| ESRF | **Experiment title: In-situ observations of short fatigue crack behaviour in heterogeneous metal microstructures** | **Experiment number**: ME-387 |
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## Report: (Preliminary Report)

### Experiment Aim

The aim of this experiment was to obtain the first in-situ tomographic observations of short fatigue crack development in a heterogeneous metallic microstructure. This aim was achieved. The full analysis of the data is currently in progress, and preliminary results are reported here.

### Experiment Background

Fatigue is a major cause of failure in engineering components, particularly in the automotive and aerospace industries. Traditional structural integrity assessment procedures, such as the S-N approach (stress-lifetime to failure) are being supplemented by the damage tolerance approach, as it is recognised that manufactured materials contain quantifiable defects and imperfections. Knowledge of the rate at which fatigue cracks develop from these defects, coupled with statistical analysis of defect populations, can provide a realistic assessment of the risk of failure during the service life of components.

Engineering fracture mechanics can model the connection between the fatigue life and defects, such as porosity and inclusions. However, the current models do not take account of the interaction between the defect size and shape and heterogeneity of the microstructure on the same size scale. Small defects are becoming more significant as improved production methods and quality control eliminate larger defects. It is therefore necessary to develop fracture mechanics models applicable to small defects and long lifetimes. Damage tolerant design requires an understanding of short cracks and microstructure fracture mechanics.

Modelling the fatigue lifetime of components above the fatigue limit requires knowledge of the **development** of the **three-dimensional crack shape**. Interactions between adjacent small defects, such as crack coalescence may accelerate failure or lead to non-damaging shallow defects. Previously studies of short crack behaviour have been restricted to two-dimensional observation of the crack length at the free surface. This provides no information about the development of the crack shape. Serial metallographic sectioning can only determine crack shape at the **end** of the test, principally for larger cracks. Crack propagation is also influenced by the plane stress conditions at the surface, in contrast to the higher levels of constraint within the material.

Preliminary studies (Marrow, Çetinel et al. 2002), using small samples containing fatigue cracks that had been removed from large specimens, had proved the feasibility of imaging fatigue cracks using tomography. These observations were obtained using the 2µm camera in ID19, and the cracks had been opened by plastic deformation to increase visibility. In this experiment, we aimed to obtain the first **in-situ** images of nucleation and growth of a fatigue crack.

## Experimental Method

The fatigue specimens (Figure 1) had a 0.3 mm gauge diameter. These were tested in rotating bending at a frequency of approximately 45Hz using a compressed air driven, portable fatigue rig separate from the beam line. The tests were interrupted and the specimen was removed from the rig at intervals for tomographic analysis. A specimen after testing above the fatigue limit is shown in Figure 2. Our intention was to make the tomographic observations with the specimens under a tensile load, using the loading stage developed by JY Buffiere (Lyon) for use in ID19. The aim was to increase the crack opening displacement to assist with resolving the position of the crack tip. Observations both with and without the tensile load were therefore made using a pre-prepared specimen that had been tested below the fatigue limit for $10^6$ cycles, to determine the effects of tensile loading on the resolution of short cracks. This specimen was known to contain a short fatigue crack (Figure 3). However, the fragility of the miniature fatigue specimens proved to be a problem when inserting the specimens in the tensile loading rig for repeated observations, and after initial difficulties the remaining observations were made without the tensile load.

One specimen was tested to $5x10^5$ cycles without failing at a stress amplitude of 400 MPa. A total of 24 observations were made at intervals of $5x10^3$ cycles up to $2x10^4$ cycles, at intervals of $10^4$ cycles to $1.8x10^5$ cycles and also at $2x10^5$, $2.5x10^5$ and $5x10^5$ cycles. All observations were made without a tensile load. Preliminary analysis of the data has revealed fatigue microcracks, nucleated at porosity and graphite nodules (Figure 4). The crack lengths did not increase measurably between $5x10^4$ cycles and $5x10^5$ cycles, indicating that the fatigue cracks were stable, and had been arrested. This implies that the specimen was tested below its fatigue limit. Initial analysis of the change in shape of the crack plane with distance from the nucleating defect also shows the expected transition from a shear controlled stage I crack inclined to the loading axis, to a tensile controlled stage II crack perpendicular to the loading axis.

The full quantitative analysis of the data is in progress. We have been able to identify several cracks in the gauge volume, and will determine their rate of crack growth and the sequence of the development of crack shape using the data. This will be correlated with the transition from stage I to stage II growth. Interactions between cracks will also be studied. The analysis requires identification and measurement of defects in over 20 "volume replicas", which is proving to be very time-consuming. We expect to complete the data analysis over the next few months. We shall then perform serial-sectioning of the specimen to compare the true crack shape with the tomographic observations, and also to correlate the position of the arrested crack tip with microstructure.

## Conclusion

Our results demonstrate that short cracks can be successfully resolved using the 0.7 µm camera on ID19. We have also obtained the necessary data to demonstrate for the first time the nucleation, growth and arrest of short cracks with in-situ three-dimensional observations.

High resolution in-situ X-ray tomography has therefore been demonstrated to be an important technique for the study of short cracks. We now aim to extent the technique to the study of short stress corrosion cracks and the behaviour of short fatigue cracks in near-surface residual stress fields.

## Acknowledgement

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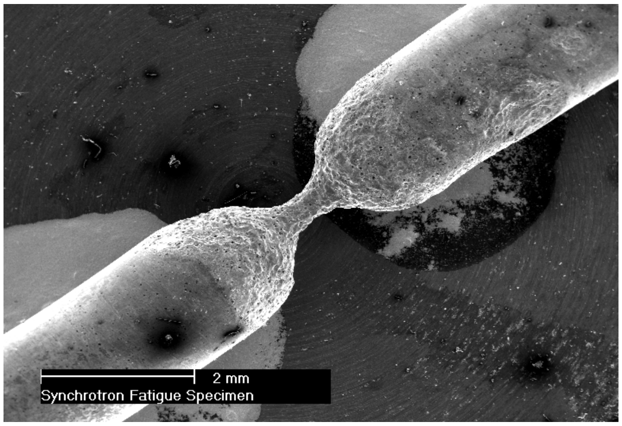


*Figure 1: Miniature fatigue specimen.*

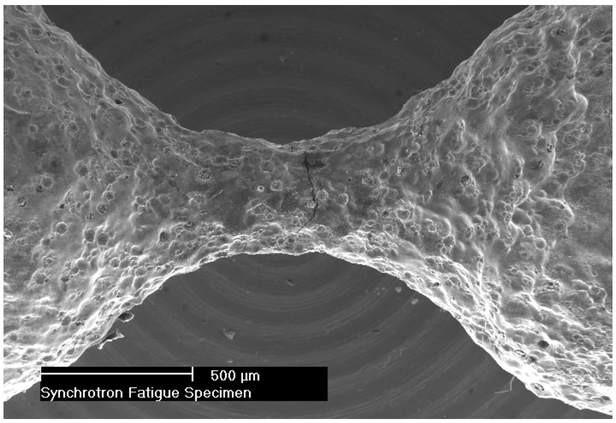


*Figure 2: Miniature fatigue specimen, containing a fatigue crack.*

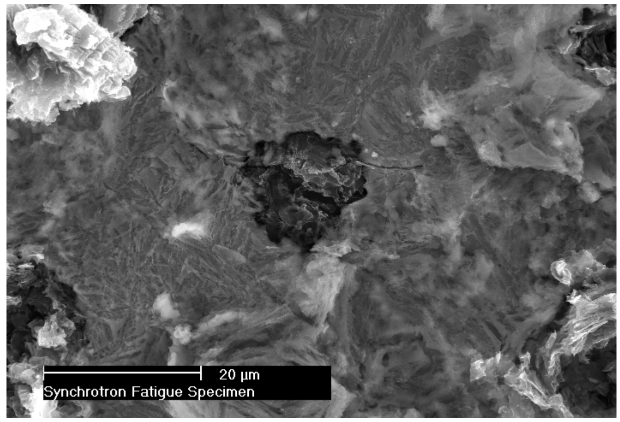


*Figure 3: Short fatigue crack, nucleated at graphite nodule.*

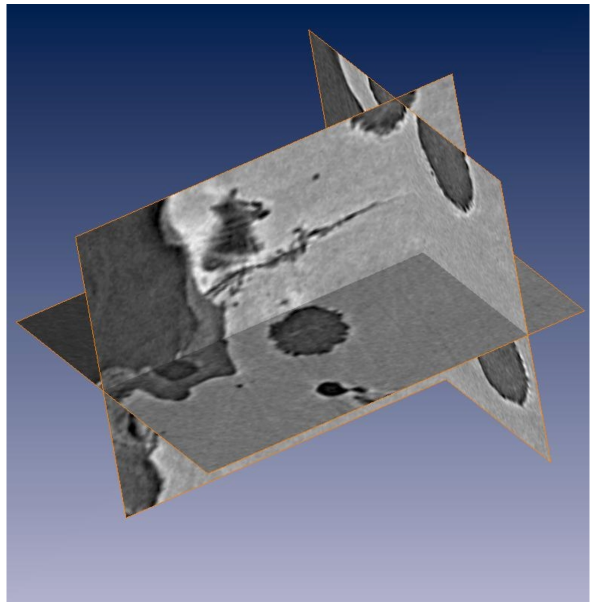

*Figure 4: Fatigue crack nucleated at pore, imaged after $5x10^4$ cycles. The crack length is approximately 50 $\mu$m.*

## References

Marrow, T. J., H. Çetinel, et al. (2002). "Fatigue crack nuclei in austempered ductile cast iron." Fatigue & Fracture of Engineering Materials & Structures 25(7): 635-648.