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# Evaluation of fatigue crack network growth in cast iron for different biaxial loading paths via full-field measurements

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ABSTRACT

This paper proposes a new method for monitoring fatigue crack network initiation and growth based on Digital Image Correlation (DIC), and reports on in-plane biaxial fatigue experiments with two different loading paths and two amplitudes on nodular graphite cast iron. The central thinned part of cross-shaped samples is observed on two scales. Regularized Digital Image Correlation (DIC) is used to measure displacement fields and to reveal DIC residuals, *i.e.*, image differences that cannot be accounted for with registration. The detailed strain histories are compared at different scales and for the different loading regimes. DIC and mechanical residuals, *i.e.*, local deviations of the displacement field from being the solution to an elastic problem, enable for the crack network detection and quantification with respect to the number of cycles. The relative damage severity and fatigue lifetime of different loading paths experiencing identical load magnitudes are analyzed for the tested material.

## 1. Introduction

The prediction of fatigue life of structures is still a difficult task because it is a multiscale process. For defect-free media, the major part of damage growth corresponds to multiple initiations and propagations of short cracks, which eventually coalesce to form a macroscopic crack. To account for such phenomena, different models have been proposed [20,23,17,2,13,36,21,26]. However, on the experimental side, the quantitative analysis of such phenomena remains a difficult and challenging task.

In this paper it is proposed to utilize Digital Image Correlation (DIC [29]) to study the development of fatigue crack networks. DIC has been used to detect and quantify fatigue crack growth [30,15,19,9,34,10,22,18]. All the cited references essentially deal with a single crack. Only few studies have reported results on fatigue crack networks [12,25,16]. In the present work, it is proposed to use an optical setup enabling for two scale observations in biaxial tests. Such configurations have already been utilized to analyze macroscopic cracks [1,35,6]. However, they all used an artificial random pattern at both scales of observation, with the risk of masking the occurrence of microcracks. For this reason, the bare sample surface was used herein.

This study focuses on the fatigue behavior of spheroidal graphite (SG) cast iron under in-plane biaxial experiments. The low ductility of the material [33] induces the formation of crack networks during cyclic loading. The strain fields and correlation residuals are analyzed to detect multiple crack initiations via DIC simultaneously performed on both scales. Due to the ability of multiaxial experiments to prescribe a wide variety of loading histories two different paths, namely, “equibiaxial” (i.e., simultaneous loading and unloading in the two arm directions) and “square” (*i.e.*, successive loading and unloading in the two arm directions as detailed below) will be used. One of the challenging parts of this work is the performance of DIC related to the poor natural texture of the studied material. A regularization technique [31] is used to overcome this limitation. From the measured displacement fields, the strain histories are extracted and compared on both scales. For each loading path two different tests are considered. The first one is designed to initiate the crack network during the first cycle. The second one is set so that a first stage of cycling takes place without cracks. Correlation and mechanical residuals obtained via DIC analyses are presented in order to reveal the crack network history.

## 2. Experimental protocol

### 2.1. In-plane biaxial experiments

The in-plane biaxial experiments presented herein are carried out on the triaxial servo-hydraulic testing machine Astrée [27,7,8,11,24,10,14,32]. For the present experiments, four

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horizontal actuators are used. The material studied herein is an SG cast iron whose chemical composition is reported in Table 1.

The main feature of SG cast iron is its heterogeneous microstructure (Fig. 1). SG cast iron consists of a ferrite/pearlite matrix containing randomly distributed spheroidal graphite inclusions (Fig. 1(a)). Due to the size of the biaxial samples it was necessary to cast a bigger block with dimensions $280 \times 280 \times 500\,\text{mm}^3$. The heat-treatment and especially the cooling rate of the cast part had to be adapted to such sizes. Consequently the nodules are not spherical (*i.e.*, the mean circular shape factor (CSF) is equal to 0.62, and the nodularity by area when the CSF > 0.5 is equal to 70%). By revealing the secondary microstructure (Fig. 1(b)) it is possible to observe the volume fraction of graphite nodules (10%), ferrite (31%) and pearlite (59%) grains.

In spite of this heterogeneous microstructure, at the macroscopic level the mechanical behavior of SG cast iron can be considered as homogeneous with isotropic properties. From previous work carried out on the same material (*i.e.*, quasi-static uniaxial tests) low elongation to failure was reported (*i.e.*, 4.85%) with a yield stress of 290 MPa, and an ultimate tensile strength of 460 MPa [33]. This phenomenon is linked to the presence of pearlite in rather high volume fraction and very dense distribution of irregular nodules.

The in-plane biaxial test consists in loading a cross-shaped specimen in tension and/or compression along two perpendicular directions. The samples considered herein have a maltese cross shape that is thinned in the central part to form spherical caps. This uneven thickness gives rise to higher stress levels in the central region, and this stress enhancement is designed to induce crack initiation within this zone (Fig. 2).

The global size of the sample is $274 \times 274\,\text{mm}^2$. The lowest thickness at the center is equal to 1 mm (*i.e.*, ten times the average graphite particle size) and gradually increases to 5 mm out of the gauge zone, which creates a calotte with of circular base 30 mm in diameter. The dimension of the fillets of the gripping arms is 12 mm.

### 2.2. Two-scale optical setup

Since the geometry of the specimen is complex, the natural choice is to use full-field measurements to have access to the displacement/strain fields during the experiment. The goal of the experiments presented herein is to observe the material response to biaxial loading regimes on two scales. In order to capture displacement fluctuations a two-scale optical setup is selected (Fig. 3). The thinned central part of the cross-shaped specimen was observed on both sides (Fig. 3(a)–(b)). The bottom side of the sample is observed on a macroscale (Fig. 3(b)) for which the camera monitors the whole gauge zone. Images were taken with a CCD camera (*Dalsa*™, 12-bit digitization) and a telecentric lens with ×4 magnification (Fig. 3(c)). The picture definition is $1024 \times 1024$ pixels with a physical pixel size of 48 μm (Fig. 3(d)). This optical setup is classical for DIC analyses.

For optimal DIC conditions, the sample surface is illuminated with a perpendicular light and the camera sensor is parallel with the observed zone. To achieve a diffuse illumination, oil paper is placed on the beam-splitter surface illuminated by a *DedoCool*™ lamp. Another CCD camera (*PixelFly*™, 12-bit digitization, see Fig. 3(f)) equipped with ×1 magnification telecentric lens is used to monitor the gauge zone. Mesoscale pictures (Fig. 3(g)) have a definition of $1280 \times 1024$ pixels with a physical pixel size of 6.7 μm. The gauge zone has a size of $8.6 \times 6.9$ mm.

Before conducting the two-scale analyses, the surfaces of the investigated regions of interest (ROIs) are prepared. To enable for DIC analyses of macroscale pictures an artificial pattern is

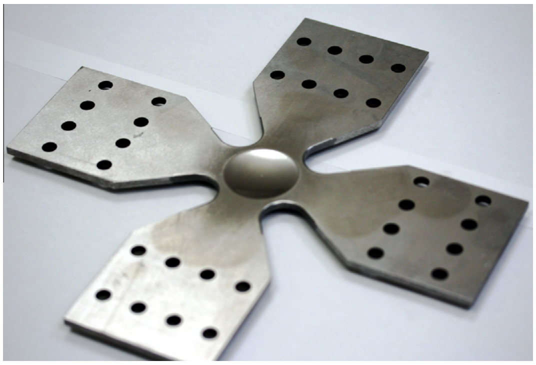
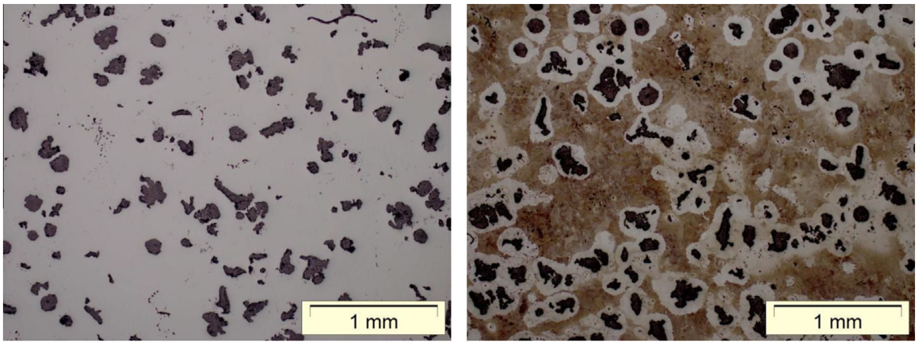


**Fig. 2.** Maltese cross-shaped specimen designed for in-plane biaxial experiments.

**Table 1**
Chemical composition in vol.% of the studied grade of SG cast iron.

| C | Si | Mn | P | S | Cr | Ni | Mo | Cu | Mg | Fe |
|---|---|---|---|---|---|---|---|---|---|---|
| 2.26 | 2.09 | 0.15 | 0.041 | <0.01 | 0.04 | 0.63 | <0.01 | 0.025 | 0.06 | Bal. |



(a) Polished primary microstructure (b) Etched secondary microstructure with nitric acid

**Fig. 1.** Metallography of the studied SG cast iron.