Abstract

Fatigue life extension has been achieved by the application of ultrasonic peening to high stressed areas on pallet stool to deck and longitudinal to frames weld details on FPSO installations. High stressed welds showed too short fatigue lives in as-welded condition. The aim with the ultrasonic peening treatment was to avoid any further weld repairs during the remaining service life of these installations. Fatigue test results of treated relevant weld details have been used to assess the potential life extension. The results showed four to six times fatigue life extension. The fatigue test was designed to confirm that relaxation by external loads of the induced compressive stresses during treatment would not diminish the benefit. The fatigue lives for the treated welds were extended up to twenty years which often is the targeted service life for these installations. Quality Assurance and Quality Control were covered by Ultrasonic Peening Procedure Specification, applied for every treated weld. It ensures that the treatment is exactly reproduced to achieve the expected life extension.
Fatigue life improvement techniques can contribute to reduce maintenance cost by the avoidance of recurring weld repairs. Furthermore life extension techniques are the only remedy when higher stresses and/or fatigue cracks occur in a structure with many years remaining service life.

The fatigue life assessment of the treated details in the as welded condition was based on spectral fatigue analysis carried out by Bureau Veritas. The assessment showed too short fatigue lives for structural integrity relevant welds before treatment and the aim with the ultrasonic peening was to avoid any further weld repair during the remaining service life of the installations at these specific locations.

1.1. Fatigue strength of welds and structural integrity

Allowable design and service stresses and hence the structural integrity of offshore structures is nearly always governed by the fatigue strength of welded joints. The poor fatigue strength of welded joints can be attributed to the conjoint effect of three factors: local stress concentration of stress due to the geometric discontinuity of the joint; the presence of sharp crack-like flaws like undercuts, slag intrusions, cold-laps, etc introduced by the welding process; and the presence of high tensile residual stresses in the weld metal and the surrounding heat affected zone, HAZ. In order to achieve fatigue life extension on a welded detail it is necessary to address these three factors.

1.2. Ultrasonic Peening Treatment

The three factors mention in 1.1. are modified by ultrasonic peening in a solely working operation. Hence the fatigue life extension by ultrasonic peening is achieved in part by the reduction of the geometrical stress concentration at weld toe and in part by the redistribution of weld induced residual stresses, see Fig 1 and Fig 2. The redistribution of tensile residual stresses originated during and after welding procedure interacts with the compressive residual stresses which are induced into the HAZ during the ultrasonic peening treatment. The redistribution of residual stresses, including the introduction of compressive stresses, contributes towards fatigue life extension by locally lowering the mean stress. However, these induced compressive stresses could be relaxed during the remaining service life of the structure.

Fig 1 Weld toe groove

Fig 2 UP Treatment
The most apparent result of the ultrasonic peening treatment is the modification of the weld toe region. This modification consists of the introduction of a groove at the weld toe which effectively cleans any existent cold laps, intrusions, weld spatter, etc, Fig 1. Simultaneously it clearly reduces the previous existent sharp transition at the weld toe which means a substantial reduction of the local stress concentration, Fig 2. The parameters showing the modification of the weld profile due to the ultrasonic peening treatment are presented in Table 1. It is also important to mention the influence on fatigue strength of the weld flank angle after the ultrasonic peening treatment has been applied.

Table 1
Geometrical weld parameters before and after application of the ultrasonic peening treatment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before treatment</th>
<th>After treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld flank angle</td>
<td>Varies</td>
<td>45°</td>
</tr>
<tr>
<td>Weld toe radius</td>
<td>n/a</td>
<td>2 mm</td>
</tr>
<tr>
<td>Weld groove depth</td>
<td>n/a</td>
<td>0.5-0.8 mm</td>
</tr>
<tr>
<td>Weld groove width</td>
<td>n/a</td>
<td>4.0 mm</td>
</tr>
<tr>
<td>Weld surface</td>
<td>Spatter, start/stop</td>
<td>Smooth shiny</td>
</tr>
</tbody>
</table>

The weld flank angle could play an important roll if not taken into account by the ultrasonic peening procedure [6]. This subject is extensively treated in ref. [6] but here we could name that an extreme weld flank angle could limit the enhancement achieved by the ultrasonic peening. Therefore the LETS Global® ultrasonic peening procedure allows for the weld flank angle to be machined to a certain maximum value to achieve the full benefit of the ultrasonic peening treatment.

1.3. Ultrasonic peening procedure

The selection of weld connections for ultrasonic peening treatment is based on local FEA model and its result presented in 3. Thus, the procedure described here below is achievable and will be beneficial only if the local FEA results are precise and its analysis is accurate. *The full benefit of ultrasonic peening treatment is strictly dependent on this ground.* The LETS Global® ultrasonic peening procedure consist of five distinct steps which have been developed in accordance with our extensive experience with ultrasonic peening treatment on offshore installations.

1.3.1. NDT inspection previous to ultrasonic peening treatment

A selected weld joint for treatment on an operating structure have normally been in service for at least half of its design life before we carry out the ultrasonic peening. As a result we need to ensure that if any fatigue crack would be found, their size(s) would be such that the treatment will still restore its fatigue life and/or reset the clock to zero as a minimum value for that specific weld location. If the crack found shows to be too deep in relation to plate thickness the crack would need to be weld repair previous to the application of the ultrasonic peening treatment.

1.3.1.1. Crack depth which can be treated with avoidance of weld repair

Fig 8 shows a comparison between the fatigue life improvements achieved by ultrasonic peening and hammer peening. Fatigue test results reported in literature [8], [9] demonstrated that cracks of 2.5 mm or less could be effectively treated by hammer peening and the fatigue life of these welds would be restored. Furthermore, the results in Fig 8 shows higher allowable stress ranges for the ultrasonic peening treated welds than for hammer peening. Hence, the strength factor for ultrasonic peening improved welds is 2.1 and for hammer peening 1.6. Nevertheless, the absolute depth of the hammer peening treatment could be
deeper than ultrasonic peening since normally some pre-machining of the groove takes place. This would be however compensated by the depth of the plastic deformed layer and the induced compressive stresses down to a 1.5 mm achieved by the ultrasonic peening treatment. Consequently, a weld with a crack of 2.0 to 2.5 mm deep, plate thickness 20 mm, treated by ultrasonic peening would be restored to its original fatigue strength as a conservative estimate. It should be mention that the majority of the fatigue cracks detected by us previous to the treatment are long cracks located along the weld toe and relatively shallow.

1.3.2 Preparation of weld toes previous to ultrasonic peening

The weld toe and weld reinforcement must be cleaned previous to the treatment using sand blast or needle gun. This is to remove all coating and other surface impurities and to ensure the peening working tool have access to a clean metal surface on the weld and HAZ. After this cleaning operation is completed the preparation of weld toe area can start with a pin tool of 3.0 mm diameter. This is to achieve the complete removal of all cold laps, lack of fusion defects, weld spatter, etc which are located at weld toe. This stage of the procedure is finished when the groove at weld toe shows a shiny and clean surface. The same course of action will apply for weld toes in between inter-pass weld passes. Also start/stop locations should be treated to remove any potential crack sites at these weld imperfections.

1.3.3. Weld toe groove formation

Weld toe groove formation is done with a 4 mm pin tool diameter to achieve a reduction of geometrical stress concentration. The final radius at weld toe transition to plate will be 2.0 mm and groove 0.5-0.8 mm deep. Furthermore, the metal surface at the weld toe groove will be completely clean from any impurity and/or weld spatter. It is also important that the weld toe groove follows the contours of all weld toes including eventual start/stop located on the weld. The same requirement will apply for inter-pass weld toes. In addition the entire weld toe groove should have a constant radius of 2.0 mm and a constant deep of 0.5-0.8 mm. Fig 3 shows all the contours at weld toes including those in the weld reinforcement.

1.3.4. Treatment of weld reinforcement or weld surface

Structural welds are normally done as multi-pass welds. As a result it will exist besides the normal weld toe to plate additional weld toes adjacent to the first one but situated on the weld reinforcement. It is also normal to encounter weld spatter on the weld reinforcement of a multi-pass weld. All these stress risers plus “normal” cold laps could and will act as fatigue crack start sites and therefore it is of paramount importance to remove all these sites when and if they are situated in high stressed areas. Therefore a standard part of our ultrasonic peening procedure, but only when required, is to treat the
entire weld reinforcement with a multi-striker working head, Fig 4. The multi-striker peening tool contributes also towards the fatigue life extension of the weld by redistributing tensile stresses inherent to every welding procedure and/or by the introduction of compressive stresses.

1.3.5. Quality Control & Quality Assurance of the ultrasonic peening treatment

The application of LETS Global® ultrasonic peening procedure can only be performed by certified and qualified operators [12] with the appropriate equipment. These operators have both the theoretical understanding of the fatigue process and several years of continuous practice with the application of the treatment on offshore structures. The starting point for our QA & QC is the qualification and experience of the ultrasonic peening technicians who apply in-situ the treatment, carefully described in [12].

Table 2
Example of ultrasonic parameters for one pass weld on single pin, Ø 4 mm

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Ultrasonic Power</th>
<th>Fast Sweeping</th>
<th>Sweeping</th>
<th>Tracking</th>
<th>PWM Period</th>
<th>PWM Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.7 kHz</td>
<td>1500</td>
<td>40%</td>
<td>0</td>
<td>26</td>
<td>0-15</td>
<td>10ms</td>
</tr>
</tbody>
</table>

The parameters presented in Table 1 and Table 2 are part of the ultrasonic peening procedure and ensure that the improvement achieved in previous treated welds in laboratory, and used as reference to assess the degree of fatigue life extension, can be exactly reproduced on every structural member treated on the installation.

2. Experimental procedure and fatigue test results

In order to evaluate the degree on the fatigue life extension of ultrasonic peening treated welds extensive fatigue testing has been carried out and it is regularly undergoing. A representative welded detail in reference to weld connection in the real structure has been selected for fatigue testing.

2.3. IIW Recommendations for the specific weld detail.

The denominations of the relevant fatigue tested welded details are Class F or Class F2 according to the BS 5400 [11]. Currently this denomination has been widely replaced by the denomination proposed by the IIW Recommendations [2] in which both fatigue test details, Class F and Class F2, are classified as FAT 71 detail. FAT 71 refers then to fatigue strength of 71 MPa at 2 \(10^6\) cycles. This value is called the SN Design Curve and it is calculated as the mean value minus two standard deviations for series of predetermined number of specimens. The IIW Recommendations for this weld detail are presented in Table 3 both in terms of mean value and as design values.

Table 3
FAT Values, Design Curve and Mean values according to IIW Recommendations for Class F2 and Class F weld details

<table>
<thead>
<tr>
<th>As-welded</th>
<th>As-welded + Ultrasonic Peening</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAT design</td>
<td>FAT – 50 %</td>
</tr>
<tr>
<td>71 MPa</td>
<td>102 MPa</td>
</tr>
<tr>
<td>112 MPa</td>
<td>60 MPa</td>
</tr>
</tbody>
</table>

The fatigue test series for Class F specimens have been carried out on three point bending samples. This
specimen allows for the application of compressive stresses direct to the ultrasonic peening treated weld toes, Fig 6.

2.2. Class F Detail

The fatigue life improvement by ultrasonic peening is normally achieved in part by the redistribution of weld induced residual stresses and in part by the change of the geometrical stress concentration at weld toe, see Fig.1. This redistribution of residual stresses, including possible introduction of compressive residual stresses would act positively towards life extension but could also be relaxed during the remaining service life of the structure.

Therefore the weld details were preloaded in compression bending 5 times up to 85% of yield strength (nominal stress) before fatigue testing, see Fig 7. Since the ultrasonic peening treatment is responsible for certain redistribution of residual stresses, as previously explained, it is critical to document how the mechanical relaxation by compressive loads of by the treatment induced residual stresses affects the general degree of improvement. The results are shown in Fig 8 [7].
2.3. Class F2 Detail

The Class F2 test specimen is shown along the test results in Fig 9. The specimen has a non-load carrying full penetration weld attaching a longitudinal stiffener on both sides of the plate. One feature, which makes this fatigue test specimen particular, is the high degree of residual stresses concentrated at the crack site, which is designed to be the weld toe at the stiffener.

Fig 9 presents the fatigue test results as mean SN Curves for Class F2 weld detail where we can also see fatigue test results for UIT [5] along with the UP treated specimens. The fatigue test results for these two treatments are almost identical which is also the general opinion within the IIW Recommendations. The ultrasonic peening process is also known under the names “ultrasonic treatment”, “ultrasonic hammer peening”, “ultrasonic impact peening”, and “ultrasonic impact treatment”. Strictly speaking the treatment is performed in the same way and the results are almost identical.

3. FEA Modeling of high stressed areas

The example presented hereby is a structural weld connection in an offshore structure [13]. Finite Element Analysis and spectral fatigue analysis carried out by Bureau Veritas for a FPSO offshore installation demonstrated critical fatigue lives for some welded connections on the ballast tanks. The level of current stress ranges, taken as max principal stresses, were used to assess the potential life extension that could be achieved as well as to assess the areas and/or extension to be treated by ultrasonic peening.

FEA Element size is normally chosen as a multiple or equal to relevant plate thickness and as result the extension of the high stressed areas which is also the area to be treated by ultrasonic peening can
easily be assessed. However, some caution must be exercised due to certain approximations in within the FEA model and/or elements as well as variations in real plate thickness.

3.1. Fatigue assessment and ultrasonic peening treatment

A side shell longitudinal stiffener connection to a transverse web frame was modelled and assessed in terms of stresses and fatigue life with FEA. The model represented a typical weld connection showed in Fig 10. The FEA model confirmed high stressed locations at the weld connection of longitudinal to web frame and to bulk head. As a result of these high stresses critical fatigue lives were found by the spectral fatigue analysis for these specific locations.

Fig 10 FEA model courtesy of Bureau Veritas

Fig 11 UP treated connection

The weld quality encountered in the real structure could differ from the weld quality described in as-build drawings or assumed at the design stage of the installation. Therefore the ultrasonic peening procedure [12] needs to take into account these uncertainties when applied to achieve the desired fatigue life extension. The weld in Fig 11 shows a high degree of irregularities on the weld reinforcement. The ultrasonic peening treatment has been applied to the entire weld surface. This ensures the removal of all the potential fatigue crack sites of concern on the weld.

4. Results

Fatigue life extension of weld connections on offshore installations in service is performed on existent welds if not previous weld repair is needed. The quality of these welds do not always corresponds to the assumed quality and therefore the ultrasonic peening procedure [12] needs to take into consideration the as-built quality as a base-line to achieve a desired fatigue life extension. Therefore fatigue life extension is a relative concept where the as-built weld quality plays an important role. We have determined a window [6] where the variations of the as-built weld quality are taken into consideration.

4.1. Fatigue test results of treated specimens

In the IIW Recommendations [2], the allowances for improved welds by peening methods are assessed in terms of SN Design Curves or FAT Classes. For steels with specified minimum yield stress below 350
MPa, the improvement factor is 1.3 in stress corresponding to a factor 2.2 in fatigue life. It means an increase from FAT 71 up to FAT 90 or 30% increase in stress for our specific weld detail. It is important to note that the factor 2.2 in life comes from an assumed slope, m=3, for all SN Design Curves in [2]. Hence, \((1.3)^{m} = (1.3)^{3} = 2.2\) would be the improvement in life for peening methods according to SN Design Curves. However, it is important to note that previous SN Design Curves showing fatigue test results for ultrasonic peening improved welds demonstrated a less steep slope or \(m>3\) and therefore it would be reasonable to conclude the improvement in life could be greater than 2.2. If we assume a slope \(m=5.7\) from [5] or \(m=5.5\) from [14] for ultrasonic peening improved welds, the improvement in life would be from \((1.3)^{m} = (1.3)^{5.7} = 4.5\) to \((1.3)^{m} = (1.3)^{5.5} = 4.3\). For the sake of simplicity for slope \(m=5.5\) and \(m=5.7\) we assumed a 30% increase in stress.

As an example we could assume a stress range of 250 MPa. The fatigue life for such stress range in the as-welded condition, FAT 71, is 50,000 cycles according to [2]. Furthermore assuming FAT 125 and stress range 250 MPa, would give us a fatigue life of 280,000 cycles. Hence an improvement of 5.6 times in life is achieved for ultrasonic peening treated welds. Consequently, the suggestion of a general 4 times fatigue life extension for ultrasonic peening improved welds seems to be in good agreement with current Fatigue Design Standards and also on the conservative side. This value could be applied also if compressive peak loads would occur during the remaining service life of the structure.

4.2. Considerations about the application of the ultrasonic peening treatment in the offshore installation

As mentioned in 3 cautions must be exercised when selecting the area and extension to be treated by ultrasonic peening. This is due to approximations in within the FEA model and/or its elements as well as to account for possible variations in real plate thickness from current production drawings to details in the installation. Standard commercial FEA codes express the principal stress in a specific element as a mean value of nodes or integration points. The implication of this algorithm is that a principal stress value of one element is not necessarily the same as the maximum stress in within the same element.

Furthermore, it is assumed that a certain level of accuracy, or minimized error level in the model is achieved. There is a number of ways to bring the error under certain acceptable level as n-convergence, p-convergence and/or energy norm error. The other aspect which needs to be taken into account is the relation between the element size in the local FEA model and the plate thickness in the structure. FEA elements showing certain level of stress will indicate the extension of the ultrasonic peening treatment. Therefore the relation between the FEA element size and the plate thickness is important otherwise the area estimated to have high stresses and hence the area to be treated by ultrasonic peening will not be the correct one.

5. Conclusions

Fatigue life extension by ultrasonic peening has been achieved in high stressed areas on structural details of offshore installations in service. The fatigue life assessment of these structural details was based on FEA and spectral fatigue analysis. The assessment showed critical fatigue lives for the relevant welds before treatment and the aim with the ultrasonic peening treatment was to avoid any further weld repair during the remaining service life of the structure at these specific locations. The application of ultrasonic peening for fatigue life extension had two main grounds:
• For some of treated weld connections the ultrasonic peening treatment was the only solution left to enhance the fatigue life since no structural modification option was possible.

• For other weld connections ultrasonic peening treatment was done before any of the analyzed fatigue problems occurred, since it was an easy relatively low cost solution rather than wait for cracks and implement weld repair an subsequent ultrasonic peening.

On the basis of fatigue testing and relevant fatigue design standards the increase in fatigue capacity due to weld improvement by ultrasonic peening is estimate to be four times in life as a conservative estimate. The economical benefits due to reduced maintenance of structures as a result of the ultrasonic peening treatment include:

• Avoidance of long term plan for extensive repair work
• Avoidance of long and unscheduled operational disruptions
• Increased structural safety for the structure during remaining service life

References