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The effect of superimposed high-cycle fatigue on thermo-mechanical fatigue in cast iron

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ABSTRACT

The effect of superimposing a high-cycle fatigue strain load on an out-of-phase thermo-mechanical fatigue test of a lamellar, compacted and spheroidal graphite iron has been investigated. In particular, different total mechanical strain ranges, maximum temperatures and high-cycle fatigue strain ranges have been studied. From this, a new property has been identified, measured and compared, namely the thermo-mechanical and high-cycle fatigue threshold, defined as the high-cycle fatigue strain range at which the life is reduced to half. Using a previously developed model, the lifetimes and the threshold have been successfully estimated for the lamellar and compacted graphite iron, however underestimated for the spheroidal graphite iron. Nevertheless, an expression of the threshold was deduced based on the model, which possibly can estimate the value in other cast irons and its high-cycle fatigue frequency dependence.

1. Introduction

Thermo-mechanical fatigue (TMF) has become a successively more important concept in the design of engine components in the heavy-vehicle automotive industry [1]. It refers to the fatigue damage accumulation due to a combination of a conventional cyclic mechanical load, either displacement or load controlled, and a varying temperature [2,3]. Such a loading condition is typically encountered as the engine is exposed to repeated warming up and cooling down as it starts up and stops during every-day operation; a cycle often referred to as the start-operate-stop cycle [4].

The elevated material degradation is often observed in critical locations, in general in all parts where the thermal expansion of heated material is impeded by less hot surrounding material. This has been identified as one of the main limitations of the overall service lifetime of many engine components, as well as an obstacle in fulfilling the demands of higher efficiency and reduced exhaust emission. On top of this, there is an additional factor which has become an increasingly more studied research topic, namely the possible detrimental synergy effect of combined high-frequent mechanical loading, often referred to as superimposed high-cycle fatigue (HCF) [5–8]. Many materials, including aluminium, steels, superalloys and cast irons, have been proven to be sensitive to a superimposed HCF load and it is therefore important to characterise this effect [5–10]. In a previous study [10], it was identified that there exists a HCF load threshold independent of the underlying TMF cycle, beneath which the overall fatigue life is unaffected, in the compacted graphite iron EN-GJV-400.

The concerned components constituting a heavy-vehicle engine, such as the cylinder head, the cylinder block and the exhaust manifolds, are cast using different varieties of cast irons. The different grades of cast irons may differ significantly in mechanical properties but have a characteristic phase structure in common, consisting of graphite phase particles embedded in a steel matrix phase. The wide diversity in properties is often ascribed to the large variety of feasible graphite shapes and matrix structures, *i.e.* ferritic, pearlitic structures etc. These two parameters are governed by the phase transformations that occur during the cooling and are partly controlled by variation of the chemical melt composition, cooling conditions and inoculation.

To address the above mentioned problems a substantial effort has been put on the development of simulation-based design tools, employing finite element software and lifetime assessment modelling, in order to estimate the properties of new component designs as a more rapid substitute compared to prototype testing [1,4,8,11]. Such an approach should be of use for engine constructors to avoid employing inappropriate geometries from a TMF

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perspective. However, much research is still required for successful lifetime assessment models.

The purpose of this study is to present and compare the effect of combining superimposed high-cycle and thermo-mechanical fatigue on three representatives of different cast iron families, namely a lamellar (LGI), a compacted (CGI) and a spheroidal graphite iron (SGI). Presently, the existing TMF-HCF data of these materials are highly limited and no comprehensive comparison of different cast irons has yet been carried out regarding the TMF-HCF interaction. In particular, this study will report the HCF threshold levels and also employ the lifetime assessment model developed in [10].

1.1. Thermo-mechanical fatigue and superimposed high-cycle fatigue

A thermo-mechanical fatigue test is a special version of a low-cycle fatigue (LCF) test where the temperature is allowed to vary together with the mechanical load, which most commonly is strain controlled [2,3]. The cycle period is normally the same for the thermal and mechanical cycle, however different phase shifts between the two are often studied. The two most commonly employed are the extremes cases, namely when the phase shift is zero, called in-phase testing, or 180°, also called out-of-phase testing. In the latter, the maximum temperature coincides with the minimum strain, while the opposite pertains for the former case.

If a HCF load is to be added, then the mechanical load will oscillate with some amplitude about the base signal which corresponds to the signal applied in the standard TMF test, see Fig. 1. As often done for strain-controlled tests [7,10], the base strain signal is referred to as the *thermo-mechanical fatigue strain* ε_{TMF} while the oscillating strain signal is denoted *high-cycle fatigue strain* ε_{HCF}. Added together, they will constitute the *total mechanical strain* ε_{Mech} corresponding to the combined strain signal in Fig. 1b. The prefix *total* is included to emphasise that the variable is composed of two mechanical strain signals and pertains to a TMF-HCF condition. For consistency, the mechanical strain will be referred as the TMF strain when in a TMF condition for which the HCF strain is zero. Thus, in a TMF-HCF test, the uniaxial strain ε measured by an extensometer is at any instant t equal to

$$\varepsilon(t) = \varepsilon_{Th}(t) + \varepsilon_{Mech}(t) = \varepsilon_{Th}(t) + \varepsilon_{TMF}(t) + \varepsilon_{HCF}(t) \qquad (1)$$

where ε_{Th} is the thermal strain representing the thermal expansion. The definitions of the different strain ranges, $\Delta\varepsilon_{Mech}$, $\Delta\varepsilon_{TMF}$ and $\Delta\varepsilon_{HCF}$, follow accordingly, see Fig. 1. It is important to realise that the resulting uniaxial engineering stress $\sigma(t)$ is only explicitly dependent on the applied mechanical strain and not on the induced thermal strain.

Only a handful of experimental studies have been carried out on the TMF-HCF behaviour of cast irons [6–8,10]. Nevertheless, it has been reported for different cast irons that there exists a HCF strain range threshold $\Delta\varepsilon_{HCF}^{Th}$, henceforth referred to as the *TMF-HCF threshold*, below which the fatigue life is unaffected by the superimposed HCF load [6,10]. However, the data is scarce and there are some inconsistencies between the different investigations. For instance regarding SGI, in which no threshold was observed by Beck [7] in opposition to the observations of Metzger et al. [8].

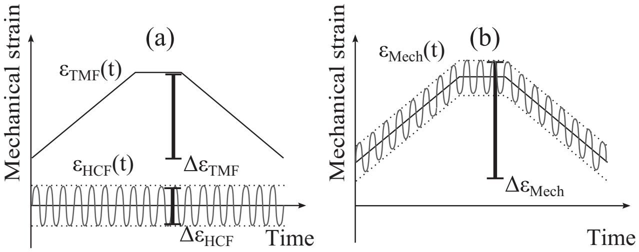

Fig. 1. A schematic illustration of the TMF and HCF strain signals.

1.2. Fatigue crack behaviour in cast iron under uniaxial loading

Many investigations of the microscopic damage in monotonic and cyclic tension have been conducted on cast irons at room temperature [12,13]. For instance, it has in monotonic tension been observed that the graphite and the steel matrix debond perpendicularly to the load direction at low levels of strain, namely about 0.03% for both LGI and SGI [13]. In addition, at the same level of straining, internal fracture of the graphite has been seen in the case of LGI, CGI and SGI [12]. Thus, the graphite phase appears to fracture at a very early stage, either within the phase itself or along the phase interface shared with the steel matrix. As the load is further increased, these early fracture events result in the development of small cracks, or *microcracks*, extending into the matrix at multiple locations [12]. At even higher load levels, the microcracks successively propagate and eventually coalescence.

Regarding cyclic loading, these microscopic fracture processes appear to be similar to the static case, namely the initiation, propagation and coalescence of microcracks, which are schematically illustrated in Fig. 2. Small fatigue cracks have been observed to emanate from graphite particles in both isothermal and thermo-mechanical fatigue [8,14,15]. More importantly, small crack initiation has also been concluded to occur within the first fatigue cycles of both the mentioned fatigue modes [14,16], which is a commonly stated assumption in many life assessment approaches, *e.g.* [8,10,17,16]. The microcracks have been experimentally verified to initiate at multiple graphite locations for LGI, CGI and SGI [14,15], and the following propagation regime is associated with individual microcrack propagation and subsequent onset of microcrack coalescence [8,14,15]. In fact, Socie and Fash [14] observed that the microcrack length at the moment before the final coalescence resulting in the final fracture plane, was about 1–2 mm in all three cast iron types, LGI, CGI and SGI. Nonetheless, it should also be noted that the distinction between fatigue crack initiation and propagation might be somewhat unclear because of the discontinuous growth of microcracks into a crack of macroscopic proportions.

Casting defects and the free surface might also have a certain impact on fatigue crack behaviour [17,18], in particular in the case of high temperature [16]. Defects have been proven to have a significant influence on the fatigue properties of SGI, as fatigue crack initiation has been traced back to naturally occurring casting defects such as microshrinkages [18]. Furthermore, in an earlier study of Nadot et al. [17] it was established that the crack propagation rate of microcracks emanating from casting defects at the surface was similar to the long crack propagation rate when the crack

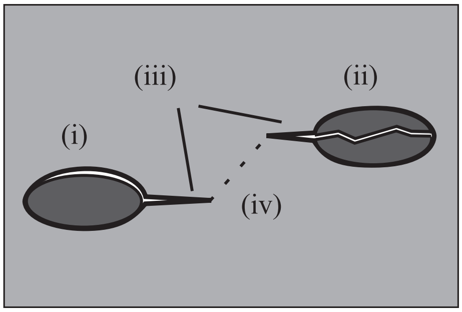

Fig. 2. Schematic illustration of the microscopic fracture processes: (i) graphite-matrix debonding, (ii) internal graphite fracture, (iii) microcrack propagation into the matrix and (iv) microcrack coalescence.