Stroboscopic neutron diffraction to capture crack closure during high cycle fatigue

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Abstract. Crack closure is a phenomenon that appears during fatigue crack growth measurements when crack faces contact during positive applied loads. Crack closure is caused by various mechanisms, such as compressive residual stresses acting on the crack tip. This is turn reduces the effective stress intensity factor range (*ΔK*) applied to the crack tip. Capturing and understanding crack closure can lead to a greater understanding of how fatigue cracks grow through residual stress fields.

In the present work a stroboscopic neutron diffraction measurement was performed on welded samples during fatigue crack growth rate measurements on the SALSA beamline at the Institute Laue Langevin (ILL) [1]. This is the first time that stroboscopic neutron diffraction has been performed on welded samples. The data is compared to crack mouth opening displacement (CMOD) measurements, to validate the measurement of the crack closure phenomenon. This method is valuable as it can help maximise the utilisation of beamtime and minimises issues of stress relaxation during measurements.

Possible sessions

8. Fatigue & Fracture, 16. Novel Experimental Techniques, and 20. Residual Stresses.

Introduction

In linear elastic fracture mechanics, the growth rate of a fatigue crack per cycle (da/dN) can be calculated using the Paris law (1),

$$\frac{da}{dN} = C\Delta K^m, \tag{1}$$

where C and m are material constants and ΔK is the stress intensity factor range. In isotropic, homogeneous materials ΔK is calculated based on the difference of the maximum and minimum applied stress intensity factors, K_{max} and K_{min} respectively. When confounding factors are involved such as residual stresses, corrosion product buildup, or viscous fluid ingress, crack faces can come into contact at positive applied loads, known as crack closure.

Crack closure can adjust the actual ΔK that the crack tip experiences by increasing the K_{min} value. This is often inferred by looking at the CMOD vs. load curve, and comparing the slope of the curve to see when the crack closes. One issue with this method is that it is a remote measurement and does not provide any information about the crack tip conditions. One way to gain insight into the crack tip conditions can be to measure the crack tip strains using non-destructive methods such as neutron diffraction. Typically when using neutron diffraction to measure crack tip strains, a sample will be loaded into a tensile rig, then the load incrementally increased and the neutrons measured between each loading step to capture the crack tip strains. As count times for neutrons can be on the order of minutes, this can lead to stress relaxation during the neutron measurement, and the loss of dynamic effects. Stroboscopic neutron diffraction, which was successfully demonstrated on the SALSA beamline at the ILL by Coules et al. [2] in constant ΔK conditions in aluminium alloys, allows for capturing of crack tip strains in-situ during cyclic loading.

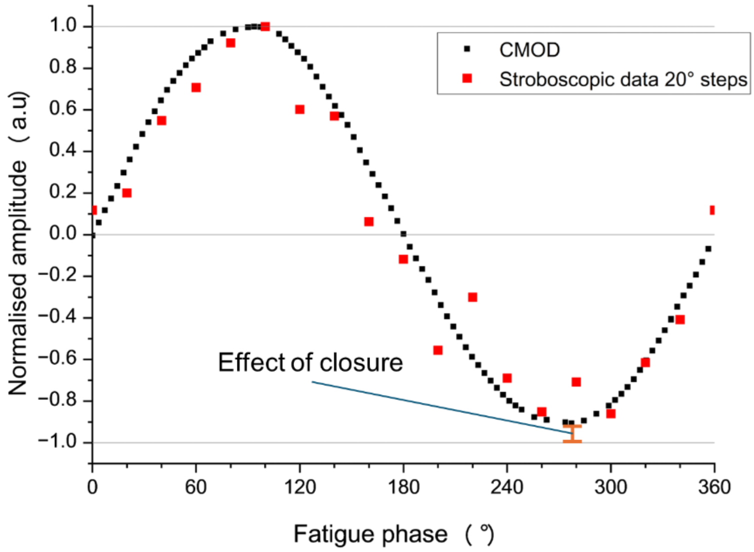

Fig. 1 - normalised stroboscopic neutron diffraction data taken at 20° steps and normalised CMOD data, showing the effect of crack closure.

In this work we have expanded on the stroboscopic neutron diffraction method by using it to investigate the crack closure phenomenon during constant load range tests (ΔK increasing), in welded samples where compressive residual stresses interact with the applied load.

Methodology

The material used was a compact tension (CT) specimen cut from an SAE 316L(N) stainless steel pipe, which had been circumferentially electron-beam welded [3]. The CT specimen was machined so that the crack would grow along the weld plane, where compressive residual stresses acting on the crack tip promote crack closure.

The stroboscopic neutron diffraction measurement during fatigue crack growth was performed on the SALSA instrument at the ILL. The fatigue crack growth rate test was performed using a constant load range in line with ASTM E647-23a [4] on an Instron tensile test machine. The load and CMOD values from the Instron were synchronised with the neutron detector at SALSA so that each neutron event can be associated with the cyclic loading phase. Neutrons from a number of cycles were then binned based on their loading phase, and a detector image created. This was then analysed using the LAMP software [5] and the opening strain calculated for each load phase. This is then normalised and compared to the CMOD cyclic response for validation (Fig. Fig. 1).

Conclusion

This work successfully demonstrates the ability to capture the crack closure phenomenon during fatigue crack growth rate tests using stroboscopic neutron diffraction, for welded samples. Allowing for dynamic effects to be captured in-situ to develop a further understanding of the crack tip conditions during cyclic loading. The ability to be implemented during any standard neutron diffraction measurement of fatigue (such as mapping of crack tip strains) to maximise the use of beamtime is a key benefit of this method.

References

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