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► To cite this version:

Nathalie Limodin, Ahmed El Bartali, Long Wang, J. Lachambre, Eric Charkaluk. Application of X-ray microtomography to study the influence of the casting microstructure upon the tensile behaviour of an Al-Si alloy. 1st international conference on tomography of materials and structures; ICTMS 2013, Jul 2013, Ghent, Belgium. hal-01736294

HAL Id: hal-01736294

<https://hal.science/hal-01736294v1>

Submitted on 30 Dec 2021

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Application of X-ray microtomography to study the influence of the casting microstructure upon the tensile behaviour of an Al-Si alloy

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Keywords: Cast Aluminium Silicon alloys, Digital Image Correlation, Laboratory X-ray CT

ABSTRACT

In cast aluminium alloys used in the automotive industry the microstructure inherited from the foundry process has a strong influence on the mechanical properties. In the cylinder heads produced by the Lost Foam Casting process, the microstructure consists in hard intermetallic phases and large gas and microshrinkage pores. To study its influence, full field measurements at the microstructure scale were realized during a tensile test performed in-situ under X-ray microtomography. Intermetallics were used as a natural speckle pattern. Feasibility of Digital Volume Correlation on this alloy was proved and the accuracy of the measurement was assessed and discussed in light of the small volume fraction of intermetallics and in comparison with the accuracy of Digital Image Correlation realized on optic images at a finer spatial resolution.

1. INTRODUCTION

Aluminium alloy automotive parts produced by the Lost Foam Casting (LFC) process have a coarser microstructure than parts produced with conventional casting processes at faster cooling rates. This coarse microstructure has a major influence on the fatigue properties. Although pores above a critical size play a decisive role by providing preferential crack initiation sites, an influence of oxides (Wang et al. 2006), iron-based intermetallics (Tabibian et al. 2010) and Si particles (Buffière et al. 2001) is also observed. In order to study the influence of the casting microstructure upon the fatigue behaviour of an Al-Si alloy, an experimental protocol, which relies on the coupling of full field measurements at the microstructure scale, either in 2D or 3D, with prior microstructural characterization of the specimen, has been set up and validated.

The present study will focus on the uncertainty analysis of the 3D displacement field measurement performed on X-ray microtomographic data as compared to 2D measurement.

2. EXPERIMENTAL

X-ray microtomography was performed at a 1.7 μ m voxel size at the Mateis laboratory (Lyon, France). The aim was first to obtain 3D characterization of pores and iron intermetallic in the A356 Al-Si alloy and then, to assess the feasibility of Digital Volume Correlation (DVC) for this alloy where natural markers are scarce. Thus a tensile test was realized inside the lab-CT (Figure 1) and scans were acquired at ten incremental loading tests before the specimen's failure at about 214MPa. Displacement field

measurements were then realized with CorreliC8 software (Stéphane Roux et al. 2008) using an isotropic element with a 24 voxel edge for a region of interest of $768 \times 768 \times 768$ voxels³ inside the original volume of $900 \times 900 \times 900$ voxels³.

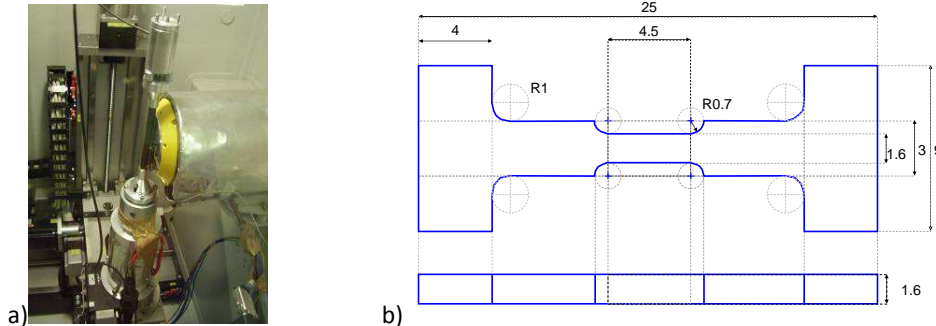


Figure 1: (a) In-situ tensile rig used inside the lab-CT and (b) specimen geometry (dimensions in mm)

Besides, in order to study the surface damage micromechanisms at a fine microstructure scale, an experimental protocol was developed to obtain a surface suitable for image correlation without using a speckle pattern that will mask the microstructure. Once an appropriate colour etching (Zwieg 2003) has been found, tensile tests were realized and a Questar long distance microscope was used for the in-situ observation during tensile tests.

3. RESULTS AND DISCUSSION

At a voxel size of $1.7 \mu\text{m}$, the pores, either microshrinkage or gas porosity, are easily observed and quantified as shown in Figure 2. The microstructure inherited from casting at a slow cooling rate is coarse, i.e. Dendrite Arm Spacing is about $79 \mu\text{m}$. Therefore, the coarse intermetallics are detected although their morphology is not fully resolved and they could be used as a natural speckle for DVC in order to measure the 3D strain fields. A $1.7 \mu\text{m}$ voxel size was chosen as a compromise between resolution and specimen size as higher resolution would require smaller, hence possibly less representative, specimens.

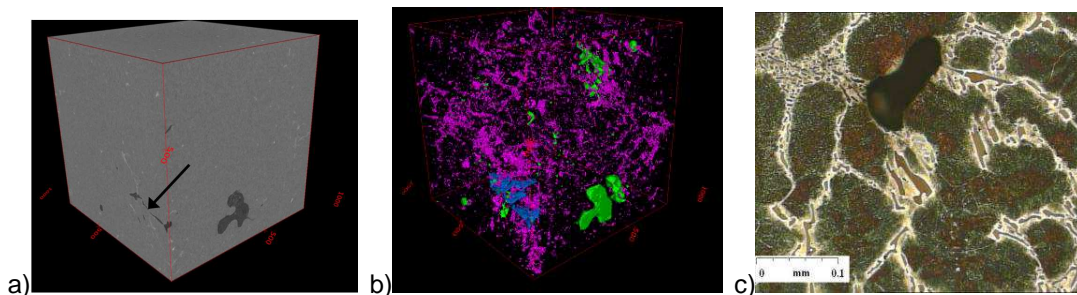


Figure 2: Microstructure of the A356 alloy: (a) 3D rendering of the specimen at 213MPa showing the raw tomographic data (the cube's edge is 1.3mm) and (b) the inner microstructure with intermetallics in purple, pores in green and crack in blue while Al matrix is made transparent and (c) metallographic image

In the present test, coalescence of two neighbouring pores, highlighted with an arrow in Figure 2a, has led to progressive crack growth until final failure. Figure 3 shows the displacement and corresponding strain field along the loading direction; one half of the fractured sample has been scanned and its tomographic image has been registered to the reference image and superposed to the strain field to allow for comparison of the crack path with local deformation. A good correlation can be observed between strain localization and displacement discontinuity in the measured fields and the crack location at pores.

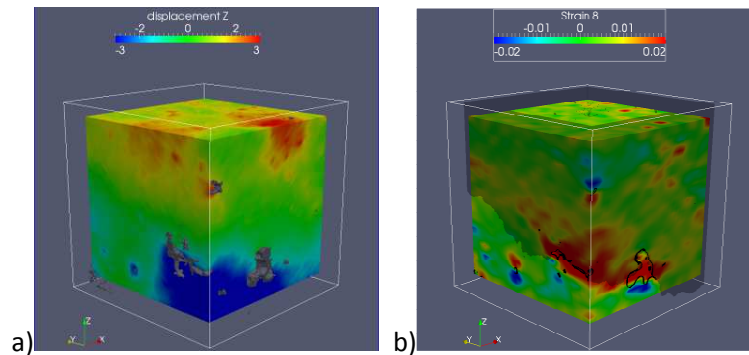


Figure 3: (a) 3D displacement field (in voxels) along z with pores shown in grey colour and (b) ϵ_{zz} strain field with the fracture surface shown in transparency

Usually, uncertainty of the displacement field in 2D is determined from the standard deviation of the displacement field computed between two images of the specimen: one at a reference position and one after a small shift, e.g. $10\mu\text{m}$ in the present case. In 3D, three shifts are needed to catch uncertainty in all directions. As the lab-CT X-ray beam is conical a translation along the beam direction will change the voxel size, e.g. from 1.7 to $1.695\mu\text{m}$ in the present case. This trick allows applying a known displacement field in all directions, i.e. a dilatation, which correspond to a maximum displacement of 1.5 voxel. The Figure 4 shows that the uncertainty amounts to about 0.2 voxel ($0.36\mu\text{m}$) at a size of element of 24 voxels ($40.8\mu\text{m}$) for the 3D measurement. It is a fairly high value when compared to what was obtained in (Limodin et al. 2010) for a nodular cast iron. The uncertainty of the 2D measurement varies from 0.13 to 0.37 pixels (0.04 to $0.12\mu\text{m}$) for a size of element that varies from 16 to 128 pixels (5.4 to $42.9\mu\text{m}$). As shown in Figure 2, colour etching enables to reveal Si segregation in the aluminium dendrites and gives a fine spatial resolution. The spatial resolution of the measured displacement field in 2D is thus much higher than in 3D with an uncertainty that remains smaller than in 3D whatever the element size.

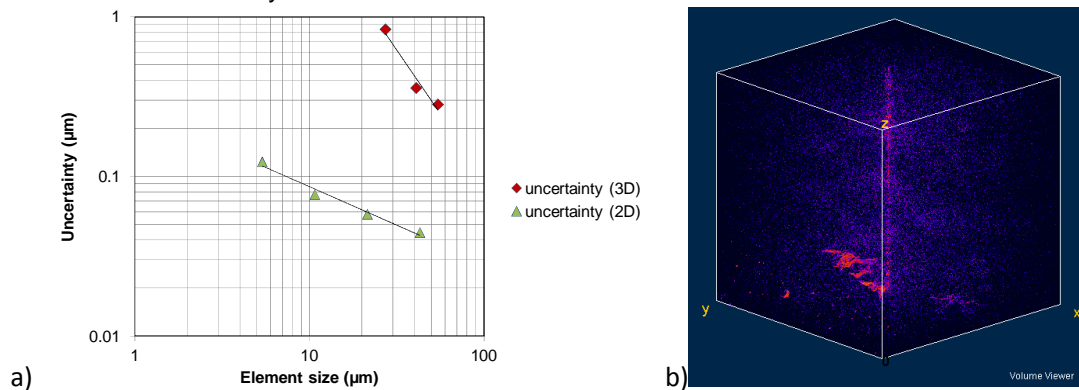


Figure 4: Uncertainty of the measured displacement field in 3D and 2D and residual error of the 3D displacement field

The results of the surface field measurements (Wang et al. 2012), although not reported here as we decided to focus on the measurement uncertainty, were indeed rather encouraging with, for example, strain localization at the locations of microcracks in the eutectic Silicon which were not observed at the resolution of the Questar image but with a Scanning Electron Microscope. The spatial resolution of surface field measurement seems difficult to achieve in 3D. The main reason must be the low volume fraction of natural markers in the bulk of the specimens. Considering that iron intermetallics are almost the sole detectable features, apart from porosity, and that their volume fraction amounts to about 0.28% , the results obtained with DVC are encouraging. Although for high spatial resolution, the uncertainty of the 3D displacement field is about one decade higher than for 2D measurements, the strain concentration at pores is well assessed although at a coarse resolution. The residual error of the correlation is maximum at the crack and helps reveal its 3D shape in Figure 4b. For the A356 alloy, DVC based on X-ray tomographic data obtained with a laboratory X-ray source has potential applications to measure strain

localization at the pores scale during a mechanical test. However, in order to obtain field measurement at smaller scales i.e. at intermetallics or at eutectic Si, which are not visible with lab-CT, surface field measurements performed on etched surface seem up to now the only possibility.

4. CONCLUSIONS

The usefulness of X-ray microtomography to study the influence of the casting microstructure upon the mechanical properties of an Al-Si alloy has been proved. Intermetallics were used as a natural speckle pattern. Feasibility of DVC on this alloy was checked and the accuracy of the measurement was assessed and discussed in light of the small volume fraction of intermetallics and in comparison with the accuracy of DIC realized on optic images at a finer spatial resolution.

The experimental procedure presented in this paper is now applied to an A319 silicon-copper based aluminium alloy grade. LFC A319 alloy has been recently extensively introduced in the automotive industry for a downsizing and lightweight objectives and cost reduction goals. It is particularly suited for in-situ X-ray tomography mechanical testing as it possesses a larger volume fraction, i.e. about 6%, of coarse X-ray visible inclusions, i.e. intermetallics and eutectic Al-AlCu₂. Then, to further increase the volume fraction of visible natural markers and enhance the spatial resolution and precision of the field measurements, in-situ fatigue testing will be realized with a synchrotron X-ray source. It is expected that the use of phase contrast in addition to attenuation contrast will allow resolving the eutectic Si as reported in (Tolnai et al. 2009) in addition to the inclusions already visible by simple attenuation contrast.

5. ACKNOWLEDGEMENTS

The authors wish to thank Jérôme Adrien from Mateis for his help and advices with the X-ray tomography experiment.

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