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INFLUENCE OF THE LOST FOAM CASTING MICROSTRUCTURE ON LOW CYCLE FATIGUE DAMAGE OF A319 ALUMINUM ALLOY

Nora Dahdah¹, Nathalie Limodin¹, Ahmed El Bartali¹, Jean-François Witz¹, Rian Seghir¹, Long Wang¹, Eric Charkaluk¹, Jean-Yves Buffiere²

¹Laboratoire de Mécanique de Lille (LML), CNRS UMR 8107; Cité Scientifique; Villeneuve d'Ascq, 59650, France

²Laboratoire Matériaux, Ingénierie et Sciences (MATEIS), INSA-Lyon, CNRS UMR 5510; 20; Villeurbanne, Rhône, 69621, France

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In cast aluminum alloys used in the automotive industry the microstructure inherited from the foundry process has a strong influence upon the fatigue behavior. In the cylinder heads produced by the Lost Foam Casting process, the microstructure consists of hard intermetallic phases and large gas and microshrinkage pores. In order to study the influence of this complex 3D microstructure on fatigue crack initiation and propagation, an experimental protocol using laboratory and synchrotron tomography, Finite Element simulation and 3D Digital Volume Correlation has been used. Full field measurements at the microstructure scale were performed during a low cycle fatigue test at room temperature performed in situ under synchrotron X-ray tomography (TOMCAT beamline, SLS). Synchrotron tomography allowed characterizing the eutectic Al–Al₂Cu, iron based intermetallics phases and above all eutectic Si, which could not be distinguished with laboratory tomography; these constituents were proved a suitable natural speckle for Digital Volume Correlation.

The 3D cracks were observed to initiate at large pores and then to propagate along the hard inclusions towards the free surface. The DVC of in-situ fatigue tests allows observing the relations between cracks and displacements discontinuities and strain localizations in measured field. The experimental protocol proposed will be further improved for a validation at a temperature characteristic of in-service conditions of cylinder heads (250°C).

1. Introduction

In the automotive industry, economical constraints together with environmental requirements have led into process modification of some engine parts like cylinder heads. Nowadays, the Lost Foam Casting process (LFC) replaces the conventional Die Casting (DC) process due to cost reduction and geometry optimization goals. Even if this process seems promising, there are some drawbacks such as a coarsening of the microstructure, which consists in hard second phase particles (eutectic Si, eutectic Al–Al₂Cu, and iron based intermetallics), large pores and microshrinkage cavities. Above a critical size, pores [1] play a decisive role by providing preferential crack initiation sites. However, an influence of oxides [2], iron-based intermetallics [3] and Si particles [4] are also observed. The cracks could initiate at any large defects present in bulk. In order to study the

influence of this casting microstructure upon the fatigue behavior of the A319 Al–Si–Cu alloy, an experimental protocol using synchrotron tomography and 3D digital volume correlation has been set up.

2. Experimental procedure

The material studied was an A319 aluminum silicon alloy (Al bal.– Si 7.18 wt.% – Mg 0.32 wt.% – Mn 0.15 wt.% – Cu 3.17 wt.% – Fe 0.43 wt.% – Ti 0.05 wt.%). Specimens with a 2.6x2.6mm² cross section were cut out from a cylinder head in the fire deck area by electro discharge machining. X-ray microtomography was realized prior to the low cycle fatigue test to screen ten specimens not presenting large defects away from the specimen's shoulders and with a maximum size of defects compatible with the specimen cross-section. Laboratory X-ray microtomography was performed at the MATEIS laboratory (Lyon, France) in fast scan mode with a 80 kV acceleration voltage to ensure a 10% transmission of the X-ray beam through the cross-section of the sample. The scan was made at a medium resolution with a voxel size of 5µm and an acquisition time per image of 500 ms; this medium resolution images allow revealing the size and shape of the large pores in the bulk of the specimens gauge length rapidly.

The aim was first to obtain 3D characterization of pores in the ten selected samples which were then mechanically polished on all faces using SiC paper and diamond suspension. The matrix, i.e. the material without the pores, of these specimens was segmented from the 3D image obtained from X-ray tomography and a geometric model with a volumetric tetrahedral grid was created using Avizo software. The model was used for elastic finite element simulation using Abaqus software in order to predict the most strained region under tensile loading and to focus the subsequent in-situ observation by high resolution X-ray tomography on this small volume.

The low cycle fatigue tests were realized at room temperature and monitored by synchrotron X-ray tomography on TOMCAT beamline at the Swiss Light Source. The coherence of the synchrotron monochromatic X-ray beam (25keV) allowed performing absorption contrast tomography in edge enhancement mode with a voxel size of 1.625 µm. 1500 radiographs were taken while the specimen was rotating over 180° along its vertical axis. With an exposure time of 300 ms per image, one scan lasted about 7 min. A specially designed fatigue machine was used to load the specimen in situ. The fatigue test ($R \approx 0.1$, $\sigma_{max} \approx 151\text{MPa}$) was performed step by step, only a few cycles were launched between each step. The test was conducted until crack initiation or failure with periodic interruptions to acquire tomographic scans under minimum and maximum load of the considered cycle in order to detect and follow fatigue crack initiation and growth. All the 3D images were reconstructed by using the reconstruction platform [5] developed by SLS. Then, they were binned to reduce the amount of data and the time needed to process them; this results in an effective voxel size of 3.25µm.

Synchrotron tomography allowed to visualize the eutectic Al–Al₂Cu, iron based intermetallics phases and above all eutectic Si, which could not be distinguished with laboratory tomography; these constituents were proved a suitable natural speckle for Digital Volume Correlation. The 3D displacement field was measured with the Digital Volume Correlation (DVC) technique [6], which is an extension of the well-developed Digital Image Correlation (DIC) method. In the present study, a 2D/3D image correlation platform newly developed at LML laboratory (Lille, France) has been

used. This correlation platform is based on C++ and it has been optimized to process large 3D volumes in a limited time. For a 780x725x1080 voxels image the calculation lasts about 40min with an isotropic element of 16 voxel edge on a 32Go RAM laptop. The correlation calculation is a sequence of optical flow integrated and finite element methods using regularization with a median filter [7] to compensate for poor microstructural textures avoiding thus the extremes values.

3. Results and discussion

The analysed specimen, as well as all the ten selected samples contains rather large number of pores in the gauge length volume (Figure 1(a)).

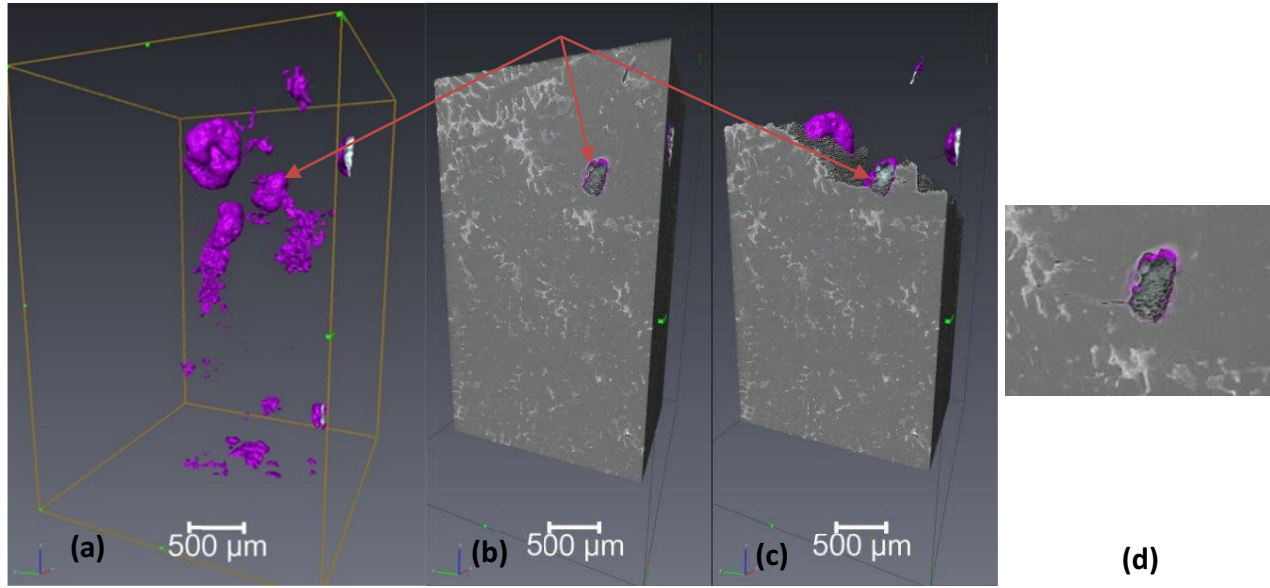


Figure 1. (a) Rendering of pores in the fatigue test specimen, (b) Specimen microstructure before failure (c) Specimen microstructure after failure (d) crack zone

The distribution of Feret diameter of these pores shows a peak around 70μm with a maximum Feret diameter of 940μm. Although scarce in number, the largest pores represent most of the pores volume fraction; this implies that large pores may have a significant influence on fatigue behaviour.

The displacement and strain fields were computed by DVC zone of the sample (779x724x1030 voxels³) containing the largest pores fraction (upper of the block shown in Figure 1(a)). The pore shown with the arrows in Figure 1(b) has led to progressive crack growth (Figure 1(d)) until final failure (Figure 1(c)).

Figure 2 and 3 show the displacement and corresponding strain field along the loading direction; the image of the microstructure was superposed to these fields to allow comparison of the crack path with local deformation.

The fields were studied at different steps of the fatigue cycles. The figures 2 and 3(a) show respectively displacement and strain fields between 300 cycles and 500 cycles (300c-500c), the crack initiation was detected at 500 cycles and sample broke after 2500 cycles; the figures 2 and 3 (b) show fields between 500c and 1000c where the propagation of the crack is observed, the figures

2 and 3 (c) are the last steps before the failure between 1000c and 2500c where crack growth is the most important. The figures 2 and 3 (d) allowed a better visualization of the microstructure in the crack neighbourhood. A good correlation is observed between the crack location, the displacement discontinuities and the strain localizations.

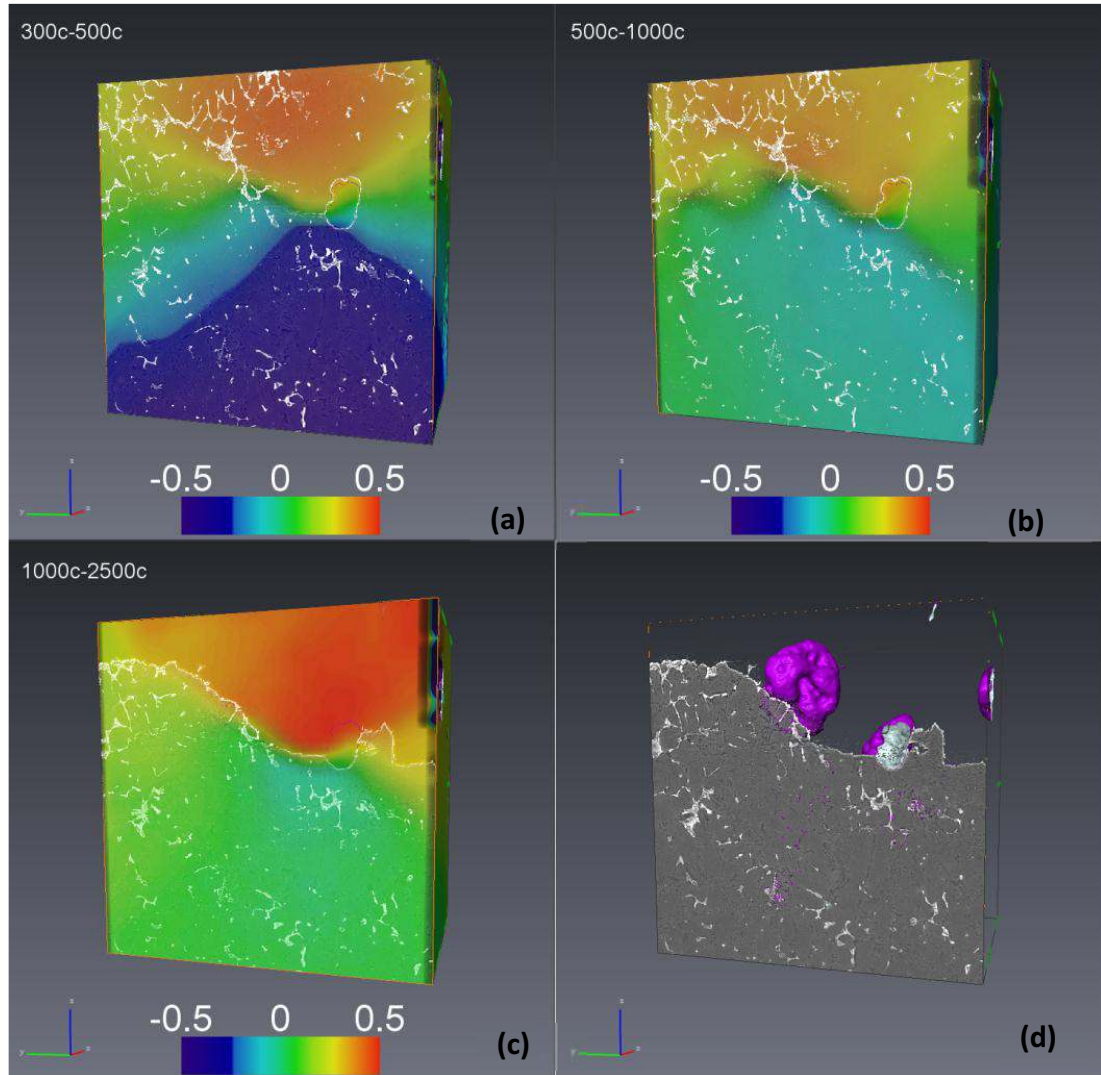


Figure 2. 3D displacement field (in voxels) along z with the microstructure shown in transparency between (a) 300c-500c, (b) 500c-1000c, (c) 1000c-2500c and (d) the fracture surface

The results show that the 3D crack initiated first at large subsurface pores and then propagated along the hard inclusions towards the free surface.

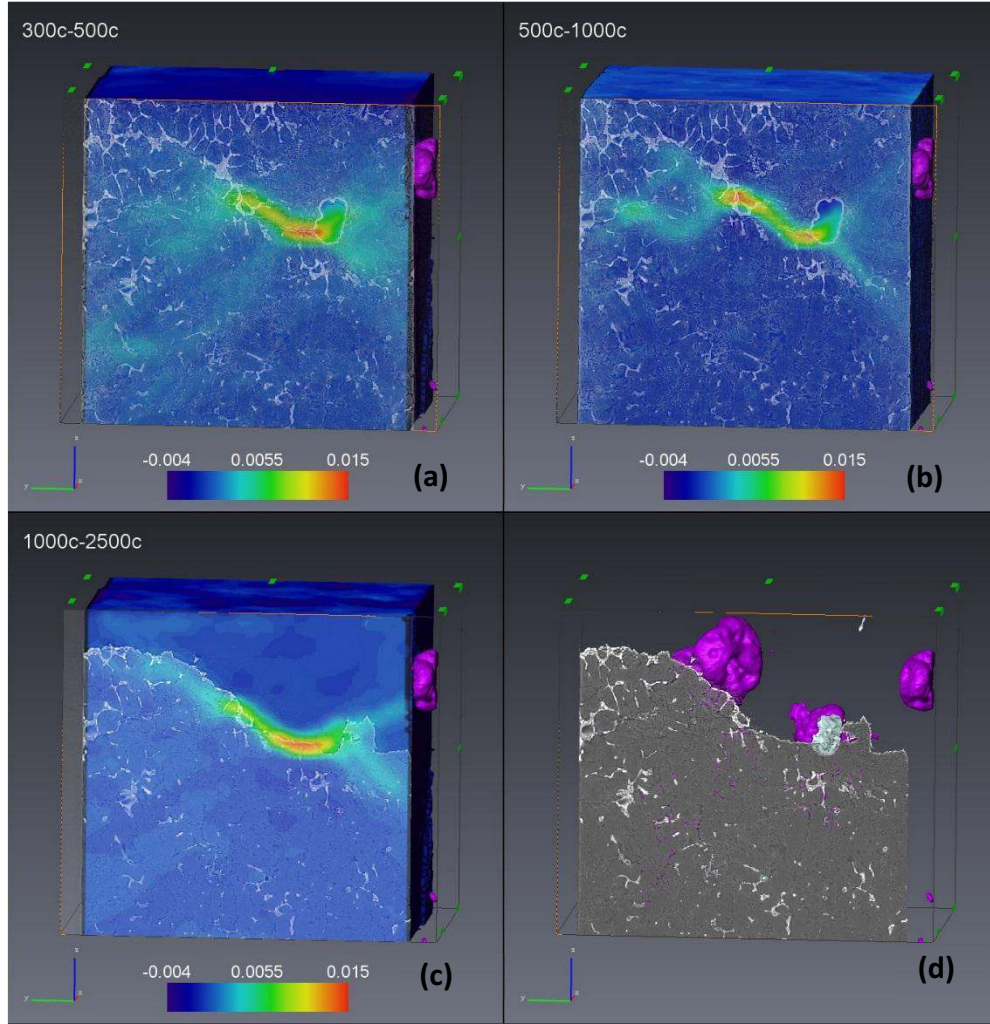


Figure 3. ϵ_{zz} strain field with the microstructure shown in transparency between (a) 300c-500c, (b) 500c- 1000c, (c) 1000c-2500c and (d) the fracture surface

The Finite Element results showed a large strain concentration at the pores cluster; where crack initiation was indeed observed. As a result, in the present case crack initiation were porosity driven while propagation was correlated with the presence of hard intermetallic phases.

4. Conclusions

The efficiency of the experimental protocol using laboratory and synchrotron tomography, FE simulation and 3D digital volume correlation to study the influence of the casting microstructure upon the mechanical properties of an Al-Si alloy has been proved. By prior screening the fatigue samples, it was to focus the X-ray tomography on a volume where cracks are likely to initiate. The synchrotron tomography permitted to increase the volume fraction of visible natural markers compared to laboratory tomography and thus allowed to enhance the spatial resolution and precision of the field measurements [8]. The DVC analysis of in-situ fatigue tests emphasized the relations between cracks, displacements discontinuities and strain localization in the measured fields. The results obtained at different steps of the fatigue cycles allowed the observation of crack

initiation close to the largest pores and of the crack propagation along the hard inclusions towards the free surface. The method illustrated here will now be systematically used to analyze the fatigue behavior of the 4 samples broken during the SLS fatigue experiment in order to make correlations between initiation sites and crack path and the local microstructural features. In a second step, similar fatigue test will be carried out at temperature around 200°C which are more representative of the service temperature of the cylinder heads.

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