Thermomechanical fatigue behavior of cast iron alloys for applications in heavy-vehicle engines

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Abstract

The automotive industry has been committed in developing combustion engines with more energy efficiency by sustainability demands. Consequently higher-pressure peaks and temperatures, has demanded cylinder heads and engine blocks with improved mechanical resistance and ductility. The thermo-mechanical fatigue life of cylinder head has been one of the limiting factors in heavy-duty engine design. This work compares the thermomechanical fatigue strength of two cast iron types used for cylinder head fabrication, named as gray cast iron grade 300 (GI300) and compacted graphite cast iron grade 500 (CGI 500). Therefore, out of phase thermomechanical fatigue tests were carried out in temperature range of 50-420ºC, considering a trapezoidal wave shape and complete mechanical constraint. By the results, the fatigue strength in the materials lifetime is related to the differences in the graphite cells morphology and their effects as stress concentrators on the pearlitic matrix.

Keywords: Thermomechanical fatigue - cast iron - gray iron - compacted graphite iron - cylinder heads.

Introduction

Many mechanical and structural components made for application in sectors of aerospace, nuclear, automotive, and oil industries, on numerous occasions, perform activities under severe conditions of temperature and pressure. As an example, are the automotive cylinder heads, which are subjected to sudden temperature and loading variations during the operation period. And the most common material used to make for this kind of application, that require complex geometries, thin sections and, simultaneously, the combination of thermal and mechanical properties to achieve the desired performance are the cast irons [1].

In the cylinder heads of heavy vehicles engines, the valves regions, which are very close together, are heated rapidly by the process diesel combustion and, at the same time, cooled by the cooling system, restricting the material thermal expansion. This results in a high compressive stress state at high temperature, inducing plastic deformations in places where the yield limit has been reached [1]. After the engine shutdown, the temperature drops and tensile stresses are developed as a consequence of the compressive plastic deformations that can generate small cracks and leading to component failure. These internal stresses, generated by the regular engine-working period (start-up, operation and shutdown), reveal a stress-strain hysteresis cycle, called out-of-phase thermomechanical fatigue, OP TMF.

Academic works to develop new materials of higher strength, are being carried out in many research centers and foundry companies, however in the automotive context, engineers are facing design improvements for engine weight reduction, therefore, the knowledge of the materials´ thermomechanical strength, as well as the micromechanisms of failure involved in the cylinder head is of prime concern. These difficulties arise from four main steps of design, that are: the identification of the thermomechanical loadings, the material´s mechanical constitutive behavior and its temperature dependence, the damage driving force identification and the fatigue criterion itself [2].

Experimental Procedure

The materials investigated in this work were a grey cast iron Grade 300 and a compacted graphite cast iron grade 500. They are the higher strength grades of their families used for cylinder heads. Specimens were taken from the combustion face of a 13 liters cylinder head with a microstructure as found on the valve bridges regions of this one component (GI 300, Flake graphite, pearlitic matrix and CGI500, Vermicular graphite with 22% nodularity, pearlitic matrix). Table 1 shows tensile properties hardness values.

Table 1 – Mechanical properties (at RT) of the tested materials. Specimens from the combustion face of a 13 liters cylinder head.

Cast Iron	UTS (Mpa)	YS (Mpa)	HB 5/750
GI 300	319	285	220
CGI 500	585	378	226

The thermomechanical fatigue tests were performed according to ASTM E2368-17. The fatigue machine is a MTS servohydraulic (MTS Systems Corporation), model 810, capacity of 250 KN. This test system has special claws of super cooled Ni for high temperature testing, extensometer with ceramic rods, induction furnace and pyrometer for thermal cycling. The specimen was taken from the ASTM E606-00, as shown in figure 1:

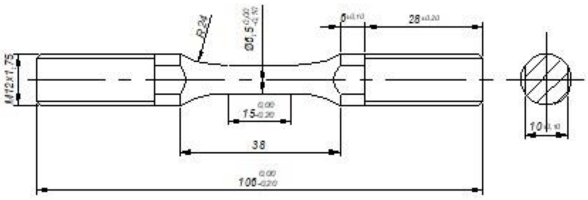

Figure 1 – Thermomechanical fatigue specimen.

The tests were carried out at temperatures between 50 and 420ºC, considering 100% of restriction (complete mechanical constraint). The thermal cycle to be applied is shown in Figure 2.

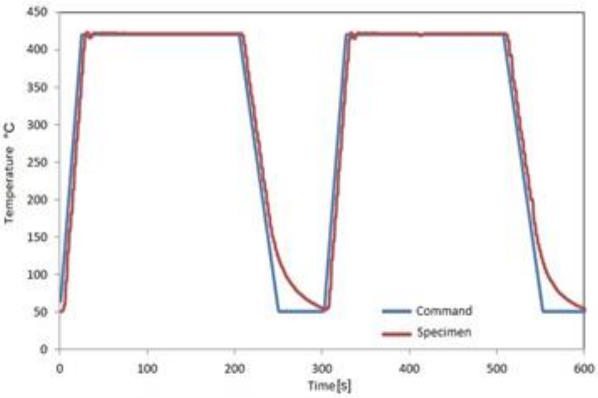

Figure 2– Trapezoidal wave shape applied in the thermomechanical fatigue testing.

Results and Discussion

The results of tests with the newly developed materials, gray cast iron 300 (GI300) and compacted graphite iron 500 (CGI 500) are listed in Table II. The results of lifetime obtained with CGI 500 are much higher than grey iron grade 300. We can also observe the higher tensile stresses that CGI can support, compared to grey iron.

Table 2 – Experimental results for TMF tests based on a Circular Cross Section of 6.5 mm diameter.

Material	SP	N_{10}, cycles	Max Stress (Mpa)
GI 300	1	65	225
	2	97	203
	3	42	235
	4	148	192
CGI 500	1	592	358
	2	335	363
	3	680	352
	4	820	350

The TMF average life of GI 300 is 88 cycles and , while the CGI500 is 606 cycles. The figure 3 shown the Temperature and stresses evolution during the first two cycles of TMF testing.

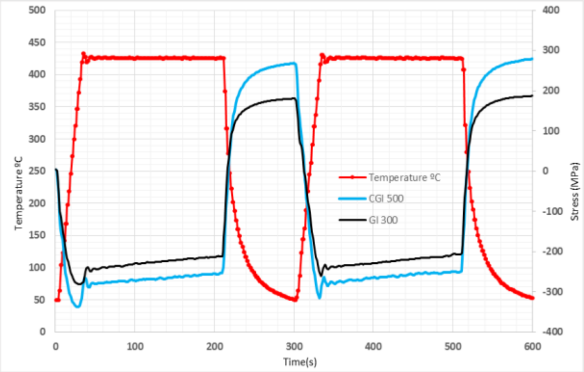

Figure 3- Example for GI300 and CGI 500.

Conclusions

The variance in the materials lifetime is related to the differences in the morphology of the graphite cells and their effects as stress concentrators on the pearlitic matrix. Confirming that compacted graphite iron has more strength on thermomechanical fatigue loadings compared with gray cast iron because CGI can withstand the presence of a higher number of cracks than GI, before the final fracture.

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