Fatigue Crack Shape Control under Bending by Cold Working

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ABSTRACT. *This paper presents an experimental study of crack shape evolution in mild steel specimens under cyclic loading. It is widely known that the introduction of compressive residual stresses by cold working the surface can be highly beneficial in improving the fatigue performance of structural components. Although it is recognised that relaxation of surface compressive residual stress can reduce the potential benefits, the effects of residual stress on crack shape evolution are often overlooked. Previous studies have shown that the intensity of the surface compressive residual stress has a pronounced effect on fatigue crack initiation. A recently developed technique termed controlled stitch rolling, which applies differing intensities of compressive residual stress at specific regions in a structure, is shown in the paper to influence fatigue crack propagation life considerably.*

The paper presents the results of five fatigue tests under bending load in different thickness plates. Crack growth retardation is apparent in all tests and this is attributed to the constrained crack shape. Rerolling after crack initiation and number of rolling passes are also considered. Stitch rolling is shown to alter the fatigue crack propagation path and has promoted localised failures in the fatigue specimens. The results suggest the method might be efficiently utilised to implement the leak before break design philosophy but not under bending.

INTRODUCTION

The benefits of compressive residual stresses in alleviating and enhancing fatigue performance are well known. Screw thread roots, shaft fillets and many other machine details are routinely cold rolled for this reason and improvements in resistance to fatigue crack initiation by a factor of up to five fold are not uncommon [1 -3]. Features of residual stresses in metals are that they are often transient in nature and can relax under cyclic loading and at high temperature. The magnitude of residual stress a material can contain is related to its yield stress, thus high strength materials can contain higher residual stresses and in theory can therefore benefit more from cold working treatment.

A previous paper at the *International Conference on Fatigue Crack Paths* [4] introduced the idea of controlling fatigue crack propagation through “stitch cold rolling”. The study was at the time in its infancy. This present paper reports further tests including one on a cracked specimen approaching 1 x 10^7 cycles, still exhibiting a slow linear crack growth rate.

Firstly, to briefly describe the context for the work, it should be appreciated that crack shape can be just as influential on crack propagation as applied load magnitude [5]. To illustrate this, Figure 1 below shows the well known Newman Raju flat plate surface crack Stress Intensity Factor (SIF) solution [6] around a crack front under tension, plotting Normalised SIF (or Y Factor) against crack angle ($0 \rightarrow \pi$) for a range of crack shapes (crack aspect ratio).

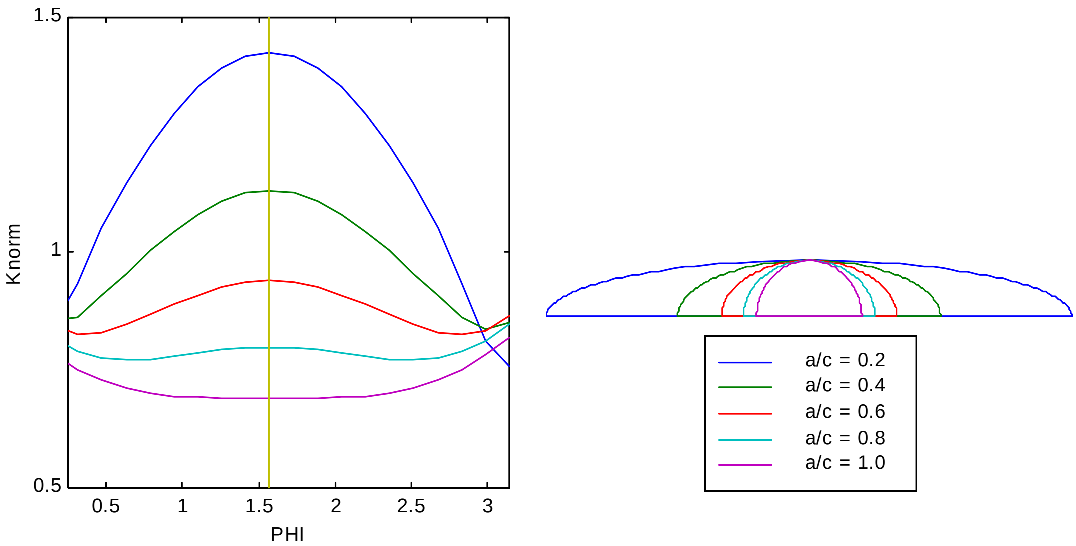

Figure 1. Newman Raju SIF Solutions [6] for different Shaped Cracks

At the crack deepest point ($\pi/2$) a very long crack with an aspect ratio of a/c = 0.2 will have a high SIF compared with the value at the surface point. This crack will therefore tend to grow faster at the deepest point meaning the crack aspect ratio will become higher as the crack grows. A shorter crack of the same depth, say a/c = 0.6 will have a far lower SIF at its deepest point, but still this is higher than the SIF at the surface. Taking the other extreme, a semi-circular crack (a/c = 1.0) will have a higher SIF at the surface than at its deepest point meaning it will extend faster at the surface under cyclic fatigue loading resulting in a semi-ellipse with a lower aspect ratio. These observations are important for the predication of crack propagation behaviour but also suggest that if a crack shape can be prescribed or crack growth restricted in one direction, then the crack growth rate can be controlled.

Taking the Newman and Raju solutions [6] with an RMS SIF [7] approach crack aspect ratio evolution behaviour can be predicted. Figure 2 below shows this for an a surface crack in a flat plat under pure bending. Many researchers have observed the behaviour illustrated by Figure 2 and that irrespective of the initial or starting crack shape, the crack will tend to an optimum aspect ratio. This is independent of applied stress range assuming a single crack but can be effected by material anisotropy and certainly by loading mode (e.g. tension, bending, shear, etc.,).

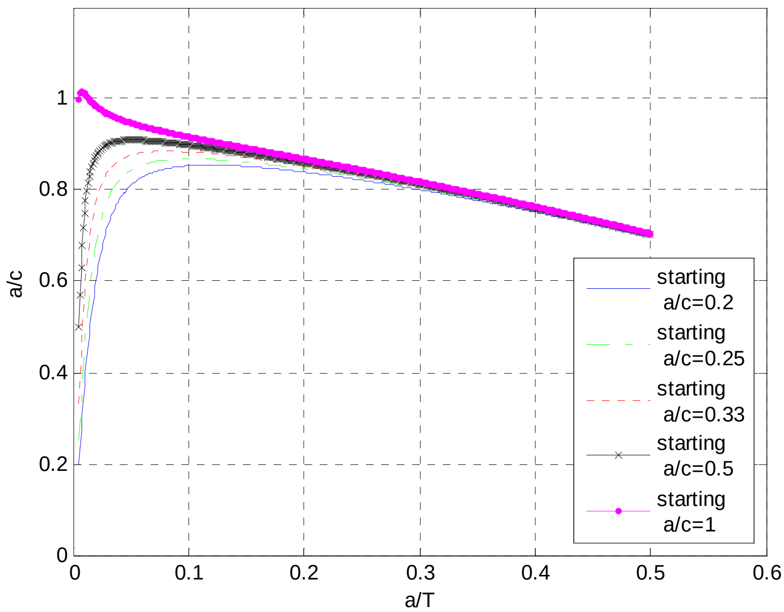

Figure 2. Predicted Crack Shape Evolution.

EXPERIMENTAL TEST DETAILS

The test specimens were fabricated from BS EN 10025 Grade 275, a mild steel with a yield strength of 275MPa [8]. The plates were 790mm in length and 200mm in width, specimens 1 & 2 had a thickness of 40mm, specimens 3, 4 & 5 were 20mm thick. Stitch rolling, where the central area of the plate was left unrolled, was performed using a purpose built cold rolling rig applying a force of 21kN to the roller placed in a machined notch on the plate surface and forced along the notch by a hydraulic jack. Several rolling passes were applied, monitoring the applied load carefully during the rolling process. Table 1 below details these and summarises the test parameters.

Table 1. Test Specimen Details.

Specimen	Plate Thickness (mm)	Cold Rolling Pressure (psi)	No. of Passes	No. of Re-roll Passes (after initiation)	Unrolled Length (mm)
Test 1	40	6000	3	3	20
Test 2	40	6000	3	3	40
Test 3	20	6000	4	0	20
Test 4	20	6000	5	0	20
Test 5	20	6000	5	0	40

Tests 1 and 2 were also rolled again following crack initiation as these were the first tests completed and it was unknown whether the residual stresses due to rolling would have remained during such a relatively large number of fatigue cycles. Tests 1, 3 and 4 had an unrolled length of 20mm whereas tests 2 and 4 had a longer 40mm unprotected length. Table 2 below summarises the fatigue tests parameters and duration.

Table 2. Summary of Fatigue Tests.

Specimen	Nominal Stress Range (MPa)	Fatigue Cycling Frequency (Hz)	No. of Cycles to Crack Initiation	Total Test Cycles
Test 1	122	4	128,000	4,000,000
Test 2	122	4	100,000	4,850,000
Test 3	120	4	345,000	3,718,000
Test 4	120	4	1,161,000	9,380,000
Test 5	120	4	500,000	6,000,000

Crack sizing and monitoring was by Alternating Current Potential Difference (ACPD) that allowed the depth and length of the cracks to be monitored in a non-destructive manner during testing. Figure 3 shows the type of data obtained; this allowed minimal interruption of fatigue cycling so that a large number of fatigue cycles could be applied.

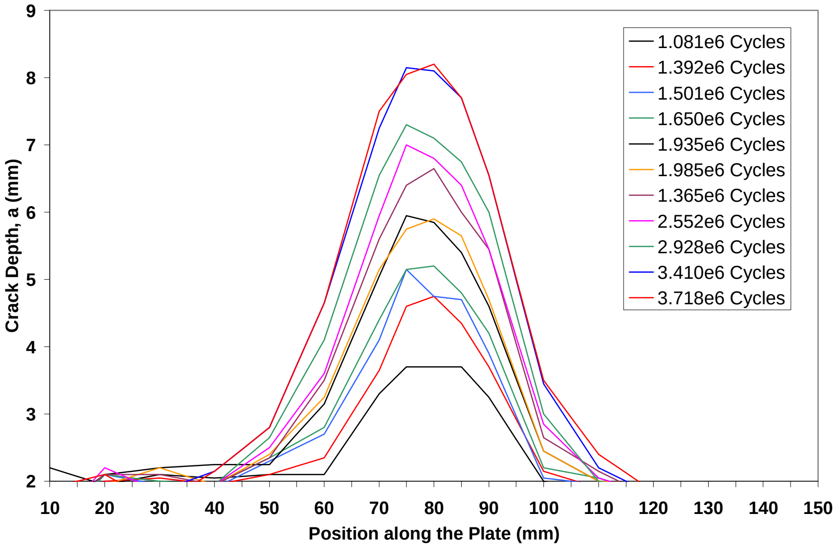

Figure 3. Crack Shape Evolution for Test 3.

FATIGUE TEST RESULTS

Figure 4 below shows the fatigue crack growth results for all the tests. None of the cracks grew through the plate thickness or width and tests were terminated due to cracks initiating at other locations (at the specimen edges) or for reasons of time and project resources.

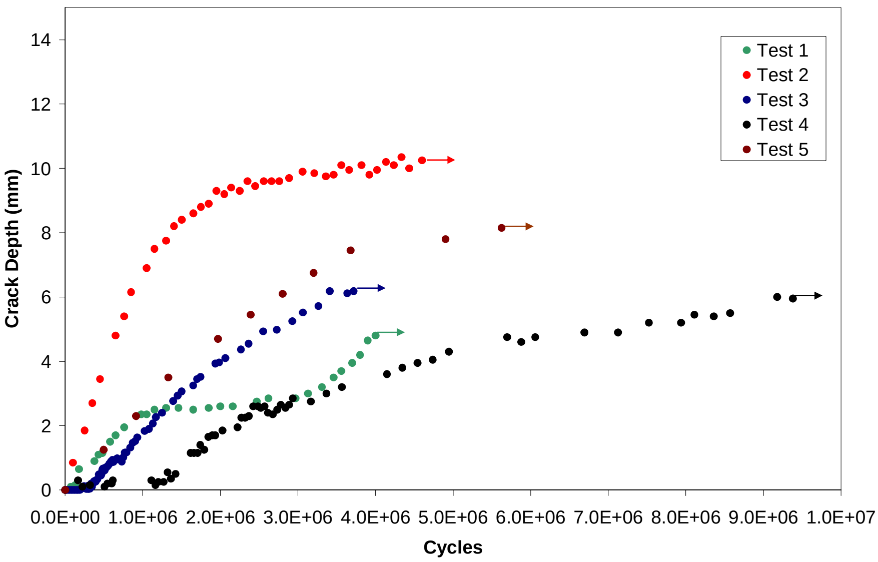

Figure 4. Crack Growth Data for all Tests.

Following testing, specimens were cooled in liquid nitrogen and broken open to observe the fatigue crack surface. Figure 5 below firstly shows a typical crack shape (beachmarked to highlight the shape evolution) from an artificial starter notch growing in a semi-elliptical manner. This is contrasted by the crack shape observed from Tests 1 and 2 and to a lesser degree tests 4 and 5. Beach marks on the surfaces of Tests 4 and 5 show characteristics of the unusual shapes seen from specimens 1 and 2.

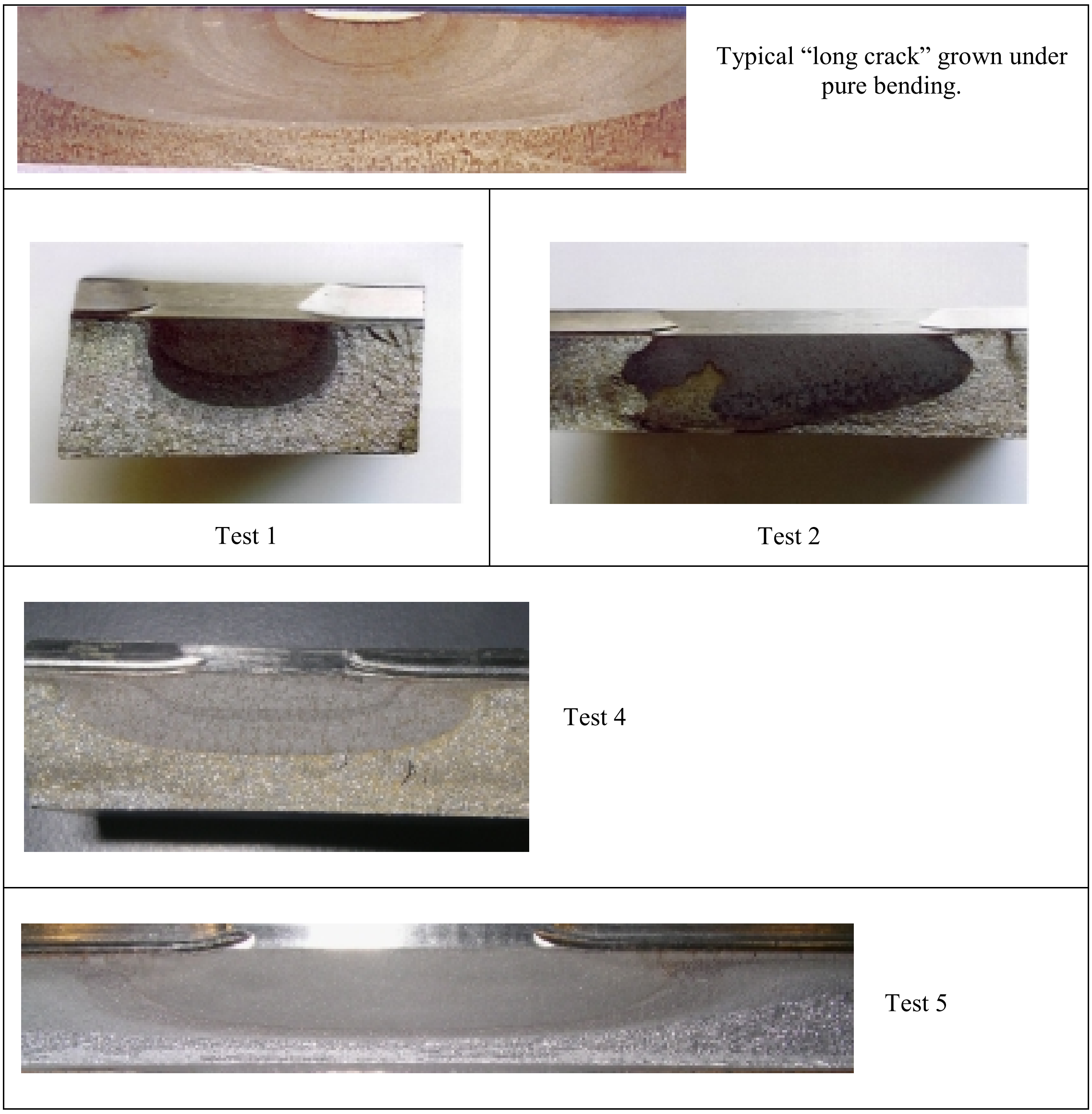

Figure 5. Fracture Surfaces.

DISCUSSION

The crack growth data in Figure 4 are clearly unusual not only due to the very slow crack propagation rates but also several tests clearly show a retardation effect. All tests show normal fatigue crack growth up until the crack extends out of the unrolled length to meet with the cold rolled region. Tests 2 & 5 had the longest unrolled length (40mm) and the results clearly show deeper cracks despite these having two different plate thicknesses. Neither test showed a clear resumption of growth following arrest but again it should be noted the tests were terminated prematurely. Test 3 showed similar behaviour, Tests 1 and 4 clearly show recovery following retardation. These tests differed in the plate thickenesses but also that Test 1 was rerolled after crack initiation. Test 4 shows the extrodinary propagation life of greater than 8 x 10^6 cycles, a comparative unrolled propagation life would be in the order of 1.5 x 10^6 cycles using a Newman Raju based prediction.

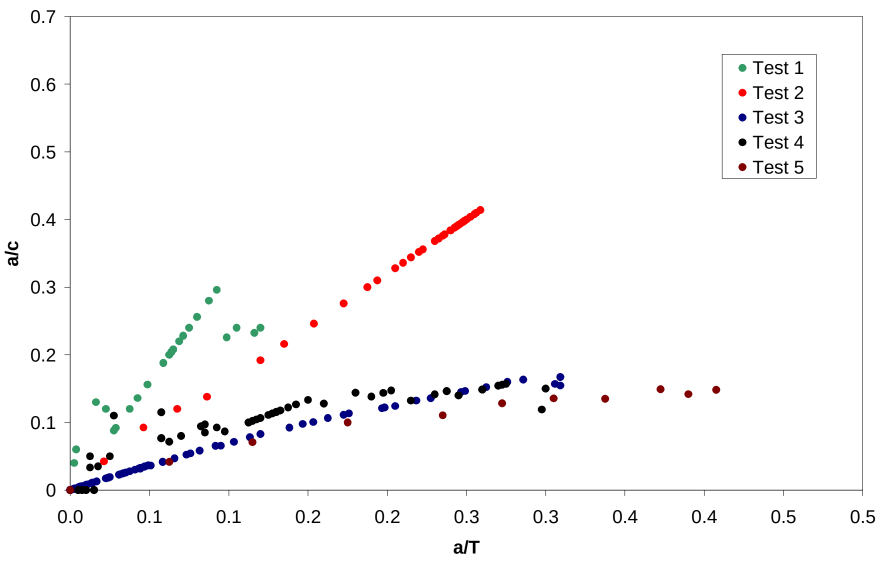

Figure 6. Crack Shape Evolution Data for all Tests.

Figure 6 above shows the crack aspect ratio data. If this is compared with Figure 2, it will be appreciated that the crack shapes have in all cases been altered significantly from their optimum aspect ratio. Under bending these cracks have higher stress at the surface point as they grow towards the neutral axis. It appears clear for the relatively thin plates tested that under pure bending it is unlikely that a crack could be encouraged to grow to through thickness. This would not be the case under axial tension and at this point, it is hypothesised that axial tension should produce a leak-before–break crack. The retardation and in some cases, the crack arrest effect however, is remarkable.

CONCLUSIONS AND FUTURE WORK

The following comclusions can be made:

- Controlled surface cold working can significantly retard fatigue crack propagation.
- The effects of cold working were observed for several million cycles at a nominal cyclic stress close to half yield stress.
- Cracks loaded under bending extended only very slowly in depth when the length was contained by cold working meaning that through thickness cracks are unlikely.

Current work at UCL involves axial tests on shot peened and laser peened specimens. In addition, residual stress measurements are being made and in parallel an analytical fracture mechanics model is under development using a weight function approach [9]. It is anticipated that experience with fatigue testing and development of analytical tools will allow the use of stitch/preferential cold working in structural components to extend life and develop the concept of controlled failure design.

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