Crack Shape Control using Cold Rolling

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ABSTRACT. *The effect of cold rolling on crack shape evolution was investigated by experimentation. A recently developed technique termed stitch rolling, which applies differing intensities of surface compressive residual stress at specific regions in an engineering structure, was adopted to introduce compressive residual stress onto test specimens to control both the rate and shape of crack propagation. Three BS 7191 Grade 275A mild steel plates having undergone different cold rolling procedures were subjected to medium cycle fatigue tests under bending. Fatigue crack growth was periodically monitored using crack sizing non-destructive testing methods and results are presented in terms of crack shape evolution. The different cold rolling procedures were seen to have a significant influence on the crack initiation, crack propagation path and the overall fatigue life of the specimens. The fatigue lives of stitch rolled specimens were significantly improved. In addition, cold rolling was observed to have caused crack arrest and retardation. Comparisons with an analytical fracture mechanics solution is also presented.*

INTRODUCTION

Fatigue has been a concern to engineers since its discovery almost one hundred and fifty years ago. Most structural failures are caused by fatigue, or at least intensely influenced by it. Since fatigue is widely viewed as an unfavourable phenomenon, many studies to address fatigue have been carried out over the past one hundred and fifty years. Metals are the most widely used materials in almost all fields of mechanical and structural engineering and metallic fatigue has long been a challenge for scientists and researchers. Since cost, weight and durability of a material are often the most important factors during material selection, a vast amount of research has been carried out seeking ways to increase the strength of metals.

Cold Rolling

One of the most effective ways of increasing fatigue life of a component is surface treatment. Nowadays, various types of surface treatments are used and cold rolling is one of them. Cold rolling, a cold working surface hardening method, has been adopted by industries for almost a century. Cold working can be defined as plastic deformation produced in a material at a temperature below its recrystallisation temperature [1]. This surface treatment introduces a layer of compressive residual stress onto the surface of the material by plastic deformation. This beneficial compressive residual stress increases the fatigue resistance of components, particularly when applied in areas of bending stress or at stress concentrations. Cold rolling, being a relatively simple and inexpensive process, has attracted the attention of many researchers [2-7]. Basically, cold rolling utilises local plastic deformation by applying pressure onto a component surface by using narrow rollers. The existence of inhomogeneous plastic deformation in the structure of material contributes to the resultant residual stress. In addition to conventional cold rolling processes, the introduction of compressive residual surface stress by localised cold rolling is adopted in many manufacturing processes. In summary, besides being a relatively economical and simple forming operation for threaded members like bolts and screws, localised cold rolling is very beneficial for fatigue resistance. Heywood [8] reported a fifty percent greater fatigue strength for rolled threads compared to cut or ground threads made of high-strength steel. Han [4] and Knight [2] demonstrated the significance and effects of cold rolling on drillstring threaded connections, grooved rods and plates.

Stitch Rolling

The control of crack shape by introducing different levels of compressive residual stress in drillstring threaded connections was investigated by Knight [2]. In an attempt to use variations in the level of compressive residual stress to influence the crack length in drill string threaded connections, Knight developed a controlled cold rolling technique termed stitch rolling [2]. The idea behind stitch rolling is to apply differing intensities of compressive residual stress at specific regions in a structural component to preferentially strengthen certain areas relative to others. Figure 1 illustrates the localised stitch cold rolling technique that was used in this study. Figure 2 shows a compressive residual stress zone either side of an untreated zone at the root of a v-notched plate. In this example the cold rolled region was strengthened while the unrolled region was left unprotected. Hence, cracks were expected to initiate in the unrolled region. The unique characteristic of stitch rolling is believed to influence the crack shape evolution. Rolling was carried out three times to provide a more uniform distribution of residual stress.

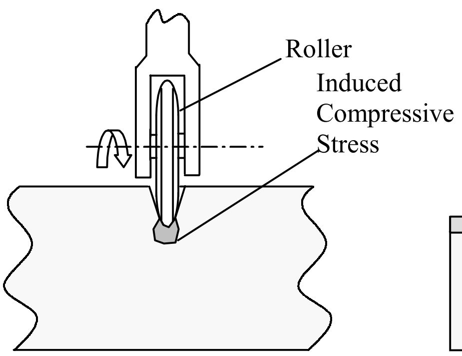


Figure 1. Stitch Rolling.

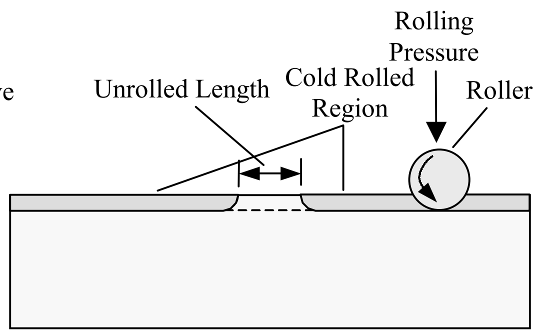


Figure 2. Compressive residual stress zone.

EXPERIMENTAL PROCEDURES

The test specimens used were BS7191 Grade 275, a mild steel with a yield strength of 275MPa and Young's Modulus of 211GPa [9]. The mild steel plates had dimensions of 790mm in length, 200mm in width and 40mm thickness. A notch was introduced into the centre of each test specimen, using a 60^0 cutter and edge radius of 0.35mm. The specimens were subjected to medium cycle fatigue tests under four point bending, which provided a pure bending and zero shear force condition at the centre of the specimen. The fatigue tests were performed on an Instron 1000kN servo-hydraulic test machine and digital controller.

All three specimens were pre-cracked at a relatively high stress range. Visual inspection methods were used as the most fundamental or secondary inspection methods, which were performed up to crack initiation. For primary crack detection and measurement, Alternating Current Potential Drop (ACPD) [13] and Magnetic Particle Inspection (MPI) [14] were used. ACPD, an NDT technique which utilises the skin effect of an Alternating Current (AC) passing through an electrical conductor to measure flaws, is a reliable method for crack depth measurement while MPI was primarily used for crack detection and crack length measurement. ACPD was performed using a "U8 Crack Microgauge".

Stitch Rolling

Stitch rolling was performed using a cold rolling jig, which was designed by one of the researchers in the UCL NDE Centre [10, 11]. This was custom built in such a way that it could be used on an Instron 250kN servo-hydraulic Test Machine. The main cold rolling tool consists of a roller piston fitted into a custom made hydraulic cylinder, which was connected to a manual hydraulic pump that provided the required rolling pressure, as shown in Fig. 3 [10]. Before any cold rolling session, the specimen notches were cleaned thoroughly using methylated spirit. Then, the specimen was placed on the roller bed shown in Fig. 3. By using a digital hydraulic controller, the roller bed set-up was then raised slowly to bring the notch into contact with the roller. Once contact was achieved, the required cold rolling pressure was applied by using the manual hydraulic pump. The plate was then displaced horizontally across the roller bed using a 2.5 tonne bottleneck jack [11]. Knight [2] demonstrated the benefit of an oversized roller radius that has the dual effect of reducing the geometrical stress concentration factor and also to induce compress residual stresses into the lower portions of the notch flanks. Therefore, a larger edge radius (0.9652mm) roller was used in this study to maximise the effect of cold rolling. Throughout the stitch cold rolling process, the applied pressure was monitored constantly to ensure that the design cold rolling force was always maintained. The above procedures were then repeated for the remaining cold rolling passes. As stated previously, three test specimens were studied. The first specimen served as a comparison between non-cold rolled and cold rolled specimens. Table 1 summarises the cold rolling parameters for the specimens.

Table1. Summary of cold rolling parameters.

Specimen	Cold rolled	Unrolled length (mm)	Cold rolling pressure (psi)	Number of passes
TS1	No	-	-	-
TS2	Yes	20	6000	3
TS3	Yes	40	6000	3

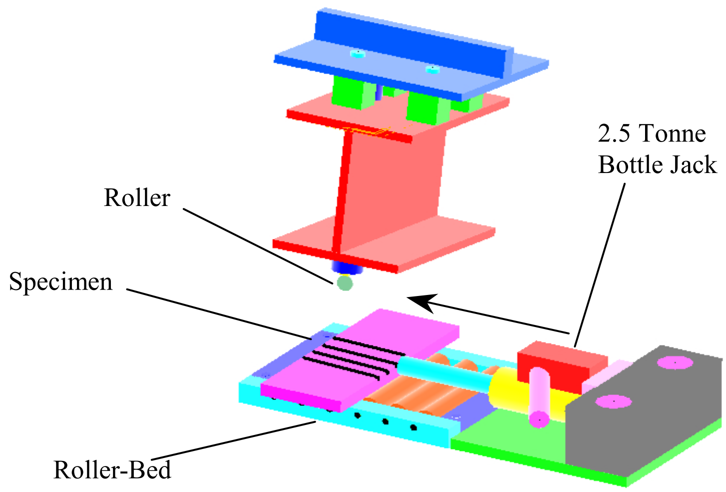


Figure 3. Virtual set-up of cold rolling jig [10].

RESULTS AND DISCUSSION

Table 2 summarised the fatigue test results for the specimens. Figure 4 shows the crack depth, *a,* versus number of fatigue cycles after crack initiation, *N,* curve for specimens TS1, TS2 and TS3. It can be observed from Table 2 that stitch rolling has significantly improved the fatigue life of TS2 and TS3. Although stitch rolling has significantly improved the fatigue life of the specimens, the crack initiation lives were unexpected. The crack initiation life of TS1 was approximately 2,000,000 cycles while the initiation lives of TS2 and TS3 were just about 150,000 cycles. The unexpected initiation life of TS1 is believed to be due to the effect of coaxing. Coaxing refers to an increase in the fatigue strength of a susceptible metal brought about by prior cycling at a lower stress level than its fatigue limit [16]. This is the most likely reason why TS1 had a relatively high fatigue crack initiation life. The nominal stress level applied to TS2 and TS3 was about 122MPa while the nominal stress level for TS1 ranged from 51MPa to 97MPa. The higher nominal/local stress level for TS2 and TS3 contributed to the lower fatigue initiation life. The crack initiation lives of TS2 and TS3 were 128,000 cycles and 120,000 cycles respectively. This was expected since the non-cold rolled notch region

Table 2. Summary of Fatigue Tests.

Specimen	Nominal Stress (MPa)	Fatigue Cycling Frequency (Hz)	No. of Cycles to Initiation	No. of Cycles to Failure	Total Fatigue Cycles
TS1	51 - 97	3	2,235,000	1,880,000	4,115,000
TS2	122	4	128,000	-	4,000,000
TS3	122	4	100,000	-	4,850,000

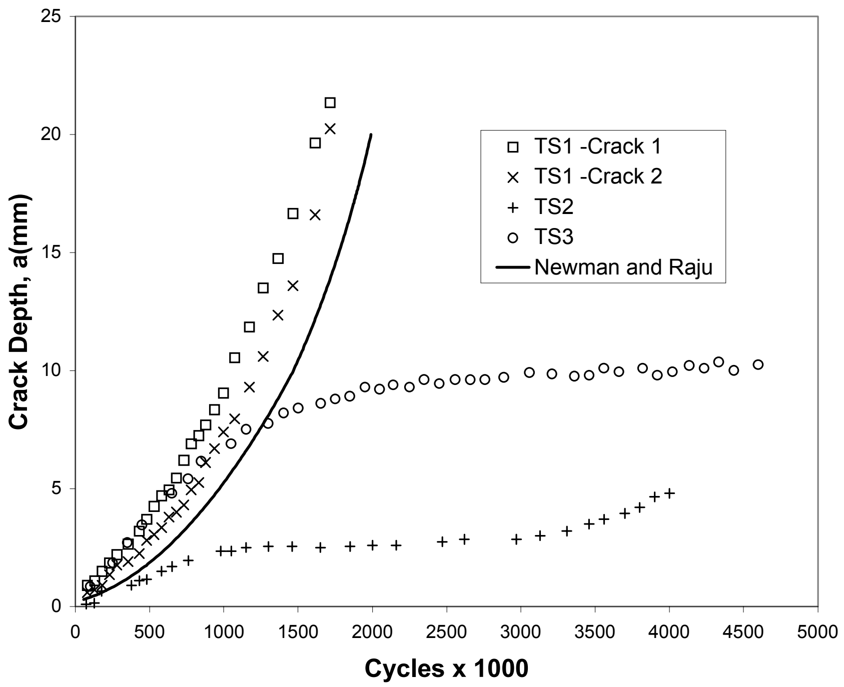


Figure 4. Crack Depth vs. Number of Fatigue Cycles Curve.

on TS3 was longer than that of TS2. The induced residual stress, which is believed to improve the fatigue life of components, is thought to be the main reason TS2 had a higher fatigue crack initiation life.

Two crack initiation sites were detected in TS1. The crack initiation at the edge of the specimen can be explained using the corner point singularity theory [12]. It was observed that the crack shape at the edges of the specimen was very unusual compared to typical quarter-elliptical corner cracks, as shown in Fig. 5a. Hence, it is thought that the edge effect [13] of the ACPD technique has over-sized the crack depth, and hence caused the discrepancies in crack depth measurement towards the edges of the specimen. On the other hand, crack initiation was detected in the middle of the non-cold rolled region in TS2 and TS3. As it is evident in Figs 5b and c, semi-elliptical surface

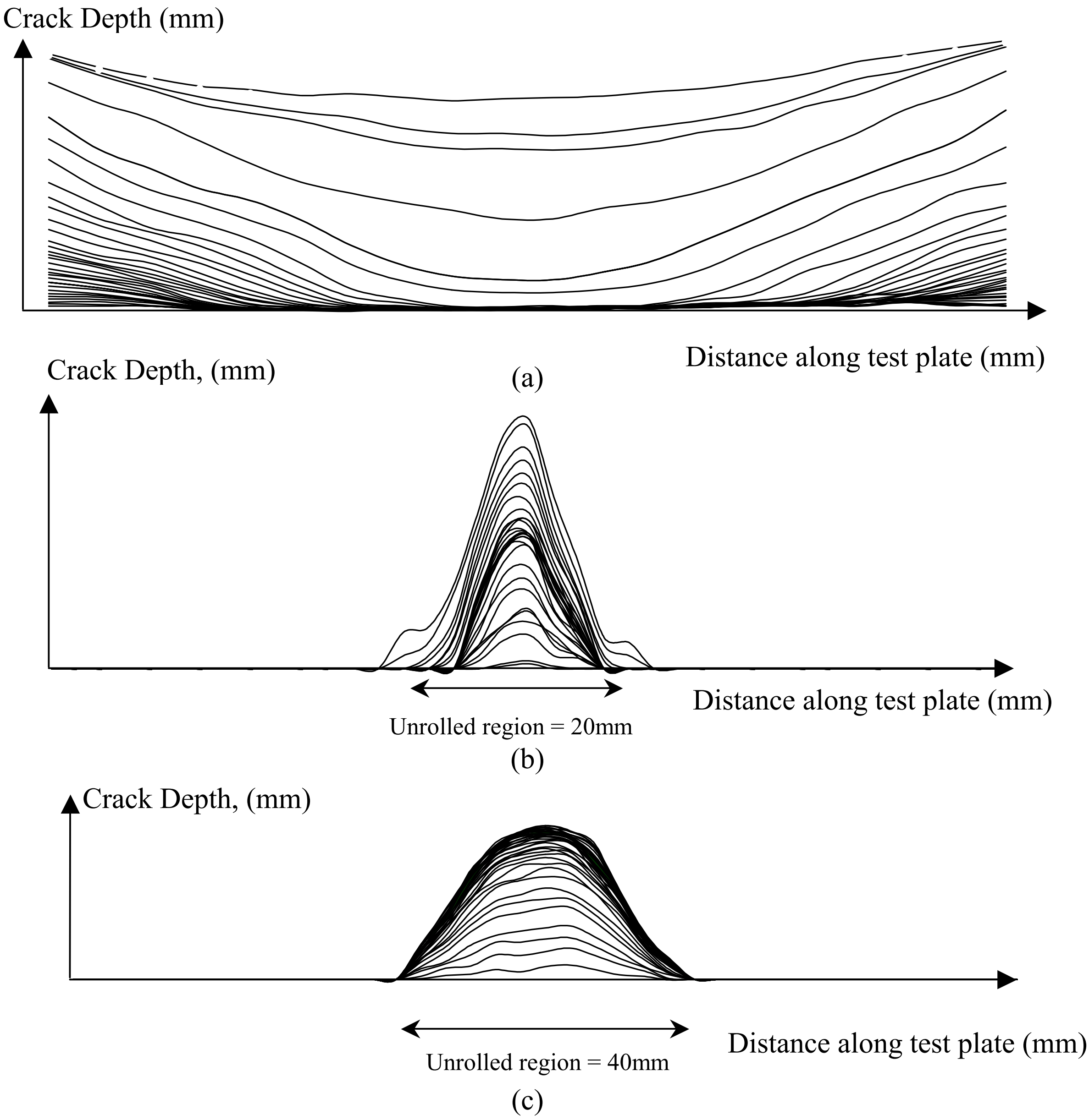
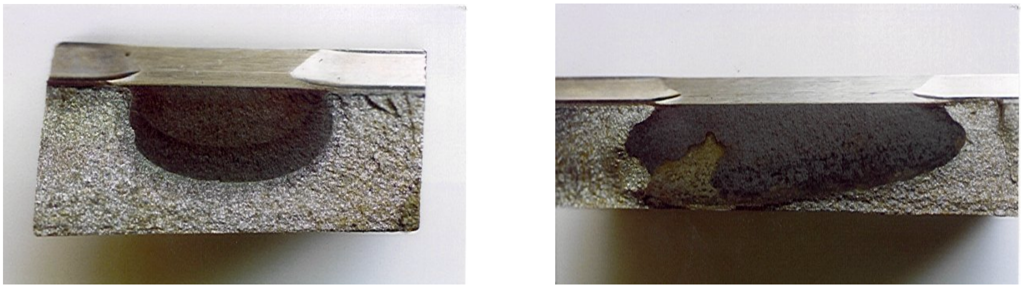


Figure 5. Crack Shape Evolution of (a) TS1 (b) TS2 and (c) TS3 (not to scale).

cracks were recorded. It can also be observed that the induced compressive residual stress at the cold rolled region served as a fatigue barrier for propagation in specimens TS2 and TS3. In other words, the cold rolled region had a double acting advantage of beneficial compressive residual stress combined with a lower stress concentration factor (SCF) (due to larger root radius), resulting in crack initiation in the non-cold rolled region.

From Fig. 4, it can be seen that the crack growth rate of TS1 gives a typical *a vs. N* curve. This is expected as the crack depth increases, the fatigue resistance decreases, hence the crack growth rate, *da/dN* increases. Figures 6a and b show the fractured crack surfaces of TS2 and TS3. Figure 4 also shows the fatigue crack retardation in TS2 and TS3 once the cracks reached the rolled regions. In other words, the residual stress had pinned the crack ends, arresting it from propagating. As the residual stress was shaken-out, the crack propagated into the unprotected region, resulting in the increase in crack depth and crack width, as can be observed in TS2 (Figs 4, 5b and 6a). It can be seen from Fig. 6a that the crack shape is not symmetrical but skewed. It is believed that the contrast in the remaining residual stress had caused this, due to the fact that cold rolling is not a completely uniform process. From Fig. 4, it can be seen that the fatigue lives of TS2 and TS3 were significantly improved compared to that of TS1 and the estimated fatigue life curve generated using Newman and Raju Stress Intensity Factor (SIF) solutions [15]. Due to shortage of time, fatigue testing of TS2 and TS3 were terminated prematurely. However, a sufficient amount of data was collected to demonstrate the significance of cold rolling on crack shape evolution.



(a) (b)

Figure 6. Fractured Surfaces of (a) TS2 and (b) TS3.

CONCLUSIONS

1. The fatigue test data proved that stitch rolling significantly influenced the crack shape evolution of cold rolled specimens.

2. Based on the results obtained and analysis performed, it can be concluded that the induced compressive residual stress is believed to be the major contribution in the improvement of fatigue life.

3. The implementation of stitch rolling, which introduces a contrast in the remaining residual stress on the surface layer, combined with the advantage of lower stress concentration factor, has proven beneficial.

4. Stitch rolling was observed to have caused crack arrest and retardation and may be used to promote short deep fatigue cracks.

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