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Fatigue Life Extension Procedure by Ultrasonic Peening

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Abstract

The service life of metallic structures is limited by its structural integrity. Additionally the structural integrity is mainly governed by the fatigue resistance of critical weld details. Depending on the type of structure and the type of load these typical weld details could differ.

Ultrasonic peening can improve the fatigue resistance of welded joints. Fatigue test results show a life extension of four times for high stress ranges and up to ten times for high cycle fatigue. For welded details which have already consumed half of their fatigue life ultrasonic peening treatment resets the clock to zero, as a minimum value.

Finite Element Analysis verified critical fatigue lives for some weld connections in the analysed structures. The level of current stress ranges at these weld connections, taken as max principal stresses, were used to assess the potential life extension which could be achieved as well as to calculate the size of the area to be treated by ultrasonic peening.

Consequently ultrasonic peening treatment was applied to several steel structures on fatigue sensitive weld connections with the objective to extend their service life. The economical benefits due to reduced maintenance as a result of the ultrasonic peening treatment include:

- Avoidance of long plan for recurring weld repairs
- Avoidance of long and unscheduled operational disruptions
- Increased structural safety for the structure during its remaining service life

1. Introduction

The application of fatigue life improvement techniques is gaining popularity in the last years. One important document in respect to the execution of improvement techniques is the IIW Recommendations, which contains extensive reference data for various fatigue life improvement techniques and quality assurance and control of their application [1]. Besides this document an evaluation of different fatigue life improvement techniques including their interaction with parent plate strength showed that ultrasonic peening is a promising method due to achieved improvement combined with its simple application [2]. As late as November 2009 ABS presented Notice No. 3 to its Guidance Notes where a general acceptance of ultrasonic peening for reconditioning of structures is stated [3].

Fatigue life improvement techniques can contribute to reduce maintenance cost by avoidance of recurring weld repairs. Furthermore the application of life extension techniques is the only remedy when higher stresses and/or fatigue cracks occur in a structure with many years remaining service life. One important field for the application for improvement techniques, almost unexplored until now, is the allowance of higher fatigue design stresses or light-weight design [6]. This will open a vast field for the use of high-strength steels and high strength aluminium materials.

Ultrasonic peening consist of introducing a groove at the weld toe, “cleaning” it from possible crack sites as well as introducing compressive stresses during the same and solely working operation. The effects of “cleaning” the weld toe region as well as the introduction of a weld groove, which decreases the geometrical stress concentration, have undisputed benefits which are also easy to quantify.

However, the effect of compressive stresses relaxation on fatigue improvement needs to be accounted for. The compressive stresses could be relaxed during the remaining service life of the structure and therefore any reference fatigue testing must include compressive peak loads.

2. Experimental procedure and fatigue test results

Fatigue life improvement 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.

This redistribution of residual stresses, including the introduction of compressive stresses, contributes towards fatigue life extension. However, the induced compressive stresses could be relaxed during the service life of the structure. In order to assess the degree of fatigue life extension in a manner which takes into account compressive peak loads might occur, the compressive stresses induced by the ultrasonic peening treatment would need to be relaxed before or during any reference fatigue testing.

Accurate fatigue testing would need to simulate the relaxation of compressive stresses if fatigue test result would be used as the basis of a fatigue life extension procedure and/or to predict the possible life extension for a treated weld. This is even of more importance if the structure is currently in service.

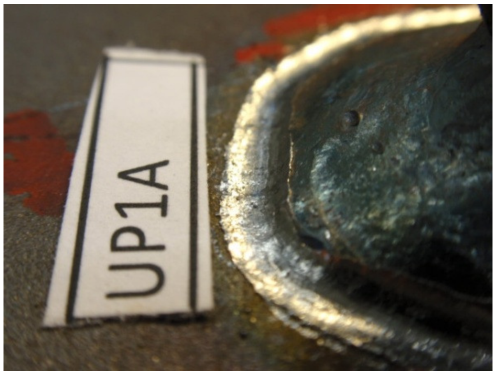
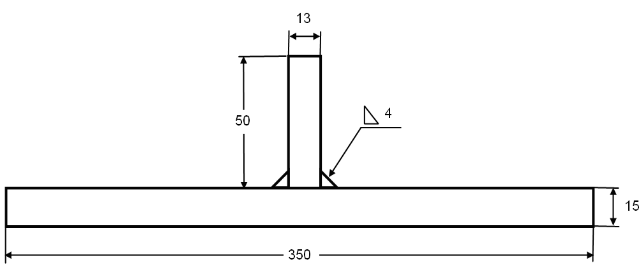


Fig 1 Weld toe groove

Fig 2 UP Treatment

2.1 Constant amplitude fatigue test with compressive preloads

Welded specimens were preloaded 5 times in compression bending up to 85% of materials' yield strength, nominal stress, Fig 3. This preloading sequence is such that yielding at the hot spot will occur and then shake down will be established for the subsequent fatigue testing [7]. This severe way to relax the compressive stresses it is not very likely to occur during the service life of the structure, Fig 4. Furthermore, if these compressive peak loads would occur they would be spread out during a considerable period of time.



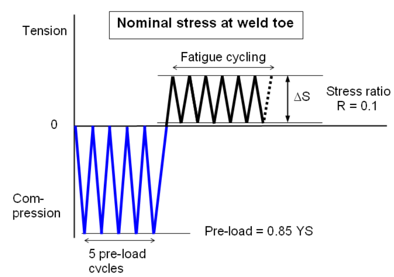


Fig 3

Fig 4

The preloading sequence in Fig 4 had been applied to every specimen previous to fatigue testing. Hence, the SN Design Curve for this fatigue test series would show the effect of shake down at hot spot regions due to the compressive peak loads.

2.2 Constant amplitude fatigue test results

After the compressive peak loads have been applied to every specimen constant amplitude fatigue testing was carried out. The intention was to produce a SN-Curve which takes into account a worst case scenario for the treated weld detail and/or a structure.

The improvement shown by these fatigue test results would be safe enough to be trusted even if a real structure would suffer similar type of severe compressive loads. Furthermore, the evaluation of fatigue test results is presented on the basis of SN Design Curves.

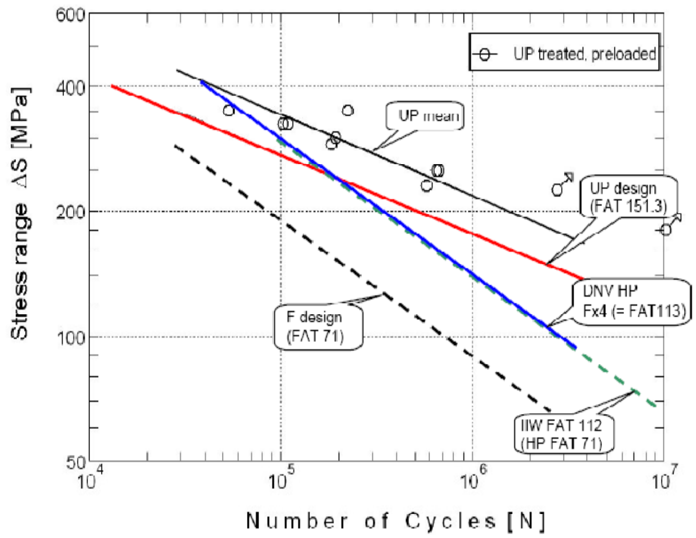


Fig 5 Fatigue test results for UP-treated weld after 5 preloading cycles [4].

2.3 Comparison of improvement level to other methods

The comparisons of fatigue life improvement methods in Fig 5 and Table 1 have been done against a SN Design Curve, which is a mean curve minus two standard deviations. The fatigue test results for ultrasonic peening treated Class F specimens are compared to grinding, TIG-dressed and hammer peened specimens. In addition a FAT Class according to IIW Recommendations have been calculated for every fatigue test series presented in Fig 5. The summary of all comparisons is presented in Table 1. The results for improved welds by TIG-dressing and grinding are from [5].

	AW	Grinding	TIG	HP	UP
FAT	71	100	100	112	151
m	3	3	3	3	5
Life factor	n/a	3.4	3.4	4	9.3
Strength factor	n/a	1.5	1.5	1.6	2.1

Table 1 Fatigue test results and comparison with other improvement techniques [8]

3. Fatigue analysis of the structure

The example presented hereby is a structural weld connection in an offshore structure. Finite Element Analysis carried out by Bureau Veritas for an offshore installation demonstrated critical fatigue lives for some welded connections. From a global FEA model which takes into account most severe loading conditions, the boundary conditions for a local FEA model were taken.

The local FEA models produced relevant stress ranges for the concerned weld connections. 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 a high stressed area which is the area to be treated by ultrasonic peening can be easily 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 location showed in Fig 8. The FEA model confirmed high stressed locations at the weld connection of longitudinal to web frame and to bulk head, Fig 9.

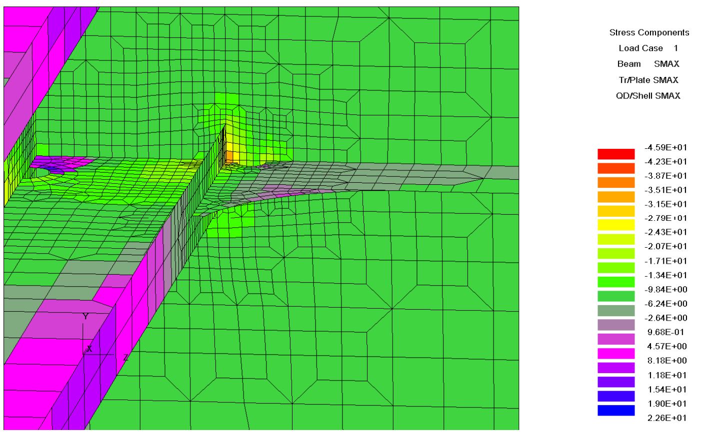


Fig 8 FEA model courtesy of Bureau Veritas

Fig 9 UP treated connection

As a result of these high stresses critical fatigue lives were found for the specific locations. Fig 9 shows the specific spot with high stresses which was selected for ultrasonic peening treatment.

The area showing high stresses in Fig 9 comprises the entire weld or both weld toes and weld reinforcement. As a result the ultrasonic peening treatment must cover the entire area showing high stresses in order to ensure a general increase of the fatigue resistance of this specific location.

4. Increase in fatigue capacity due to weld improvement by ultrasonic peening

In the IIW Recommendations [1], 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 [1]. 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= 5.5 as suggested in [16] for ultrasonic peening improved welds, the improvement in life would be, $(1.3)^{m} = (1.3)^{5.5} = 4.2$. For the sake of simplicity we assume slope m= 5.5 and a 30% increase in stress. In practice for this slope the increase in stress could be higher than 30%.

Therefore a 2.2 times fatigue life extension or 2 times as suggested in [3] is a rather conservative estimate whereas an improvement of 4 times in life is closer to reality and still on the safe side.

The highest Fatigue Class which can be claimed for ultrasonic peened welds is FAT 125 according to [1]. The reason why we are allowed to use FAT 125 instead than FAT 90 is the fatigue test results reported for the same detail [4] where FAT 151 was achieved for ultrasonic peening treated welds, Fig 5.

The FAT 90 value comes from a 30% increase from stress range 71 MPa. Therefore an increase from FAT 71 up to FAT 125 means a 76 % increase in stress. Assuming the slope of the SN Curve is m = 3 for ultrasonic peening treated welds, the improvement in life would be: $(1.76)^{m} = (1.76)^{3} = 5.45$ times.

4.1 Fatigue life extension for the considered connection

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 [1]. Furthermore assuming FAT 125 and stress range 250 MPa, it 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.

The FAT value used for this estimation is 125 whereas the FAT value obtained in the fatigue testing of this detail was FAT 151. Furthermore, the FAT 151 was obtained for compressive preloaded fatigue test specimens. For this reason, the use of FAT 125 could be considered to be on the conservative side.

4.2 Increase in fatigue capacity

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 [8].

This value for fatigue life extension by ultrasonic peening treated welds could be applied also if compressive peak loads would occur during the remaining service life of the structure.

5. LETS Global® Fatigue Life Extension Procedure

The selection of weld connections for ultrasonic peening treatment is based on local FEA model and its result see **3.1**. Thus, the procedure described here by is achievable and will be beneficial only if the local FEA results are precise and the analysis of these is accurate. The benefit of ultrasonic peening treatment is strictly dependent on this ground. LETS Global® ultrasonic peening procedure consist of five distinct steps which have been developed in accordance with our extensive experience with treatments on site. Depending on the shape of the original weld, its size and quality, quantity of weld spatter, access to previous NDT inspection protocols, etc the time required for every specific detail treatment could differ.

5.1 NDT inspection previous to ultrasonic peening treatment

The selected weld joints for treatment on an operating structure have normally been in service at least half of its design life before we carry out the ultrasonic peening treatment. 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 restore its fatigue life an/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 repair previous to ultrasonic peening treatment.

The inspection is carried out in selected high stressed areas, which are found with the information given by the local FEA model. The inspection can be carried out with MPI but the use of ACFM technique is desirable because it is easier to apply and it does not require any coating removal.

5.1.1 Crack depth which can be treated with avoidance of weld repair

Fig 5 shows a comparison between the fatigue life improvements achieved by ultrasonic peening and hammer peening. Fatigue test results reported in literature [9], [10] demonstrated that cracks of 2.5 mm depth or less could be effectively treated by hammer peening and the fatigue life of these welds would be restored.

Furthermore, the results in Fig 5 shows higher allowable stress ranges for ultrasonic peening treated welds than for hammer peening. Hence, the strength factor for ultrasonic peening improved welds is 2.1 and for hammer peening is 1.6.

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.

5.1.2 Weld repair procedure previous to UP of fatigue cracked components

If any deeper fatigue crack is detected during the NDT inspection previous to the ultrasonic peening treatment the crack needs to be weld repair. Fatigue cracks will be ground out and then an adequate weld repair procedure will be followed.

The repaired weld reinforcement and belonging weld toes will be treated by ultrasonic peening.

5.2 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, Fig 12. This is to remove all the coating and other corrosion surface impurities and to ensure the peening working tool have free access to the entire surface of the weld. If for some reason this cleaning operation can not be carried out the ultrasonic peening treatment will simply take longer time.

After the described 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 a complete removal of all cold laps, lack of fusion defects, weld spatter, etc which are located at weld toe, Fig 13.

This stage of the procedure is finished when the groove 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.

Fig 12 Needle gun cleaning

Fig 13 Weld toe UP Ø 3 mm

5.3 Weld grove formation

Weld groove formation is done with a 4 mm pin tool diameter to achieve the reduction of geometrical stress concentration at weld toe, Fig 14. The final radius at weld toe transition to plate will be 2.0 mm and groove 0.5 mm deep. Furthermore, the metal surface at the weld toe groove will be completely clean from any impurity or weld spatter, Fig 15.

It is also important that the weld toe groove follows the contours of all weld toes including eventual start and/or stop located in the weld. The same requirement will apply for inter-pass weld toes.

Fig 14 Weld groove

Fig 15 Shiny weld groove

Fig 16 Groove and contour

This stage of the procedure is finished when the entire groove have a constant radius of 2.0 mm and a constant deep of 0.5 mm. Fig 16 shows the contours of all the weld toes including those in the weld reinforcement.

5.4 Treatment of weld reinforcement

Structural welds are normally done as multi-pass welds. As a result it will exist besides the normal weld toe to parent plate additional weld toes adjacent to the first one but situated on the weld reinforcement it self.

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 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 showed in Fig 17. The result of such treatment can be seen in Fig 18.

Fig 17 Multi-striker working head

Fig 18 Treated weld surface

The treatment of weld reinforcement with a multi-striker peening tool has also other important contribution towards the fatigue life extension of the weld. It is the redistribution of tensile stresses inherent to every welding procedure and/or the introduction of compressive stresses. This becomes apparent for multi-pass welds where the volume of weld metal is considerable and consequently the by the shrinkage heat induced tensile residual stresses, Fig 19.

Fig 19 UP treated weld flange

Fig 20 Multi-pass weld after multi-striker treatment

The compressive stresses induced during the ultrasonic peening treatment will interact with the external loads and despite their possible relaxation these will contribute to effectively keep the hot spot stresses at the weld toe at a low level during the remaining service life of the structure [11].

5.5 Quality Control & Quality Assurance of the ultrasonic peening treatment

The geometrical weld parameters for the ultrasonic peening treated welds are presented in Table 2.

Besides the measurement and control of the geometrical weld parameters presented in Table 2 every ultrasonic peening treated weld is classified by its photography and identified by an unique number. This allows for the following up of every treated weld in the structure during its remaining service life and which is even more important during subsequent NDT inspections.

	Weld flange angle mean	Weld toe radius	Weld grove deep mean	Weld flange surface quality
Before treatment	45^{o}	n/a	n/a	Weld spatter, start/stop, etc
After treatment	45^{o}	2 mm	0.5-0.8 mm	Smooth, shiny

Table 2 Geometrical weld parameters for welds before and after treatment

Additionally, the ultrasonic peening parameters presented in Table 3 are recorded for every weld which gives together with weld geometry parameters documentation a complete history of the treatment.

Frequency	Ultrasonic Power	Power	Fast Sweeping	Sweeping	Tracking range	PWM period	PWM ratio
19.7 kHz	1500	40%	0	26	15	10 ms	100

Table 3 Example of ultrasonic parameters for one pass weld on single pin, Ø 4 mm.

The displacement amplitude used by our ultrasonic peening tool is determined by the design of the tool and it is kept constant during the treatment independently of any variation of the acoustic impedance or acoustic interface. Acoustic interface could be remaining coating, corrosion products, content/size of weld inclusions, etc.

The frequency is modulated by Pulse with Modulation (PWM) and its ratio, see Table 3. This allows for constant frequency and amplitude in the near field. As a result the ultrasonic parameters are calibrated for every weld size and/or plate thickness in order to achieve optimal effect of treatment in the near field.

The parameters in Table 2 and Table 3 are part of the ultrasonic peening procedure and ensure that the improvement achieved in previous treated welds, and used as reference to assess the degree of fatigue life extension, are exactly reproduced on the structural members treated in-situ in the installation.

6. Inspections subsequent to the ultrasonic peening treatment

The subsequent NDT inspections of ultrasonic peening treated welds are not a part of the ultrasonic peening procedure. However, high stressed welds of structural concern are subjected to regular planed inspections in every installation in service with the intention to find and/or to prevent fatigue cracks at an early stage.

This applies also for the weld connections treated by ultrasonic peening. Until now no fatigue cracks were found in the treated welds following the procedure described in this paper. Hence, it would be possible to re-assess the inspection intervals which could add to the benefits achieved by the ultrasonic peening treatment.

7. Discussions

The procedure described in this paper is improving as we keep applying it in practice to different structures and under different conditions. The aim with every treatment is to achieve a repair free remaining service life of the treated welded joint. Some points for further discussion follows.

7.1 Comparison between grinding and ultrasonic peening improvement

Grinding has been compared to ultrasonic peening and in some cases it has been suggested [3] these two improvement methods would have approximate the same level of improvement in fatigue life.

The fatigue test results for ultrasonic peening treated welds in this paper shows a factor 4 in fatigue life extension. However, literature [12], [13] and [5] indicate that the fatigue life improvement achieved for grinded welds would be in the level of 1.1, 2.0 and 3.4 respectively.

7.2 Comparison between TIG dressing and ultrasonic peening

The fatigue life improvement reported for TIG dressed specimens in literature varies for constant and variable amplitude [14], 1.7 - 2.5 respective, whereas in [5] a factor 3.4 in life is stated.

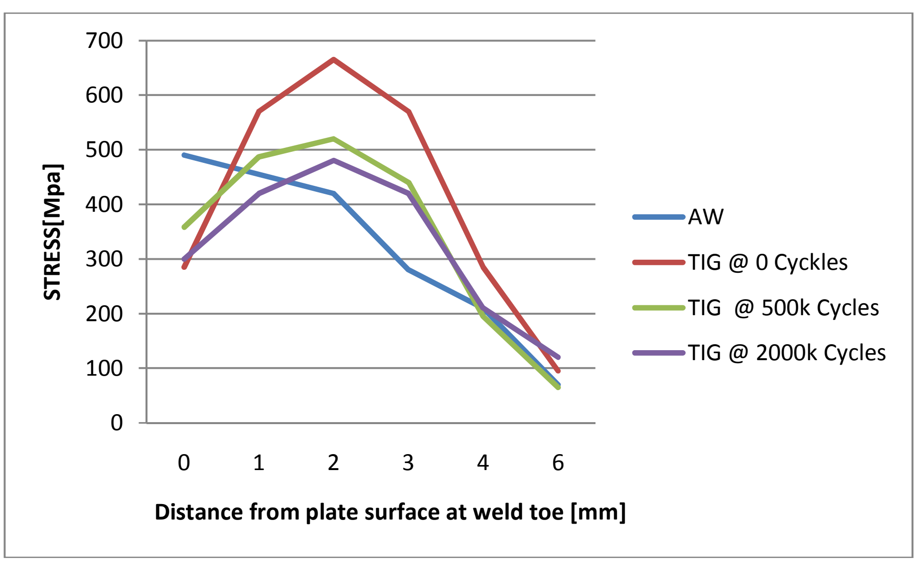


Fig 21 Spectrum rate relaxation of TIG induced residual stresses, Domex 590 [11]

It exist two main reasons to compare the level of improvement achieved by ultrasonic peening against TIG-dressing.

The first reason is that TIG dressing introduce a certain level of compressive stresses although not of the same level as the introduced by ultrasonic peening, Fig 21.

The second reason is the relative similar decrease in geometrical stress concentration achieved at the weld toe. Hence, the rate of compressive stress relaxation would be analogous for these two fatigue life improvement techniques.

7.3 Effect of compressive stress relaxation on improvement level

The stress gradient at weld toe and hence the geometrical stress concentration has an influence on the rate of residual stress relaxation under fatigue loading.

The influence of spectrum on compressive stresses relaxation for TIG-dressed specimens has been studied in [15]. Despite the fact that the level of by ultrasonic peening induced compressive stresses differs from those produced by TIG-dressing at the weld toe zone, we can have a good indication of relaxation pattern when we study in detail how spectrum fatigue load redistribute the stresses during service life, see Fig 21.

The TIG-dressing induced compressive stresses are in the order of 200 MPa, (difference red and blue lines at weld toe in Fig 21), from 500 MPa in the as-welded condition to 300 MPa after TIG-dressing. The application of spectrum load contributes to a clear and progressive redistribution of residual stresses. It is apparent from Fig 21 that the loading history in compression and tension interacts with the residual stress field producing at general redistribution of internal stresses.

Furthermore it is important to keep in mind that the level of original stresses is influenced by parent plate and weld metal yield strength as well as welding procedure parameters. Hence, the diagram in Fig 21 shows only a general shape of redistribution of residual stresses during spectrum loading.

Fig 21 shows three stages of residual stress redistribution during spectrum load. For high cycle fatigue, $2 \cdot 10^6$ cycles, the redistribution of residual stresses is accomplished. However, the level of tensile stresses at the weld toe region remains at a low level.

Even if the compressive stresses were entirely relaxed during spectrum load we can conclude that these never will be again of tensile yield level. As a conclusion we could say the worst case scenario would be an effective stress range equal to the nominal stress and its relevant stress concentration. Furthermore, for ultrasonic peening treated welds the geometrical stress concentration is reduced due to the weld toe groove.

7.4 Slope of SN Design Curve for ultrasonic improved welds

It exist an influence of the spectrum load shape on the fatigue life extension of ultrasonic peening treated welds which as also has been reported in [14]. Therefore and to take into account the influence of the relaxation of compressive stresses during the service life of the structure it is proposed to fix the slope of ultrasonic improved welds to m = 4.

7.5 Area, location and size, to be treated by ultrasonic peening

As already mention in **3**. caution 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.

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 the stress value of one element is not necessarily the same as the maximum stress within the 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 or energy norm error.

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 (solid) 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.

8. Conclusions

Fatigue life extension by ultrasonic peening has been achieved in high stressed areas on structural details.

The fatigue life assessment of these structural details was based on FEA principal stress plots. 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 as a fatigue life extension method 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 problems occurred, since it was an easy relatively low cost solution rather than wait for cracks and then peen all the other areas.

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 on structures as a result of the ultrasonic peening treatment include:

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

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