	17.90	0.12	0.36	< 0.01	0.02