Review: Effective Post Weld Toe Treatment to Optimize Fatigue Life of Welded Structures

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Abstract— Construction machineries like excavators and backhoe loaders must work reliably in severe and unpredictable working conditions. While these machines are performing their required tasks, some components of these machines are exposed to repeated fluctuating stresses, which cause fatigue cracks, especially on digging and loading components, to occur. Owing to these cracks, the components of the machines can malfunction, fracture or even cause danger to the life of people. In the structures of construction machineries, Welding is the most dominant joining method during the manufacturing process and it is the main source of cracks occurring on the components due to stress concentration at weld toe and metallurgical imperfections like Planar imperfections i.e. hydrogen cracks, lamellar tears, lack of fusion, reheat cracks, solidification cracks, and weld toe intrusions, volumetric imperfections Includes porosity and slag inclusion, geometric imperfections Includes misalignment, overfill, stop/starts, undercut, and weld ripples.

The assessment of the welded joints is a major industrial problem because the welds are the determining factor of expected life of earth-moving machines. Accordingly, the welded joints are the regions of weakness in a structure and must be fully understood to improve the expected life of the earth-moving machines. Here failure at throat can be minimized by achieving optimum strength but problem of weld toe cracking only be eliminated by reducing stress concentration at weld toe. In this context the present communication analyses the pros and cons of the post weld toe treatment on fatigue life of welded structure by reducing stress concentration at weld toe.

Keywords — Welded joints, Fatigue Failure, Fatigue life optimization, post weld toe treatment, IIW Recomendation.

I. INTRODUCTION

Construction machineries like excavators and backhoe loaders must work reliably in severe and unpredictable working conditions. While these machines are performing their required tasks, some components of these machines are exposed to repeated fluctuating stresses, which cause fatigue cracks, especially on digging and loading components, to occur. Owing to these cracks, the components of the machines can malfunction, fracture or even cause danger to the life of people.

In the structures of construction machineries, Welding is the most dominant joining method during the manufacturing process and it is the main source of cracks occurring on the components. The assessment of the welded joints is a major industrial problem because the welds are the determining factor of expected life of earth-moving machines. Accordingly, the welded joints are the regions of weakness in a structure and must be fully understood to improve the expected life of the earth-moving machines. In this Research project under study, the major observations related to the effect of fatigue life of weld are planar imperfections, volumetric imperfections and geometric imperfections [6].

II. MATERIAL AND METHODOLOGY

IIW has recommended some technique like modification of weld toe geometry and inducing compressive stresses in weld to improve fatigue life of welded joints. Literature survey has been carried out and it has found that many authors has undergone experimentation on post weld toe treatment to improve the fatigue life of welded joints and their results shows that, there is 20-50% average increase in fatigue life as after application of post weld toe treatments.

A. K.J. Kirkhope, R. Bell, L. Caron, R.I. Basu, K.-T. Ma [11] has reviewed the post weld treatment technique. From the study of all grinding methods at $2 \times 10^6$ cycles burr grinding reported 50 to 200 %, disc grinding has reported 20 to 50 %, TIG dressing reported 50 % improvement in fatigue strength but plasma dressing gives better result than TIG dressing as heat input is twice that of TIG and large weld pool forms so better transition takes place. Overloading and thermal stress relief method yet to prove its ability to improve fatigue strength. Reductions in stress concentration factor are from 3.3-5.1 for as-welded joints to 1.36-1.56 for AWS improved profile weld profile joints. At the high cycle end (about $5 \times 10^7$ cycles) an improvement in fatigue strength for the toe grinding is 100% and for disc grinding it is 40% over the as-welded condition. TIG dressed specimen reported increase in fatigue strength in air at $2 \times 10^6$ cycles as compared with as-welded joints is approximately 100%. From a statistical analysis of many tests, obtained a factor of 2.2 for improvement in fatigue life for weld toes treated by TIG dressing.
The improvement in fatigue strength obtained by peening treatments are among the highest reported and are typically of the order of 50 - 200% for hammer peening, 30% for shot peening and 50 - 200% for ultrasonic impact peening. Based on reviewed following is descending order of post weld toe improvement technique: hammer peening (50 – 200%), UIT (50 – 200%), Burr grinding (50 – 200%), TIG dressing (50), disc grinding (20 – 50%), shot peening (33%). From this Burr grinding, TIG dressing, AWS weld profile improvement, hammer or shot peening has been selected from individual category. Author also suggested that combination methods of burr grinding and hammer or shot peening, weld profile control and burr grinding / hammer or shot peening can be employed.

B. Three different techniques of post weld treatment have been investigated for fatigue life improvement (M.M. Pedersen, O.Ø. Mouritsen1, M.R. Hansen, J.G. Andersen3, J. Wenderby) [12] namely burr grinding, TIG dressing and ultrasonic impact treatment. T- Joint of 250 × 50 × 40 mm with weld size of 4 mm and 6mm plate thickness prepared by MAG welding. Fatigue testing was performed using a 100kN Schenk hydraulic fatigue testing machine in four point bending, at constant amplitude. The stress ratio was kept at R=0.1, and the frequency was varied from 7-28Hz. Post weld treatment was carried out according to IIW recommendations. It was observed that the compressive residual stresses introduced by the UIT treatment were expected to relax, thus not improving the fatigue strength of the specimens. However, the UIT treatment also improves the local geometry of the weld toe, which might explain the improvement in fatigue life seen in this investigation. At 2 × 10⁶ cycles, the fatigue strength improvement levels obtained is 49% for burr grinding, 78% for UIT and 70% for TIG dressing and TIG dressing is the most effective treatment in the medium cycle regime and UIT the most effective in the high cycle regime.

C. Bertil Jonsson, Jack Samuelsson [13] from Volvo construction equipment have developed new weld class system which eliminates the drawbacks present in “weld class system” i.e. ISO 5817 where acceptance limits are given for different quality levels. The problem with these systems is an inheritance from old rules and nominal stress based methods, when designers used hand formulas in design, so it is inconsistent, subjective and not well connected to fatigue life.

The new weld class system is divided into three different quality levels (VD, VC, VB) for fatigue loaded structures and one for static loaded structures (VS). The two first classes stand for the ‘as welded condition’, normal quality (VD) and high quality (VC). The last and highest class (VB) stands for ‘post treated welds’ regardless of kind of treatment.

D. Based on the evidences that fatigue strength of improved welds increases with material’s yield strength, 228 experimental results for longitudinal, transverse and butt welds subjected to R = 0.1 axial loading has been reviewed (Halid Can Yildirim, Gary B. Marquis). By taking reference yield strength as 355 MPa, approximately 12.5 % increase in strength for every 200 MPa increase in yield strength was found.[15]

E. Slag entrapment and cold lap present in weld eliminates the fatigue crack initiation life. To avoid this post weld toe treatment techniques like burr grinding of toe, full face grinding, shot peened weld, remelted weld toe has been suggested. For improving the bad weldment suggestions like apply the load transverse to the welded plate, usage of diffuser can substantially improve the fatigue life of terminations without post-weld processing has been given.[16]

F. “SSAB” [17] Study come out with six ways of counteracting the fatigue failure which are occur due to stress concentration, presence weld defect and internal tensile stresses. First kind of it is, smooth force flows that will reduce stress concentration by maintaining same spacing between stress lines. Second, by achieving higher weld quality with defect free weld and smooth transition between parent metal and the weld for this post weld treatment can be used. Third, apply the load to the weld longitudinally because stress condition along the weld is “mild” and stress concentration is lower in this type of load. Forth, as stress pattern is not same all over the welded structure so weld can be placed in low stress area. Fifth, by carrying out the sizing means that, load on the structure are compared with the strength of the material i.e. placing the more thick plate in weak region and thin plate in strong region.
G. Teppei OKAWA, Hiroshi SHIMANUKI, Tetsuro NOSE, Tamaki SUZUKI has developed the system which will predict the fatigue life accurately by employing the crack growth analysis based on sequence involved in fracture mechanics of weld which consist of small initial cracks are assumed to form first at the surface of a weld toe, where fatigue cracks are likely to occur then stress intensity factors are calculated for the deepest and surface points of the surface cracks; followed by an effective range of the stress intensity factor is defined using a crack opening/closing model; and the propagation behaviour of the fatigue cracks is simulated by applying the fatigue crack growth law. Developed system has been predicted by applying it to the fatigue strength improvement technique like ultrasonic impact treatment and results are well matched with the actual fatigue test. Author stated that the system can be used in the fields of fatigue design and maintenance for ships, bridges, plants, construction machinery, and other welded structures as a means for improving their reliability, extending their service life, and reducing environmental loads.[19]

H. Norio Takeda and Panos Y. Papalambros have demonstrated the weight minimization of welded structure by constraining stresses. For this LPP model has been derived for weight optimization and with the help of nominal and structural hot spot stress in welded structure calculated by FEM analysis (element type and size for the approaches has been selected as per IIW recommendations), the weight of plates used for L-Shape structure has been calculated and results has compared for equal fatigue life which has calculated based on FAT 90 (for hot spot stress) and FAT 63 (for Nominal stress approach) design curve. It has shown that plate thickness calculated based on hot spot stress approach is less and so the mass (Kg). Almost 10% & 17% weight reduction has been found at high cycle and low cycle fatigue respectively. Then two samples have been prepared wise, optimum weight and non-optimum weight and test has been conducted for fatigue life analysis. Based on the fatigue test results it has found that optimum structure based on hot spot stress approach has given better fatigue life. So for weight optimization structural hot spot stress approach and for fatigue failure assessment local notch stress approach has to be used when carrying out FEM analysis. [20,21]

I. Wolfgang Fricke, Adrian Kahl [22] has compared the structural stress approach based on IIW recommendations, based on Dong study and based on Xiao and Yamada. IIW recommends some guidelines about the distances at which hot spot stress has to calculate, element type and size for FEM analysis, FAT design curve selection. Dong’s approach has consider the effect of stress gradient along the anticipated crack path is taken into account using fracture mechanics but this approach can only be useful for decreasing stress distribution and still under study. Xiao and Yamada approach assumes the computed stress at point in depth of 1mm below the weld toe in the direction of expected crack path as relevant parameter for fatigue strength calculation and still his study is in process. To compare three approaches with actual fatigue test results, three structures like doubler plate, edge gusset and stiffener on T- Bar has prepared. Fatigue life calculated using FEM analysis based on three approaches has compared with actual test results and it has found that Fatigue life calculated using FEM analysis based on IIW recommendation gives results closer to the actual test results but variation in fatigue life between three approaches is very less.

J. Farshid ZamiriAkhlaghia, Mohammad Al-Emrania, Ladislav Frybab and Shota Urushadzeb [23,24] research the application of structural hot spot stress method for fatigue life assessment of a welded detail in orthotropic bridge decks is investigated. That is fillet welded rib-to-cross beam joint with throat size of 2 mm has prepared by shielded metal arc welding technique. The structural hot spot stress is evaluated both experimentally and analytically. In this 20 node solid element and 8 node shell element were used for preparing four FEM models namely SH, OP, SW & TS by selecting different element type, weld modelled or not modelled etc. The accuracy of these shell element models was assessed by comparing the calculated structural hot spot stress values to the experimental values and to the results from the FE-model with solid element. The agreement between the results from the shell element models and solid element model was not good. It seems that the difference in the SHSS values in shell element models and solid element models is more significant when a geometric feature (such as a cope hole or a notch) exists in the hot spot region. Therefore, it is suggested that solid element models being used for these types of details.
Actual fatigue life test data has compared with nominal stress and structural stress approach; it has observed that structural hot spot stress approach is more accurate for predicting the fatigue life.

K. A. Bignonnet, H. P. Lieurade and L. Picouet [28] has suggested the way for improving the fatigue resistance of welded joint by introducing longer initiation period by improved weld procedure and post weld improvement techniques. T- Joint of E460 steel has prepared and residual stresses were measured for as-welded and shot peened specimen. Improved weld profile has been achieved by making smooth shape around toe, by performing weld toe run after the root run for accurate positioning the weld toe and by softening the toe run by heat treatment from filling run so that tensile residual stresses encountered at weld toe get relieved. FEM analysis showed that stress concentration factor for improved profile is 1.2 as compared to 1.9 for as-welded condition. This because the better stress distribution due to improved profile. Shot peening has chosen as post weld technique and three different MIL standards for shot peening has selected. MIL170 introduces -300Mpa residual stress up to 0.15mm whereas MIL330/550 has introduces -400Mpa residual stresses up to 0.45mm depth. From this Shot peening MIL 330 was chosen because of its small shot size which allows the treatment of smaller defects and compared with as-welded condition. It has shown that at high cycle, remarkable fatigue life improvement and crack initiation period corresponds roughly to 70% of the total life. From the results shot peening shows better results as it improves overall weld toe with weld toe and as crack initiation site are at weld region and not at weld toe. So improved weld profile and shot peen found better processes for fatigue life improvement.

L. Alain NUSSBAUMER and Gerhard SEDLACEK have given guideline based on IIW recommendations for post weld toe treatments. [33]

M. Veli-Matti Lihavainen and Gary Marquis [35] have investigated the constant amplitude fatigue strength longitudinal attachment in the as-welded condition is compared with the fatigue strength following ultrasonic impact treatment. Two specimen thicknesses, 5 mm and 8 mm, have been used for studying the thickness effect of UIT.

The material used is structural steel S355 J0, FAT design curve for 95% failure probability has been select with stress ratio of 0.1. They have developed the local strain approach for analytical calculation of crack initiation period of ultrasonic impact treatment based on uniform material law. The fatigue strength of ultrasonic impact treated test series is 45-50 % greater than for the as-welded test series. This means that fatigue life is approximately \( 1.45^3 = 3 \times \) times longer in the ultrasonic impact treated state. It can also be seen that the 8 mm thick specimens had greater fatigue strength than 5 mm thick specimens.

N. Clegg, R.E., McLeod, A.J. and Ruddell, W. [40] have investigated seven weld toe treatment technique namely burr grinding, disc grinding, TIG grinding, hammer peening, ultrasonic peening and thermal stress relieved and comparative analysis has been carried out on Seven specimen base plates of 16 x 150 x 450 mm made of 3678-350 plate. A 16 mm thick circular doubler plate 100 mm dia. was fixed centrally to the base plate with a 16 mm lap weld. Thermal stress relief shows poor performance, TIG dressing and disc grinding has shown medium performance and undercutting with tungsten carbide Burr grinding, UIT shows best performance on fatigue life improvement.

The overall objective of this study is to evaluate the applicability and reliability of the most common post weld toe grinding treatment methods to improve the fatigue life of components by modifying weld toe geometry with the help of post weld grinding techniques.

II. BURR GRINDING

The IIW recommendations, P. J. Haagensen and S J. Maddox, XIII-1815-00 revised 4 July 2001 [7] has given guidelines to improve the fatigue life of welded structures by removing or reducing size of the weld toe flaws from which fatigue cracks propagate and to reduce the local stress concentration effect of the weld profile by smoothly blending the transition between the plate and the weld face using post weld toe burr grinding method. In this burr diameter should be in the 10 to 25mm range for application to welded joints with plate thickness from 10 to 50 mm. The resulting root radius of the groove should be no less than 0.25t.
III. TIG DRESSING

The IIW recommendations, P. J. Haagensen and S J. Maddox, XIII-1815-00 revised 4 July 2001 [7] has given guidelines to improve the fatigue life of welded structures by deforming the material at the weld toe to introduce beneficial compressive residual stresses using hammer peening by repeatedly hammering the weld toe region with a blunt-nosed chisel. The recommended equipments are a pneumatic or hydraulic hammer with air pressure of 5 to 7 bars and delivers 25 to 100 Hz. Impact energy is typically in the range 5 to 15 Joules. Hardened steel tool bits with approximately hemispherical tips, diameters between 6 and 18 mm, and length typically 100 to 200 mm are recommended. The hammer should be held at about 45º to the plate surface and approximately perpendicular to the direction of travel.

IV. HAMMER AND NEEDLE PEEINGING

The IIW recommendations, P. J. Haagensen and S J. Maddox, XIII-1815-00 revised 4 July 2001 [7] has given guidelines to improve the fatigue life of welded structures by removing weld toe flaws by re-melting the material at the weld toe using post weld toe TIG dressing method. Argon is recommended as shielding gas but addition of helium is beneficial since this gives a larger pool of melted metal due to a higher heat input.
From the above discussion for further R & D work, following weld fatigue improvement techniques are identified and corresponding possible fatigue optimization (%) from literature survey listed in Table 1.

Table 1: Possible Weld Fatigue Improvement (%)

<table>
<thead>
<tr>
<th>Burr Grinding</th>
<th>Disc Grinding</th>
<th>TIG Dressing</th>
<th>Shot Peening</th>
<th>Hammer Peening</th>
<th>UIT</th>
</tr>
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<tbody>
<tr>
<td>50%</td>
<td>20-50%</td>
<td>50%</td>
<td>33%</td>
<td>40%</td>
<td>45%</td>
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</table>

V. CONCLUSION

The assessment of the welded joints of construction machineries is major industrial problem because welds are the regions of weakness in a structure as main source of cracks occurring on the components due to stress concentration at weld toe and metallurgical imperfections. So weld joint formed as determining factor of expected life of earth-moving machines. To improve fatigue life of welded joint post weld toe treatments like burr grinding, TIG Dressing, disc grinding, shot peening and UIT are effective techniques as possible weld fatigue improvement by these techniques were in the range of 20 – 50%.

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ASM hardness conversion Table.