Fatigue Crack Patterns in Ultrasonic Peened Welded Structures during Constant and Variable Amplitude Loading

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ABSTRACT. *Post weld improvement methods that reduce the stress concentration at the weld toe, remove weld imperfections and/or introduce local compressive stresses at the weld toe can significantly improve the fatigue strength of a structure. In some cases, however, the degree of improvement is limited by the fatigue strength of other details or locations in a component. The material strength and type of loading also influence the observed fatigue crack behaviour. This study reports on fatigue crack patterns observed for both constant amplitude (CA) and variable amplitude (VA) test results performed on high strength steel ($f_y = 700$ and $f_y = 960$ MPa) longitudinal non-load carrying welds. Some specimens were in the as-welded state while others were post-weld treated using either ultrasonic impact treatment (UIT) or ultrasonic peening (UP) equipment. These treatment techniques are generally categorized as residual stress modification processes, but they also reduce the local stress concentration near the weld toe. Failure modes were significantly different for CA and VA loading and VA loading showed less improvement. The study shows that fatigue strength of a welded structure can be significantly improved by ultrasonic peening, but that care must also be given to joint preparation, quality control of the peening procedure and the type of loading expected. Improper peening procedures can also induce unexpected and undesirable fatigue crack patterns that produce little improvement in the resulting fatigue strength.*

INTRODUCTION

Improvement techniques have been successfully used during repair operations of existing structures and the interest in using these techniques also for new structures has steadily increased [1-5]. Post weld improvement methods have been widely investigated and have, in most cases, been found to give substantial increases in fatigue strength [6-10]. The International Institute of Welding (IIW) is active in providing recommendations for post weld treatments of welded structures which include aspects process control, quality assurance and fatigue design [11]. In 2002 IIW Commission XIII WG2 "Techniques for improving the fatigue strength of welded joints" initiated a round robin fatigue test programme. The aims were to provide further background information on the practical viability of the procedures in the IIW recommendations on the use of improvement techniques and to confirm that high strength steels gain more benefit than low strength steels from the use of improvement techniques. This report

presents a brief summary of the tests performed at Lappeenranta University of Technology (LUT) on improved on longitudinal non-load carrying welds fabricated from $f_y = 700$ MPa steel and on similar welds fabricated from $f_y = 960$ MPa steel.

The vast majority of experimental results for improved welds have involved constant amplitude fatigue loading. For many fatigue strength improvement methods, the primary improvement process is attributed to modifying the harmful tensile residual stress state that exists in most as-welded structures. In such cases it is not clear whether the increase in fatigue strength observed during constant amplitude loading is retained during variable amplitude loading where local stresses approach or even exceed the yield strength of the base material. Several important studies including variable amplitude fatigue loading or overload stress cycles have been performed [12-18]. Important differences between constant and variable amplitude loading have been observed.

Sonsino [19] has provided an excellent review of the influence of residual stress of fatigue strength of welded connections. Lightweight designs can be optimized if the residual stresses and the factors that influence them are considered, i.e., material strength, loading type and joint stress concentration. Spectrum loading can significantly alter the local residual stress state so fatigue strength improvement observed during variable amplitude loading will not necessarily be observed during service loading and local weld geometry becomes the most important factor for improving the fatigue strength.

EXPERIMENTS

Material and test specimens

The S700 specimens consisted of 80mm wide by 8mm thick steel plates with longitudinal fillet welded attachments, as shown in Fig.1a. They were produced at Volvo Wheel Loaders AB by robot welding. The gusset was fillet welded along both sides without bevelling. Additional specimens were later fabricated manually at LUT using full penetration welds along the full length of the attachment. In most cases the central portion of the weld was machined to a width of 60 mm to allow lower stresses in the gripping section. The second material of interest was S960 steel. Specimens were welded with a welding robot using ϕ1 Union X96 filler wire. The welding speed was 7 mm/s approaching the end of the gusset, 10mm/s around the gusset end and 9mm/s after the gusset end. Other robot weld parameters were: I=260, V=30.2, VP=18mm, feed speed 11.5 m/s, shield gas Argon + 10%CO_2 at 18l/min. The test specimens and resulting robot weld shapes are shown in Fig. 1.
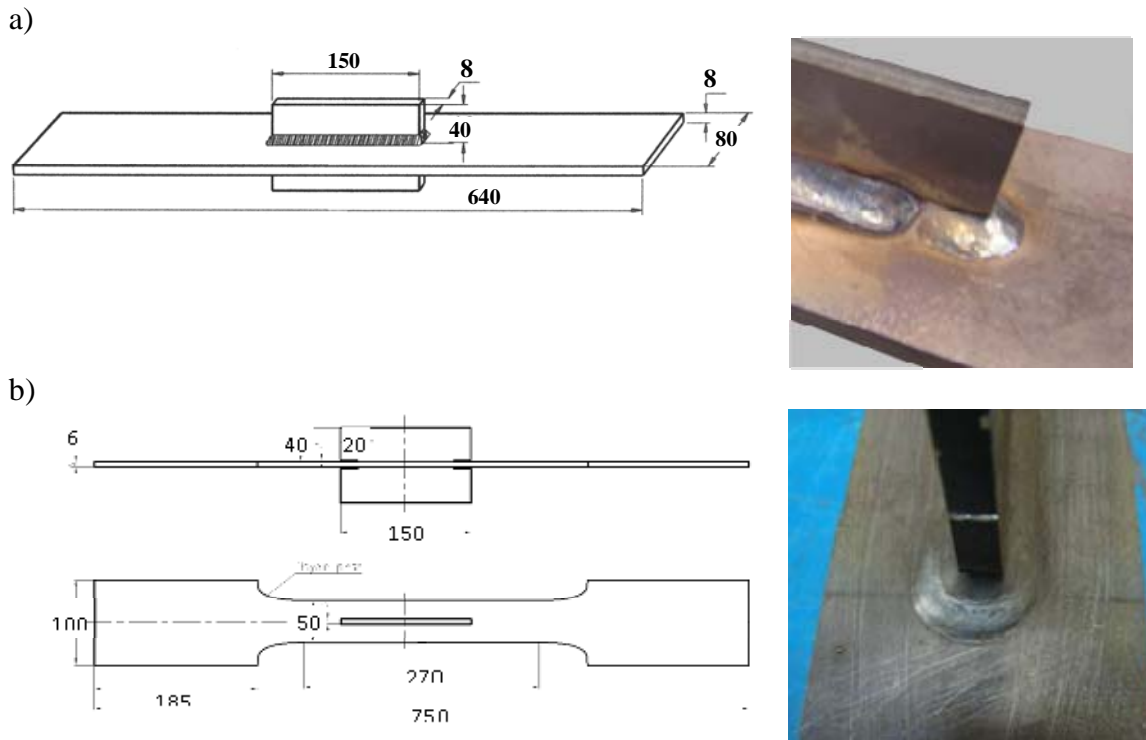
Figure 1. Test specimen geometry and example weld profile from stiffener end for a) S700 specimen and b) S960 specimen.

Loading spectrum

This study includes data obtained using constant amplitude loading and using spectrum loading. Constant amplitude loading at LUT was accomplished using $R = -1$. Some additional data performed at University of Braunschweig using $R = 0.1$ is also presented [20]. Spectrum loading fatigue tests were performed using the two alternate relative load spectra which were then scaled as needed. The spectrum used for the S960 specimens contained cycles of 14 different amplitudes and the stress range of the smallest cycle was 25% of the stress range of the largest cycle. The spectrum consisted of 100 000 cycles and was approximately linearly distributed on a semi-log plot as shown in Fig. 2a. Cycles were randomly distributed within the spectrum and each cycle in the spectrum had a stress ratio $R = -1$ as seen in Fig. 2c. The spectrum used for the S700 specimens was generated using a different program which implemented a Markov matrix and random number generator. Using this strategy, the cycle order was not identical for each specimen, but all tests had the same statistical characteristics. The largest cycle in the spectrum occurred approximately once for every 100 000 cycles and the cycles amplitudes were approximately Gaussian distributed on a semi-log plot as shown in Fig. 2b. Each cycle had a stress ratio $R = -1$ as seen in Fig. 2c. In order to avoid the risk of specimen buckling during the relatively large compressive stress cycles

that occurred regularly during spectrum loading testing, transverse anti-buckling supports were used.

Equation 1 can be used as a measured of the equivalent constant amplitude stress range for a variable amplitude history. For the S960 load spectrum (Fig 2a) used in this study, $\Delta\sigma_{eq} = 0.337 \ \Delta\sigma_{max}$ for $m=5$ and $\Delta\sigma_{eq} = 0.313\Delta\sigma_{max}$ for $m=3$. For the S700 load spectrum (Fig 2b) used in this study, $\Delta\sigma_{eq} = 0.439 \ \Delta\sigma_{max}$ for $m=5$ and $\Delta\sigma_{eq} = 0.389\Delta\sigma_{max}$ for $m=3$.

$$\Delta\sigma_{eq} = \sqrt[m]{\frac{\sum_{i=1}^{n} N_i \Delta\sigma_i{}^m}{N_{total}}} \qquad (1)$$

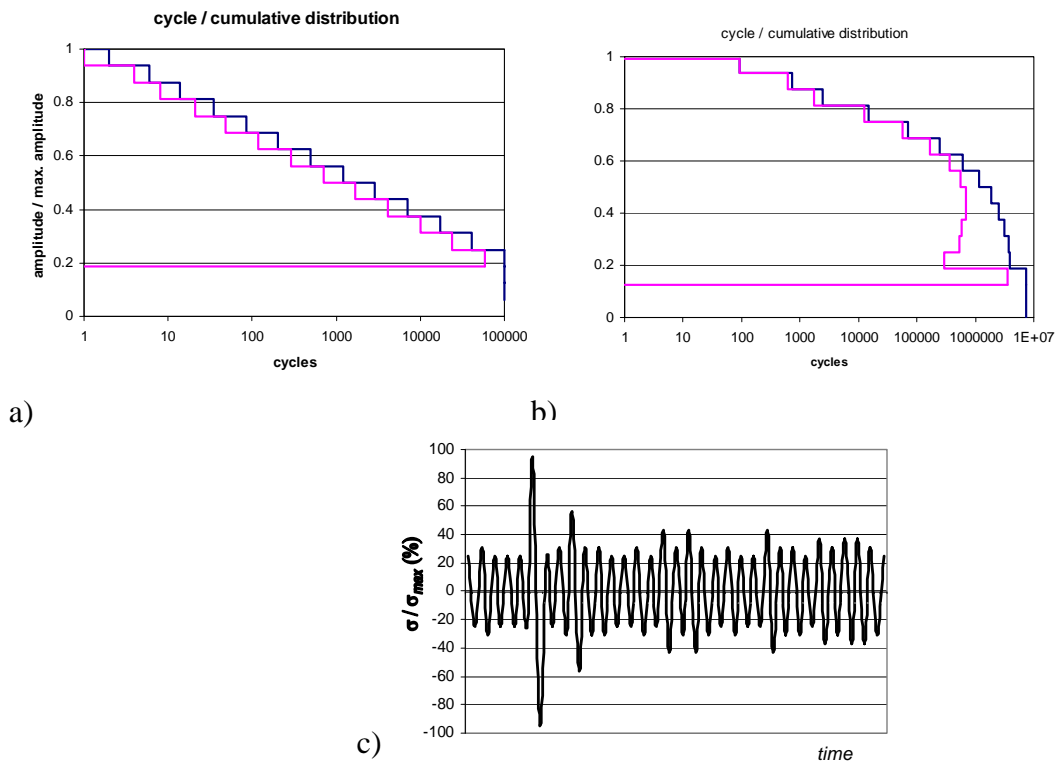a)   b)

c)

Figure 2. Distribution of fatigue cycles in the load spectrum for the a) S960 specimens and b) S700 specimens. C) Sample from one short segment of the spectrum.

Post-weld treatments

The post-weld improvement techniques chosen either ultrasonic impact treatment (UIT) [21] or ultrasonic peening (UP) [22]. Both devices are hand held units powered with ultrasonic generator. Ultrasonic elements within the body of the device cylindrical

indenters which vibrate with high frequency against a work piece, e.g. the weld toe. The impacting action of the indenters against the work piece produces significant changes in the material microstructure and reduces the local stress concentration of the joint. Residual compressive stresses are also introduced. Figure 3 shows typical UIT / UP treated welds toes for specimens used in this study.
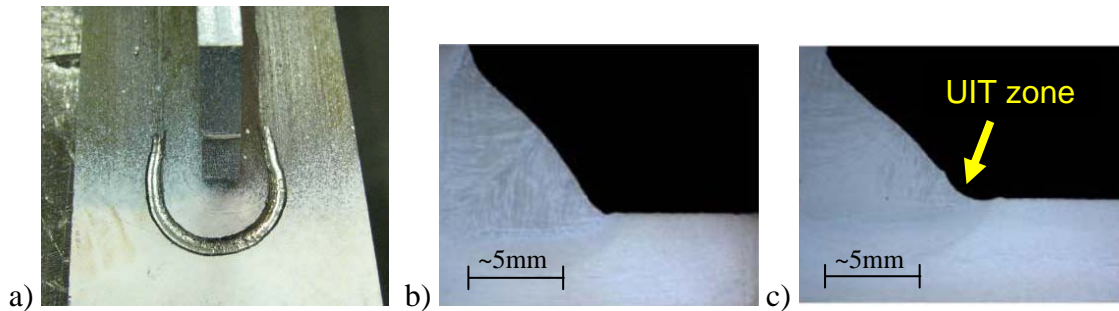

Figure 3. Typical weld toe following treatment with UIT / UP a) top view b) as-welded profile and c) treated profile.

RESULTS and DICUSSION

Fatigue fractures

As expected, all of the as-welded specimens failed at the weld toe at the end of the longitudinal stiffeners. All of the S960 improved welds tested under variable amplitude loading also failed at the weld toe at the stiffener end. A typical failure observed for VA loading is shown in Fig. 4. For the improved welds tested using constant amplitude loading, a variety of other failure modes were observed. These are shown in Fig. 5. It is interesting to note that during R = -1 CA loading, none of the S700 or S960 specimens failed in the UIT / UP treated area. However, during VA loading all of the improved specimens failed at or near the UP / UIT groove.
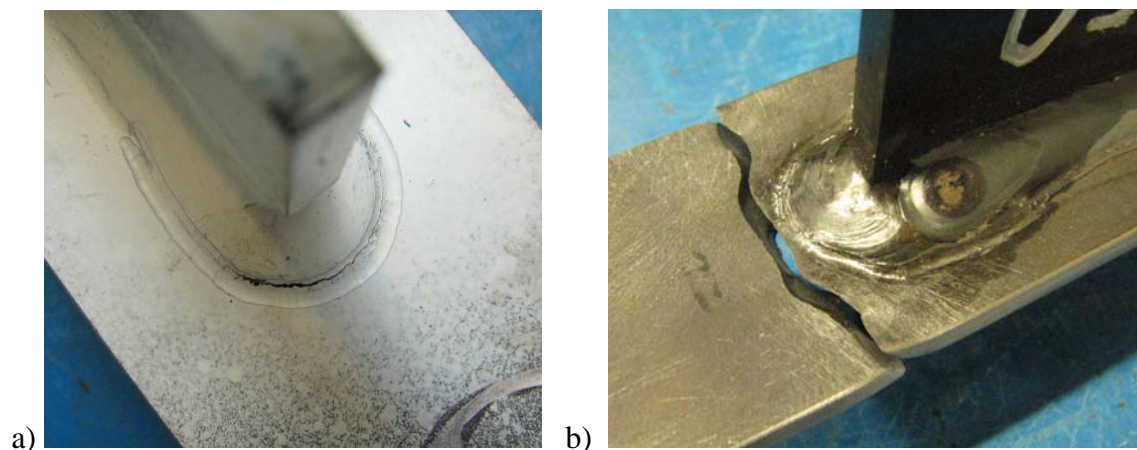

Figure 4. Failures observed during VA loading a) fatigue crack in UP groove of S960 specimen and b) fatigue crack near UIT groove of S700
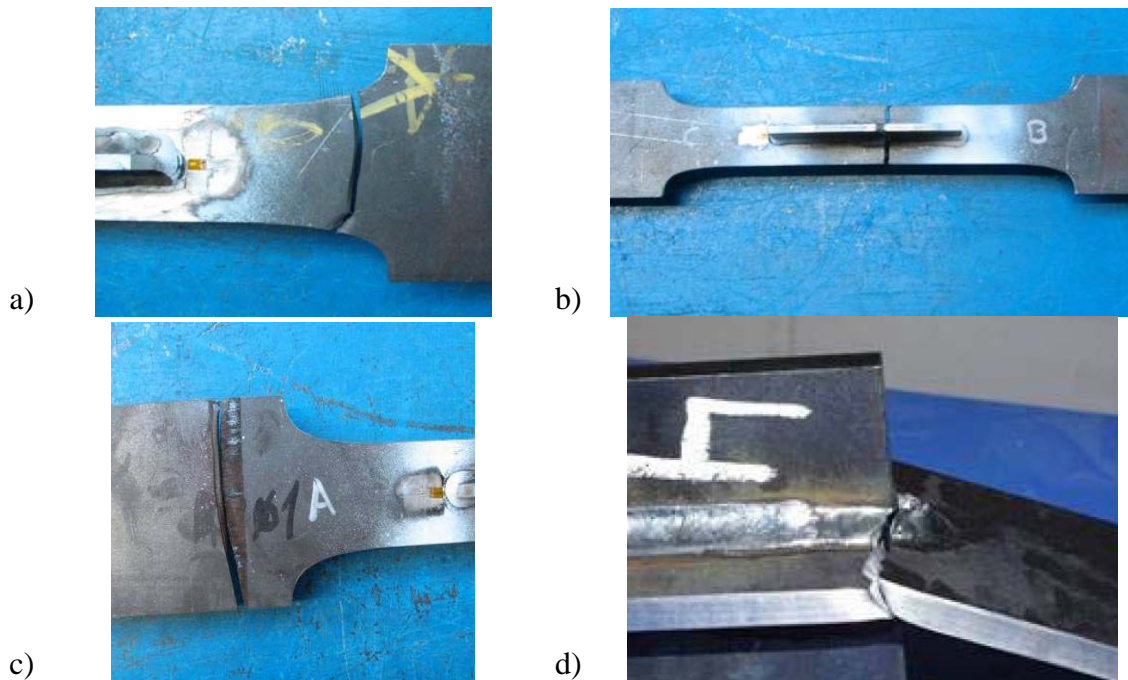
Figure 5. Failures observed during CA loading a) plate edge failure, b) start / stop position failure for a S960 UIT treated specimen, c) fretting failure in gripping end of UIT treated specimen, d) root side failure for a fillet welded gusset.

Fatigue results
Fatigue test results are shown graphically in Figures 6 and 7. Data has been previously reported numerically [18].
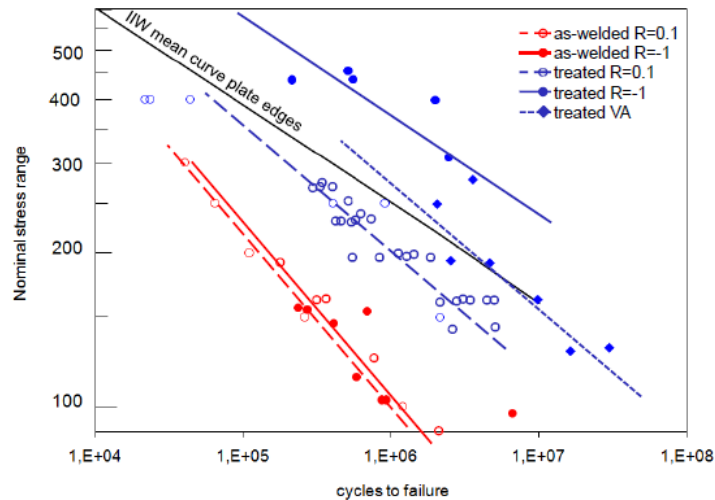

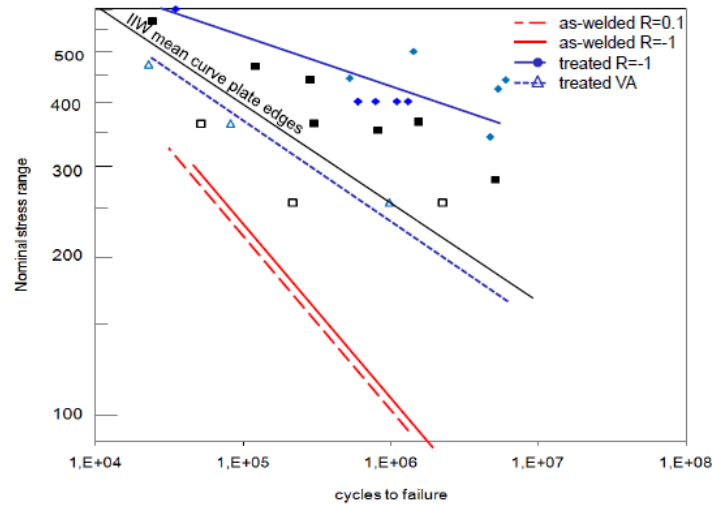Figure 6. Fatigue test results for as welded and improved S700 specimens.

Figure 7. Fatigue test results for improved S960 specimens. The as-welded base line curve is from Fig 6.

From Fig. 6 it can be seen that at $N_f=2\times10^6$ cycles, fatigue improvement observed for R=-1 was about 270% while that observed for R=0.1 was about 95%. This is consistent with earlier observations that peened welds have a fatigue strength which is also stress ratio dependent. In the as-welded state there was no stress ratio dependence which indicates a test specimen with high residual stresses. For constant amplitude loading these figures represent the minimum degree of improvement since failure occurred in all cases as some other portion of the welded specimen and not from the improved weld toe region.

A comparison of the influence of VA loading is clearly seen in both Figs. 6 and 7. The fatigue strength was significantly reduced due to VA loading as compared to CA loading. This is reinforced by the observation that failures for specimens tested with VA loading were always at the weld toe. This is consistent with observations previously reported by Manteghi and Maddox [23]. Especially for the S960 specimen tests, the maximum stress applied during VA loading were very high. Based on stress concentration factors for UIT / UP grooves for this type of specimen computed by Lihavainen [9] the local stress amplitude for the largest cycle in the spectrum was 1000 – 1800 MPa for the three specimens. These high stress concentrations indicate that the improved area underwent reversed yielding several times during one repetition of the load spectrum. Under these conditions the beneficial residual stresses introduced by UIT or UP would be greatly diminished. This is consistent with observations by Gustafsson [12], Maddox [13] and Sonsino [19]. From Fig. 6 it is observed that the improved S700 welded specimens performed approximately the same under both VA and CA loading. The loading spectrum in this case, however, was significantly different and the maximum local stresses are computed to be in the range of 410-890 MPa.

Figure 8 shows S-N curves for the as-welded specimens and the plate edge, root side and start/stop position failures from Fig. 5. The CA and VA SN-curves for the treated

specimens are also shown in this figure. The curves are based on 97.7% survival probability using an assumed standard deviation in of log$\Delta\sigma$ of 0.0687. For plate edge and start/stop position failures, curves in the IIW recommendations [24] were used. For the root side failure a 3D fracture mechanics analysis was performed using crack growth constant from IIW [24]. For comparison, all curves are drawn with an S-N slope of 3. It is clear from Fig. 8 that all failure modes have S-N curves significantly above the as-welded toe failure curve. The specimens treated with high frequency improved methods have the highest curves. To reach these highest curves, however, the other failure modes must be avoided by full-penetration welding near the gusset ends, avoidance of severe start/stop positions along the gusset edge, grinding of the plate edges and proper gripping to avoid slippage.
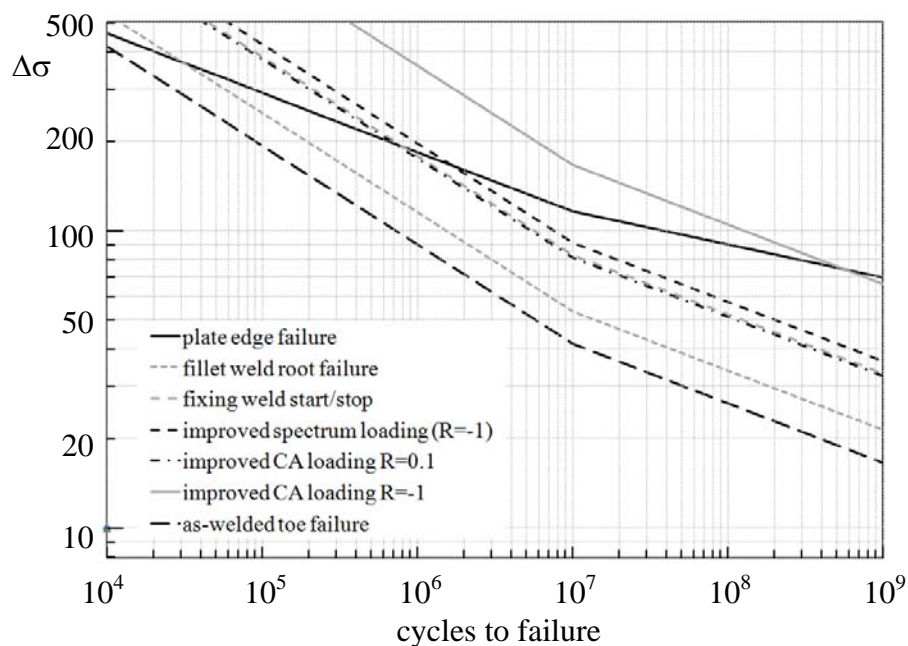

Figure 8 S-N curves of the various failure modes viewed in this study

Thus far this study has only reported only cases involving proper high frequency treatment procedures. Other fatigue fracture modes have been observed in previous studies for improperly treated welded joints. Figure 9 shows a failure mode that has been observed for specimens similar to those in this study. In this case the indenters are improperly directed at a single location. The cold formed material is gradually pressed from the weld toe region leaving a crack-like defect between the weld metal and treated zone. Failures of this type have been observed but not studied systematically.

Another type of failure that has been observed for improperly treated welds in shown in Fig. 10. In this cases the angle between the base and weld metal was close to 90° can be consider to violate the primary consideration for applying post-weld treatment procedures, i.e., that treatments should be applied as a means of improving good welds rather than simply trying to correct "bad" welds. The steep weld angle made it difficult

for the indenter to contact the weld toe. The process of defect formation and an example of the resulting defect are shown in Fig. 10. For this defect type, the fatigue strength was not significantly changed with respect to the as-welded specimens [26]. Special indenters have been developed and can be used in some cases for steep weld angles [25].
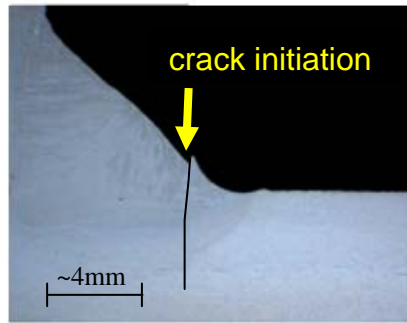

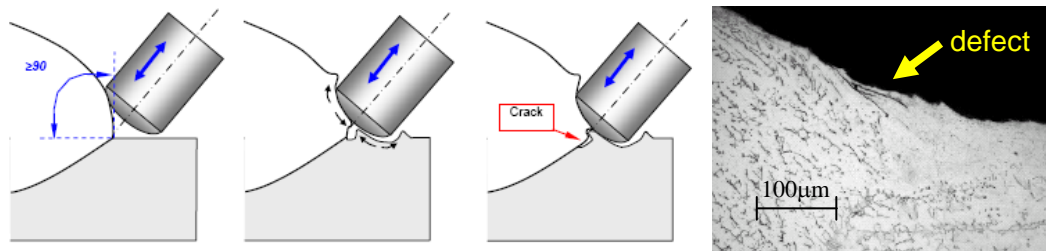Figure 9 Crack-like defect at the edge of the treated zone due to improper treatment.

Figure 10 Small defect formation due to improper treatment [25] and a micrograph of the resulting defect [26].

CONCLUSIONS

Constant and variable amplitude fully reversed (R=-1) fatigue testing has been performed on welded specimens with longitudinal stiffeners. Materials were high strength steels S700 and S960. Most of the welds were improved using ultrasonic impact treatment or ultrasonic peening. For comparison, some baseline tests were also done on specimens in the as-welded condition at R=-1 and at R=0.1. Fatigue failures in the as-welded specimens and for improved specimens tested with VA loading always occurred at the weld toe while none of the specimens tested using CA loading failed in this location. Changes in the local residual stress state are considered to be primarily responsible for this change in failure location. During VA loading the local stresses at the improved weld toes were sufficiently high that reversed local yielding is expected and beneficial compressive residual stresses are probably reduced. For most service conditions the effectiveness of post weld improvement techniques should be assessed using suitable VA loading. Numerous other failure locations were observed for

improved high strength steel welds tested using CA loading. These included plate edge failures, fretting initiated failures at the grips, failure from weld stops/starts along the side of the gusset plate and root side failures for specimens produced with only fillet welds. The advantages of post weld treatment processes can be fully realized only if other potential failure modes in a structure are considered and steps are taken to avoid these failures.

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