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Fatigue Life of Repaired Welded Tubular Joints

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ABSTRACT

The subject of this study is to investigate the effect of repair on the fatigue life of tubular joints. Six cracked specimens previously subjected to fatigue loading underwent weld repair. Two of these specimens were shot peened before primary fatigue loading. It is shown that repair for the original specimens increases the fatigue life by roughly 150%. The increase of fatigue life for shot peened and repaired specimens is around 105%. The in-depth residual stresses are measured on the repaired joints before and after fatigue loading. It can be stated that repair made a remarkable improvement on the fatigue behavior of tubular joints examined in this investigation. However, where repair is not possible, shot peening can be a good alternative to improve the fatigue life of welded joints. If repair is planned to be carried out then shot peening may not be financially or technically justifiable.

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1. INTRODUCTION

The repair and maintenance of parts and components is a major task in any industrial unit. One of the most common processes for repair is welding which is relatively safe, simple and effective. Repairs, if performed with care and precautions, can prolong the life of the components and avoid premature failures. In the repair method for pressure retaining parts, the cracks are gouged out or removed and weld repairs are carried out from both sides, where the necessary equipment is available. Because of availability of welding equipments and skilled welders, the SMAW (Shielded metal arc welding) and GTAW (Gas tungsten arc welding) are the most widely accepted welding processes in the industry [1].

Sharples et al. [2] investigated the effect of repair using finite element modeling of a matrix of relevant unrepaired and repaired weld configurations, validated by experiment. The conclusion reached was that weld repairing shallow defects and low toughness parent or weld materials are more likely to give a shorter fatigue life than leaving the weld unrepaired. Predictions of fatigue crack growth in the plate showed more rapid rates of crack growth in the repair compared with the original post-weld heat treated weld. Alam [3] studied the fatigue life assessment of welded and weld repaired joints numerically and experimentally. According to the results, the welded and weld repaired plates had lower fatigue life than unwelded plates. The weld repaired plates exhibited significant lower fatigue life than the un-welded and as-welded material. This was attributed to the much larger defects generated by the second repair-weld process employed to repair the cracks in the heat affected zone (HAZ) of the initial weld. This indicates that repair of cracks in weldments by a second weld does not extend the life of the joint above that of the welded joints. Rodriguez-Sanchez et al. [4] presented the application of a new fatigue crack repair concept defined as ‘short repair’. They showed that a short repair is an option to repair fatigue cracks, particularly for offshore structures. They also indicated that the successfulness of fatigue life extension using short repairs depends mainly on two considerations: (a) the crack is totally removed before it extends further than 30% of the plate thickness; (b) the repair depth and length comply with a short repair profile to force crack initiation to take place at the repair ends. Also, their experimental results showed that the application of short repairs in some cases can provide extensions of fatigue life greater than a factor of two. Krishnakumar and

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Weidong [5] presented experimental investigations on the fatigue crack behavior of welded 5083-H321 aluminum alloy plates and determined crack propagation in the heat-affected zone of welded specimens from tests conducted on single edge-notched tension specimens. Three-dimensional finite-element analysis was employed to determine stress intensity factors for cracks in the weld line. The conclusion they reached was that the residual stresses significantly influence the crack growth rates. They also investigated fatigue behavior of weld repairs in cracked plates. The weld-repair process significantly increased the grain size and the size of defects in the heat-affected zone. The results indicated that weld repair of cracks in welded joints provides little improvement in residual life. Vega et al. [6] presented the results of multiple weld repairs in the same area in seamless API X- 52 micro alloyed steel pipe. The results indicated that significant changes were not generated in the micro structural constituents of the heat affected zone. Grain growth in the heat affected zone at the specimen mid-thickness in a number of repairs was observed. Significant reduction in Charpy-V impact resistance with the number of weld repairs was found when the notch location was in the intersection of the fusion line with the specimen mid-thickness. A significant increase in the Vickers hardness of the heat affected zone occurred after the first repair and a gradual decrease in the Vickers hardness occurred as the number of repairs increased. Dong et al. [7] presented residual stress results from several weld repair case studies, using both advanced computational modeling procedures and experimental measurement techniques. From their results, it is concluded that weld repairs typically increase the magnitude of transverse residual stresses along the repair compared with the initial weld. Also, the shorter the repair length, the greater increase in the transverse stress. They also indicated that welding procedure related parameters (pass lumping, heat input and inter-pass temperature) appear to be more important in analyzing weld repairs than in initial fabrication welds. Wu et al. [8] employed a repair technique called the stop-hole method widely used to slow down or even to stop the propagation of a fatigue crack in structural components that cannot be replaced immediately after the detection of the crack. The principle of the method is to drill a hole at or close to the crack tip to transform the crack into a notch, reducing in this way its stress concentration effect. The comparison between the experimental and the calculation results show that the life increment caused by the stop-holes can be effectively predicted in this way. Katsas et al. [9] stated that even after the welding of aluminum ship hulls at shipyards or even during service, defects are detected in the vicinity of the weldment, if repairs are used, they can extend service life. They studied the effect of increasing the number of repairs on the corrosion resistance of the junction and concluded that from the designing point of view, any approach employing more than two repairs would render the whole process time consuming and economically unfeasible. They also concluded that at least as far as the corrosion resistance is concerned, repair welding can be safely employed as a means of extending the service life of the junction.

In this paper, the fatigue life of repaired welded tubular joints, which had been subjected to fatigue loading until a certain length of crack reached, is presented. Shot peening and repair are presented as alternatives for fatigue life improvement.

2. EXPERIMENTAL DETAILS

2. 1. Materials and Specimens

The specimens were manufactured from St52 steel pipes. The chemical composition and mechanical properties of the specimen are presented in Tables 1 and 2, respectively. The tubular X-joints were produced by welding two pipes of 32 cm in length into a pipe of 50 cm in length.

For the first pass (root pass), Bohler-E7016 electrode and for the second (filling) and the third pass (precision), Bohler-E7018 electrode were used. The welding conditions of the three passes and mechanical properties of electrodes are given in Tables 3 and 4. The schematic view of a tubular X-joint mounted on the lower part of the fixture, is shown in Figure 1. In order to perform the experiment, a fixture was required. The designed fixture consisted of upper plate and lower plate. The assembled fixture with the specimen in position is illustrated in Figure 2.

The endurance limit of St52 is 257 MPa. Using Marin factors (account for differences between the lab specimen and a real specimen) [11], the endurance limit of our specimens was calculated as 199 MPa. The stress concentration factor (SCF) at brace- saddle and chord-saddle points were calculated as 2.6 and 1.38, respectively. Further details are provided elsewhere [12].

TABLE 1. Chemical composition of St52 (%)

	C	Mn	Si	P	S
	0.17	0.61	0.204	0.01	0.007
DIN	Max	Max	Max	Max	Max
17100	0.22	1.6	0.55	0.05	0.05

TABLE 2. Mechanical properties of St52 [10]

Hardness HB	Elongation (%)	Ultimate strength (MPa)	Yield stress (MPa)
78	33.9	484	329

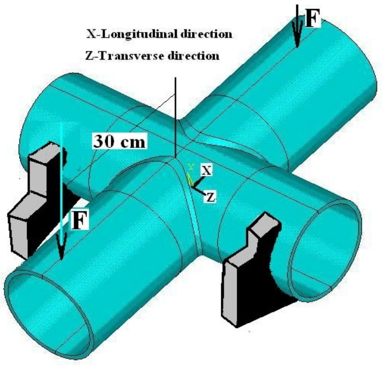

Figure 1. Tubular X-joint

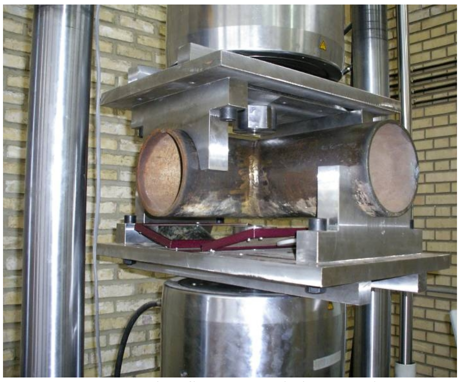

Figure 2. The fixture and the specimen

TABLE 3. Welding conditions in various passes

Welding velocity (mm/min)	Electrode diameter (mm)	Welding current (A)	Arc voltage (V)	Pass number
30-45	3.2	80-140	25	First
60-80	3.2	110-150	22	Second
95-160	3.2	110-150	22	Third

TABLE 4. Electrode properties in welding procedure [13]

Elongation (%)	Ultimate strength (MPa)	Yield stress(MPa)	Electrode
29	540	445	E7016
29	540	445	E7018

2. 2. Residual Stress Measurement Incremental center hole drilling (ICHD) [14-16] is a well known technique to measure near-surface residual stress. A strain gauge rosette was attached to the surface of the specimen at a certain location. A small hole was then drilled into the specimen through the centre of the rosette. Residual stresses along the axis of the hole were then reconstructed using elastic finite element analysis. ICHD measurements were made on the components using RS200 drilling rig. FRAS-2-11 rosettes with 7 mm gauge centre diameter were used. Strain gauges were installed within 5 mm from the weld line. Analysis of the ICHD strains was based on the Integral method explained elsewhere [14, 15]. Residual stresses were measured at two points and in directions of normal, parallel and 45^0 inclined to the weld line. The stresses in the three forgoing directions were called longitudinal, transverse and shear stresses, respectively.

2. 3. Repair of Tubular X-Joints Six cracked welded tubular x-joints including four simple tubular x-joints and two shot peened joints were repaired in this study. Simple joints were subjected to fatigue stress of 220 MPa and 265 MPa. The shot peened specimens were tested only under a fatigue stress of 265 MPa. The crack zones of the joints where they were supposed to be repaired were cleaned of superfluous materials and the defects were removed by grinding the crack openings and the area around it. Using Magnetic Particle Testing (MT) for observation of cracks, the crack regions were controlled in some stages. SMAW technique was used for the repair of the joints. Repair welding conditions were exactly the same as those used for the production of tubular x-joints.

2. 4. Fatigue Tests A servo-hydraulic Instron testing machine with a loading capacity of 600 kN was utilized. The specimens were subjected to sinusoidal cyclic loadings with frequency of 5 Hz and stress ratio of 0.1. Fatigue tests were carried out in accordance with the ASTM E466-07 [17] and API RP 2A WSD [18].

3. RESULTS AND DISCUSSIONS

The previous study [12] showed that shot peening has improved the fatigue life of the joint by about 75%. The objective of the present investigation was to study the possibility of further improvement of the fatigue life of the x-joints through repair of the cracked area. The repair was performed as explained in section 2.4. The minimum detectable crack length in the tubular x-joint, considered as the “initiation” was approximately 2 mm. The growth of the detected crack was measured up to 82 mm by optical means. In total, six specimens including four original repaired and two shot peened and repaired tubular x-joints were tested. Two of the shot peened and repaired specimens were tested under a fatigue stress of 265 MPa and the remaining joints were subjected to a fatigue stress of 220 MPa.

3. 1. Residual Stress Distribution The in depth residual stress measurement was performed at a 5 mm distance from the weld toe. The residual stress of the repaired specimen is presented in Figure 3. Figure 4 shows the measurement set-up. The repair welding introduced tensile residual stress into the specimen. The fatigue loading reduced this stress on the surface due to relaxation, which occurs more on the surface. However, in depth, it remains almost the same. The repaired shot peened specimen is almost stress free. For this reason, no change was observed after the fatigue loading (Figure 5).

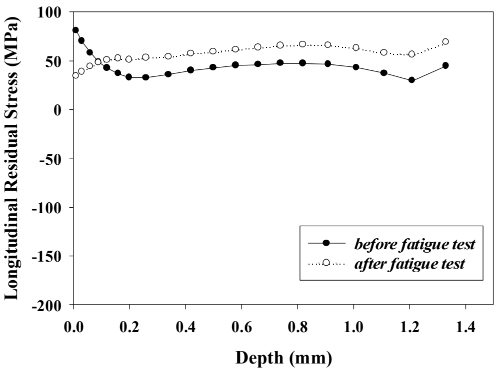

Figure 3. Distribution of residual stress on specimen #2 after repair, before and after the fatigue test

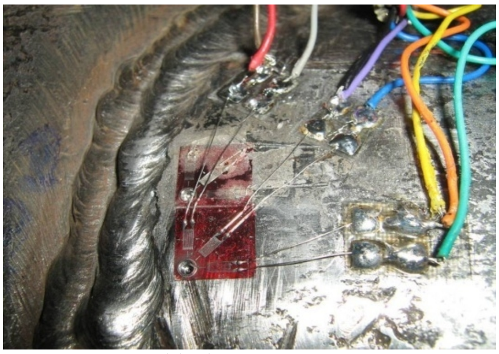

Figure 4. Residual stress measurement set-up

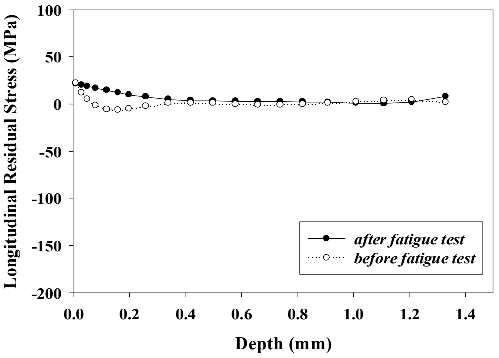

Figure 5. Distribution of residual stress on specimen #5 after repair, before and after the fatigue test

Figure 6. Crack on repaired welded tubular x-joint

TABLE 5. Details of fatigue tests and results of repaired tubular x-joints

Specimen no.	Shot peened	Applied stress (MPa)	Crack initiation life (Number of cycles)	Final life (Number of cycles)
1	No	265	1277650	1604550
2	No	265	1544877	1861345
3	No	220	1498722	1683720
4	No	220	1588500	1828500
5	Yes	265	932095	1101120
6	Yes	265	968250	1209890

TABLE 6. Comparison between the fatigue lives of unrepaired and repaired tubular joints for original and shot peened specimens

	Type of specimen		Fatigue life
Unrepaired (first stage) [12]	simple	1	916387
		2	1289680
		3	1877800
		4	1749145
	Shot- peened	5	1950000
		6	1913000
Repaired	simple	1	1604550
		2	1861345
		3	1683720
		4	1828500
	Shot- peened	5	1101120
		6	1209890

3. 1. Fatigue Life and Crack Propagation of Repaired Joints Figure 6 shows the cracks initiated and propagated from the weld toe of the repaired specimens. Details of fatigue test and life of repaired tubular x-joint are given in Table 5.

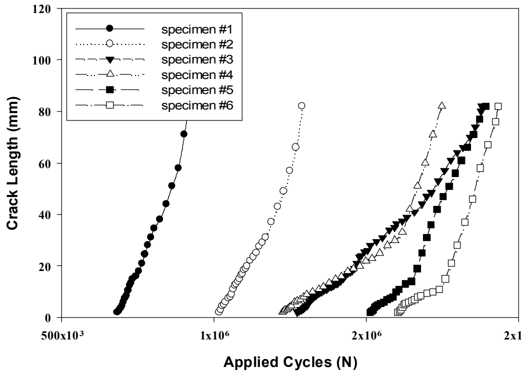

Figure 7. Crack propagation of original joints

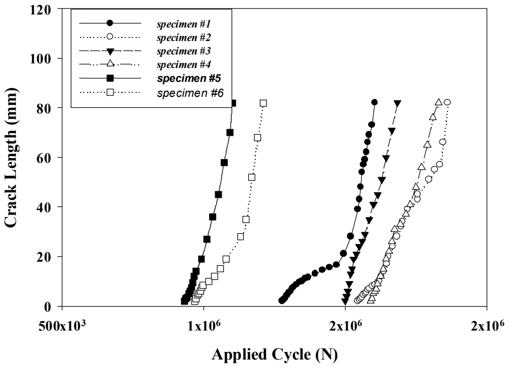

Figure 8. Crack propagation of repaired joints

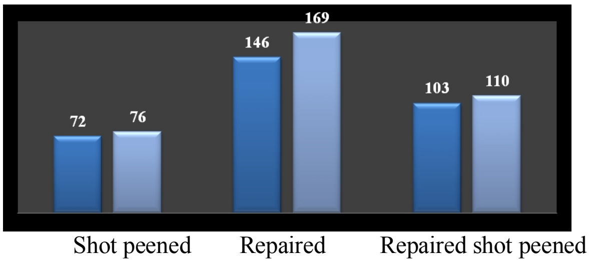

Figure 9. Fatigue life improvement by repair and shot peening

In order to have a better understanding of the effect of repair on fatigue life of tubular joints, the fatigue lives of the repaired joints for both original and shot-peened specimens were compared with original unrepaired joints, as reported from the previous study [12] in Table 6.

The increase of fatigue life for each case is considered with respect to the average fatigue lives of two unrepaired original specimens 1 and 2. The results given in Table 6 show that shot peening at the first stage improved significantly the fatigue life of the specimens. This increase for the repaired specimens was even more remarkable. As the results indicate, repair improved the fatigue life of the original specimen by 150%, while for the shot peened specimen the fatigue life increased only by 105%. As a matter of fact, whilst shot peening gave rise to the improvement of fatigue life for unrepaired specimens, it had a reverse effect on the repaired specimens. However, if we consider the total life of first stage and the repaired one, we can observe that shot peening caused an increase of 9% which is not a particularly substantial improvement in fatigue life. Therefore, according to our results, we can conclude that if repair is not possible, shot peening can be a good alternative to improve the fatigue life of a welded joint. If repair is planned, shot peening may not be financially justifiable.

The fatigue crack propagation curves for the original specimens are shown in Figure 7. This figure shows that, at a higher applied stress, the fatigue life of two identical test conditions are different; while at a lower stress level and also for shot peened specimens, the results of two identical tests are similar. The fatigue crack propagation curves of repaired welded tubular x-joints are shown in Figure 8. As the figure suggests, repair has significantly slowed down crack initiation for the original specimens 1 and 2 which were subjected to 265 MPa stress. The figure shows the results for specimens 3 and 4 where the crack retardation is not as significant for the fatigue stress of 220 MPa in specimens 3 and 4, as was observed for the specimens 1 and 2 under the fatigue stress of 265 MPa. It also shows the variation of fatigue life versus crack length for shot peened specimens. As it can be observed, the effect of repair on crack growth is profound for the fatigue stress of 265 MPa while for the stress of 220 MPa the effect is less important. It is also clearly seen that for a shot peened specimen crack initiation occurs much earlier than that of a simple joint. Figure 9 represents a bar diagram of fatigue life increase achieved by different cases studied in the present research.

4. CONCLUSION

From the experimental results obtained in this work, the following conclusions can be derived:

i. Repair gives rise to about 150% in fatigue life of original specimens.
ii. The increase of fatigue life of shot peened and repaired specimens was around 105%.
iii. It can be stated that repair made a remarkable improvement in the fatigue behavior of the tubular joints examined in this investigation. However, if repair is not possible, shot peening can be a good alternative to improve the fatigue life of a welded joint but if repair is planned, shot peening may not be financially or technically justifiable.

5. ACKNOWLEDGEMENT

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چکیده

موضوع این تحقیق اثر تعمیر بر عمرخستگی اتصالات لوله ای است. شش نمونه ترکدار که قبلا تحت بارگذاری خستگی قرار گرفته بود، تعمیر شدند. دو عدد از این نمونه ها قبل از بارگذاری اولیه خستگی، ساچمه زنی شدند. نشان داده شد که تعمیر، عمر نمونه های ساچمه زنی نشده را حدود ۱۵۰ درصد افزایش می دهد. افزایش عمر نمونه های ساچمه زنی شده تعمیری حدود ۱۰۵ درصد می باشد. تنش پسماند در سطح و عمق نمونه های تعمیری قبل و بعد از بارگذاری خستگی اندازه گیری شد. نتایج نشان داد که تعمیر باعث افزایش قابل توجه عمرخستگی اتصالات لوله ای مورد مطالعه این تحقیق گردید. چنانچه تعمیر امکان پذیر نباشد، ساچمه زنی راهکار خوبی جهت افزایش عمر خستگی اتصالات جوشی است ولی اگر تعمیر در دستور کار قرار داشته باشد، آنگاه ساچمه زنی این اتصالات از نظر اقتصادی و فنی قابل توجیه نخواهد بود.

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