FATIGUE CRACK GROWTH AND CRACK TIP CYCLIC PLASTICITY OF 304L STAINLESS STEEL AT HIGH ΔK

M. M. J. Gillet[1a], C. M. Davies[1]

[1] Department of Mechanical Engineering, Imperial College London, South Kensington Campus, London, SW7 2AZ. UK.

[a] E-mail address: m.gillet22@imperial.ac.uk (Martin M.J. Gillet)

Abstract
Pressurised water reactors in the UK are in need of life extensions, which requires a better understanding of fatigue crack growth in reactor components. Stainless steel 304L primary circuit components are subject to fatigue crack growth at very high stress intensity factor ranges over a reactor lifetime. Hence, large compact tension specimens were made to reproduce reactor conditions, and fatigue crack growth tests were carried out. Cyclic plasticity was investigated both in simulation and experimentally with DIC methods. Insights into the fatigue crack growth of ductile stainless steels in presence of significant plasticity were developed.

Background

Multiple nuclear reactors in the UK are in need of life extensions and fatigue crack growth in the primary cooling circuit can be the limiting factor on lifetime. So, to extend the life of these reactors it is necessary to understand the fatigue crack growth behaviour of 304L stainless steel: one of the main pipeline steels used in such plants. The models used so far for fatigue crack growth estimations and remaining lifetime in codes rely on the empirical Paris Law and stress intensity factor K which inherently requires small scale yielding. This is not exactly representative of 304L in plant conditions as components will be geometrically large so with crack tips that are highly constrained, and the thermal stresses will induce very high ΔK factors. There is also no universal way of interpreting crack growth rate beyond small scale yielding. It is therefore necessary to study the crack growth behaviour of this steel under severe cyclic plasticity to correctly assess the extent of conservatism and develop our models further.

Furthermore, the empirical Paris-type relationships used to describe the fatigue crack growth of 304L in valid (ASTM E647 Standard) small-scale yielding conditions is preserved all the way to the high ΔK regime in invalid high-plasticity conditions. It is suspected that a possible explanation to this could be found by investigating the cyclic hardening at the crack tip during crack growth, and the proximity to elastic shakedown of the material ahead of the crack tip.

Experimental

The first experimental stage consisted in measuring the material properties of the batch of 304L stainless steel in three orthogonal directions and carry out a classic material characterisation with grain analysis. Then, a series of cyclic tests on uniaxial specimens were performed to measure the cyclic hardening behaviour of the specimen. The intent of this being to use the hardening data both in simulation and to analyse Digital Image Correlation (DIC) results of fatigue crack growth tests.

Large compact tension specimens (LC(T)) were loaded at high ΔK ranges in load control. The tests were monitored via a clip gauge at the crack mouth; a DC potential drop method over the crack as it grows; and DIC. The objective of the experiment was to be able to track how fast the crack grows compared to how fast the cyclic plastic zone at the crack tip approaches elastic shakedown. Secondly, a general view of the full plastic zone at the crack tip as a crack grows is also of interest to understand the true extent of plasticity compared to what is predicted by standard limits and constraints on validity.

Simulation

2D Simulations were run based on the measured hardening properties in an Abaqus combined hardening model. Some simulations consisted in a static crack that was cyclically loaded to ΔK near 60 $MPa.m^{0.5}$. These showed the size of the reverse yielded cyclic plastic zone, and thus the extent of cyclic hardening with increasing cycle. These were compared against fatigue crack growth experiments and offered insight into the material. They also were used to calculate crack opening stress which can be useful in analysing the experimental crack growth. Figure 1 shows a mises stress contour of one such simulations with a similar stainless steel. The size of the cyclic plastic zone is significant compared to the crack. Hence it is suspected that the state of the material in this cyclic plastic zone could explain the crack growth behaviour in these high plasticity conditions.

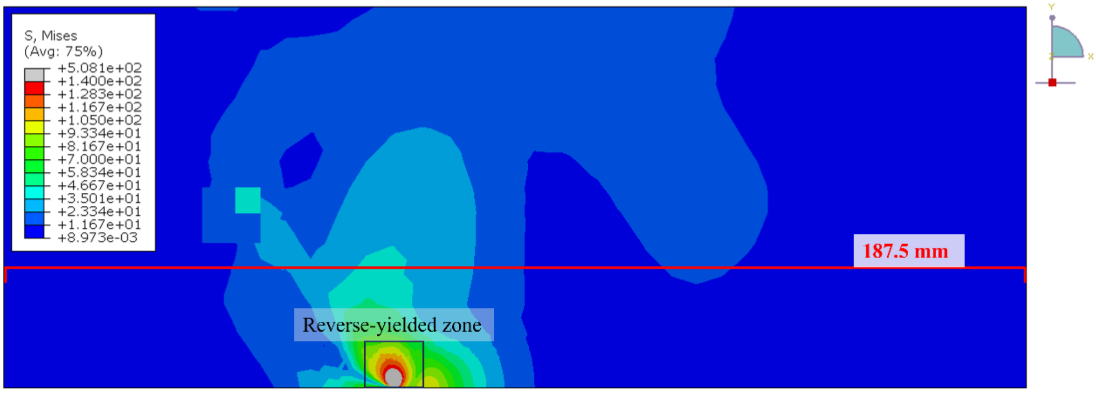

Fig. 1. Mises stress contour at the crack tip in a half-Large Compact Tension Specimen (LC(T) 187.5 × 90 × 25 mm) showing the reverse yielded cyclic plastic zone from crack closure in a ductile stainless steel. The size of the reverse-yielded plastic zone (≈ 4 mm) is highlighted relative to crack length.

Other simulations were run via a node-release method where a crack is artificially grown at a known rate. This type of simulation showed the growing plastic wake that follows crack growth, and the effects of varying crack length and thus constraint and ΔK on the plastic zone.

Conclusion

In this work, experiments were coupled with simulation to investigate the cyclic plasticity at the crack tip. Monotonic and cyclic mechanical properties of 304L were measured using classic experiments; Very large compact tension specimens and digital image correlation (DIC) were used to quantify cyclic macro-strain and deduce proximity to elastic shakedown at the crack tip. Measured properties and fatigue crack growth rates were used in simulation to offer insight past the surface of the material. Finally, the study of the aforementioned parameters was extended to different specimen sizes and constraints.

References

[1] H. Gao, Z. Lin, X. Huang, H. Shang, J. Zhan. In Situ Measurement of Cyclic Plastic Zone and In-ternal Strain Response of Q&P Steel near Fatigue Crack Tip Region Based on Micro-DIC Materials 2022; 15, 6114.

[2] Q. Wang, R. Bao, B. Liu, S. Lu, H. Peng, B. Chen. Comparison of fatigue crack growth behaviour in electron-beam and laser powder-bed-fusion Inconel 718. Materials Science and Engineering: A, 2024. 0921-5093.