Raising the fatigue durability curves in case of the rehabilitation welding techniques

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Abstract. Fatigue of the welded joints is a complex phenomena on widely debated in the worldwide literature. The phenomenon of fatigue of welded structures consists in the occurrence of failures in the case of variable loads, where the load varies between a certain maximum and a minimum values, when always the stress level is below the yield limit of the material. In practice, this type of stresses is encountered in the case of bridges in the welded structure, which has numerous cruciform fillet joints. The paper aims is to study how those two welding rehabilitation techniques “weld toe grinding” and “WIG remelting weld toe “, influence the fatigue life time of some cruciform fillet welded samples, by modifying the stress concentrators and the geometrical shape of the welding seam. It has been chosen to study the cruciform fillet welded joint, because on the one hand this type of joint is met very often in case of bridges welded structures and on the other hand it represents the welded joint with the highest susceptibility to occurrence of the defects and implicitly of the failures. The welding procedure used for welding the cruciform fillet welds is MAG (welding with shielded gas protection). The welded samples were welded in a vertical position.

1. Introduction
The failures are inevitable phenomena that occur sooner or later in all welded structures [1], [2],[3]. Of the failures that can occur in welded structures, those due to fatigue have a large proportion and can be very dangerous and sometimes fatal. Also this fatigue failures can generate real catastrophes and loss of human lives.

Fatigue of welded structures occurs as a result of the accumulation of stresses and deformations that cause cracking and sometimes the destruction of structures due to the application of variable loads in time as intensity and position, loads having a value below the static yield strength of the material from which the structure is made. The factor that influences the most powerful the fatigue lifetime is the stress concentrators. These stress concentrators occur in the case sudden section variations such as fillet and cruciform welded joints, due to the welding seam. The butt welded joint shows much smaller geometric variations of shape on the load direction, compared to fillet welded joints. Thus, the stress concentration factor in the case of butt welded joints, will be lower compared with the stress concentration factor in case of fillet welded joints, presenting a higher variation of the geometric shape. This is the main reason for the longer fatigue life of the butt welded than the fillet welded joints. For both types of joints the fatigue crack will start at the intersection of the base and filler material, at the toe welding. The weld toe region is the most critical region for most welded joints.
In the spirit of what has been explained, it is opportune to have the possibility of prolonging the lifetime of fatigue in the case of structures which have been subjected to variable loads and have accumulated many stress load cycles. Thus, the application of the specific rehabilitation techniques [4], [5],[6] which will increase the fatigue lifetime, is suitable for fillet welded joints and cruciform fillet welded joints, which also have a very high share of use in the case of welded construction bridges and many other welded structures.

The rehabilitation techniques "grinding weld toe" and "WIG remelting weld toe" modify the local geometry of the welding seam in the case of fillet and cruciform welded joints, by obtaining a smooth connection with a large radius, between filler and base material. The connection radius between the filler and the base material is the most important parameter of a fillet welded joint with a direct influence on the fatigue life time. There are many worldwide welded structures, subject to variable loads, have accumulated many stress load cycles, approaching the end of their lifetime. For these structures, it is much cheaper and feasible from economically and technologically point of view, to apply specific rehabilitation techniques such as “grinding weld toe” and “WIG remelting weld toe”. These specific rehabilitation techniques apply to already existing welding seams and practically generate the reduction of the stress concentrators from the intersection between the base and the filler material. The effectiveness of applying these techniques can be proven by raising and comparing the durability curves for cruciform-welded samples on which applies those two rehabilitation techniques outlined above.

The "grinding weld toe" rehabilitation technique [7] consists in the milling of the top of the welding cord, along the intersection line between the filler and the base material, for the joints between pipes (T, Y or K ) and for fillet weld joints between tables. The tools recommended for this process are the wolfram high-speed finger cutters. The tool radius, must be in accordance with the thickness of the plate. Milling should be done at a minimum depth of 0.8-1.0 mm below the surface of the table or 0.5-0.8 mm below the deepest visible notch at a total depth of 2 mm, or 5% of the thickness of the table, which one is smaller. The axis of the milling tool must be positioned at about 45˚relative to the base plate. Milling will be done only at the top of the welding seam at the intersection between filler and the base material not for all of the seam, and it will try the removal of any defect surface. The angle of the milling axis will be at a maximum of 45˚ in relation to the milling direction, to ensure that the milling traces are perpendicular to the line of the weld toe. The milling is applied to both the top and the bottom of the welding seam, at the both intersection points of the welding seam with the base material, as shown in figure 2a and b.

The "WIG remelting weld toe" rehabilitation technique [8] consists of remelting the weld metal to a depth of about 2 mm across the welding toe, without adding a filler material. The welding surface will be cleaned of rust, thunder and slag. The tip of the infusible Tungsten electrode must be sharp and clean and should be positioned from 0.5 to 1.5 mm above the welding toe, as shown in figure 3. At the place where the hardness of the heat-affected zone is over a certain value and could cause problems, a modified technique can be used used with a second return pass.
2. Experimental procedure

In order to determine the influence of the rehabilitation techniques "grinding weld toe" and "WIG remelting weld toe" on fatigue life time, we used cruciform-welded samples that were extracted from a cruciform-welded specimen. This research is extracted from a large study in which 5 cross welded samples were used denoted by A; B; C; D and E depending on the welding process and the welding position used. On all samples we applied the reconditioning techniques “weld toe grinding” and “WIG remelting weld toe”, then extracted samples for static and variable tests. [5]. The cruciform welded sample which is the subject of this paper with is denoted with sign B, and was welded by shielded gas welding process, in vertical position.

The shape and size of welded sample B, fabricated from S 235 JR steel type, welded in vertical position, on which we applied those two reconditioning techniques “weld toe grinding” and “WIG remelting weld toe” in order to reduce the stress concentrators between filler and base material and implicitly to increase the fatigue lifetime, are shown in figure 4.

It is seen from figure 4 that the vertical welding sample B consists of two vertical components 1 and one horizontal component 2. Specimens B1, B4 and B7 will be subjected to static tensile testing and are not the subject of this paper. The reconditioning techniques are applied before the fatigue tests as follows: B2 and B3 are specimens without rehabilitation, B5 and B6 are specimens with “weld toe grinding” and specimens B8 and B9 with “WIG remelting weld toe”. Fatigue testing specimens have been obtained by mechanical cutting of the cruciform welded sample B in strips with width of 30 mm as shown in figure 4b. After mechanical cutting, vertical parts of the specimen attached to the horizontal plate will be milled to reduce the width from 30 mm to 10 mm in welding seams area, as shown in figure 4c. This milling is done in order to reduce the cross section and to conduct the failure during the fatigue tests in the seam or in the HAZ of the seam. It is noticed that the cross section is not reduced sharply from 30 to 20 mm and milling is done with a radius R = 10 mm, in order not to introduce additional stress concentrators. The welding procedure used for sample B, was shielded gas welding procedure in
vertical position and the filler material used was G3Si1 according to EN-440. Welding regime parameters used for welding the B sample are presented in table 1, were Is is the intensity of the welding current, Ua-is voltage, ts-welding time, Lc-seam length, Vs-welding speed, Vas- wire feed speed and El- the linear energy.

| Row | Is (A)   | Ua (V) | ts (s) | Lc (cm) | Vs (cm/s) | Vas (m/min) | El (kJ/cm) |
|-----|----------|--------|--------|---------|-----------|-------------|------------|
| 1-3 | 220-228  | 19.9-20.1 | 85     | 35      | 0.41      | 5.3         | 7.67       |

In figure 5 are shown schematically the cross sections of specimens, obtained after applying the rehabilitation techniques.

**Figure 5.** The cross sections of the specimens. a-specimens B2, B3 without rehabilitation, b-specimens B5, B6 with “grinding weld toe”, c-specimens B8, B9 with “WIG remelting weld toe”.

Geometric elements K1, K2 and R of the welding seams of the specimens from sample B, are shown in table 2, where a is thickness of the welding seam, K1 and K2 are seam legs and R is the radius between seam and base material.

| Specimen | a (mm) | K1=K2 (mm) | R (mm) |
|----------|--------|------------|--------|
| B2 and B3 | 5      | 7          | 0.5    |
| B5 and B6 | 5      | 7          | 2      |
| B8 and B9 | 5      | 10         | 4.5    |

Fatigue tests were carried out with unit LVF 1000-HM. Fatigue test specimens, failure, one from each set, caught in the test machine's jets, are presented in figure 6.

**Figure 6.** Failure fatigue test specimens.
All attempts were performed at the 10 Hz frequency, the stress cycle being a symmetrical alternating one, with the asymmetry coefficient $R = -1$, the stress being that of tension-compression one. For each set of specimens, with and without reconditioning techniques applied, a durability curve was drawn and then compared. For tracing the durability curves, three variations of force were applied to each set of specimens, as follows: to the samples of set 1 without rehabilitation we apply to $B_2 \pm 14\,\text{kN}$, to $B_3 \pm 7.5\,\text{kN}$, to the specimens of set 2 with “grinding weld toe” we apply for $B_5 \pm 14\,\text{kN}$, for $B_6 \pm 7.5\,\text{kN}$ and for third set of test specimens, with “WIG remelting weld toe”, we apply to $B_8 \pm 14\,\text{kN}$ and to $B_9 \pm 7.5\,\text{kN}$.

3. Results and discussions

Forces applied to the specimens and results obtained from fatigue tests are presented centralized in Table 3.

| No. | Rehabilitation technique | Mark | Frequency (Hz) | Force +/-Fi (kN) | Time (s) | Number of cycles until failure (N=nt*f) |
|-----|-------------------------|------|----------------|-----------------|---------|----------------------------------------|
| 1   | Without rehabilitation  | B2   | 10             | $\pm F_2 = \pm 14$ | 416     | 4160                                   |
| 2   |                         | B3   |                | $\pm F_3 = \pm 7.5$ | 5169    | 51690                                  |
| 3   | Grind welding toe       | B5   |                | $\pm F_1 = \pm 14$ | 603     | 6030                                   |
| 4   |                         | B6   |                | $\pm F_3 = \pm 7.5$ | 7495    | 74950                                  |
| 5   | WIG remelting welding   | B8   |                | $\pm F_1 = \pm 14$ | 1239    | 12390                                  |
| 6   | Weld toe                | B9   |                | $\pm F_3 = \pm 7.5$ | 15351   | 153510                                 |

We notice that, with decreasing tensile stress on specimens $B_2$ and $B_3$, increases the number of cycles up to failure. We mention that on specimens without reconditioning $B_2$ and $B_3$, we have the highest value of the stress concentrator at the junction between welding seam and base material because of the smallest radius connecting seam to the base material, namely $R = 0.5\,\text{mm}$.

The specimen $B_5$ on which we applied $\pm 14\,\text{kN}$, was broken after 6030 cycles and $B_6$ on which we have applied $\pm 7.5\,\text{kN}$ failure after 74950 load cycles. We found an increase in the number of cycles compared to specimens homologous $B_2$ and $B_3$. This is explained by the stress concentrator reduction at the top seam connection, by increasing the radius of 0.5 to 2 mm as shown in Table 2.

We also observed that the specimen $B_8$ that on which we have applied $\pm 14\,\text{kN}$, failure after 12390 cycles and specimen $B_9$ that we have applied $\pm 7.5\,\text{kN}$, failure after 153510 load cycles. We determine an increase in the number of cycles compared to the homologous $B_5$ and $B_6$ specimens. This is also explained by the stress concentrators reduction at the top seam according to Table 2 by increasing the radius from 2 to 4.5 mm.

Radii measurements were made with a specialized software by entering the cross-sections pictures of the specimens, scale 1:1.

The traceability of the durability curves is based on the law of variation of the durability curve in linear coordinates, given by the expression 1, where $\Delta \sigma$ is stress variation, $1/p$ is the slope of the curve, $r = \lg A$ is the intersection between the curve and vertical axis and $n$ is number of cycles.

$$\Delta \sigma (n) = \sqrt{\frac{10^r}{n}}$$  \hspace{1cm} (1)

Using the MathCAD calculation program, for specimen $B_2$, $B_3$, with no rehabilitation technique, we found the values $p = 2$ and $r = 6.2$, for which the graph of the function $\sigma_1 (n)$ approaches most of our points $b_1 = (4160; 10400; 51690)$ and of witch represents the force vector $f = (14; 9; 6)$. The shape of
this curve is shown in figure 7, with blue dot line. For the second set of specimens B5, B6 with “weld toe grinding”, also with the help of MathCAD, the values \( p = 2 \) and \( r = 6.3 \) were found for which the graph of the function \( \sigma_2b(n) \) is closer to our points our \( b_2 = (6030; 15075; 74950) \) and the force vector is \( f = (14; 9; 6) \). The shape of this curve is also shown in figure 7, with the broken blue line. For the third set of specimens B8, B9 with “WIG remelting weld toe”, also using the MathCAD program, found the values \( p = 2 \) and \( r = 6.5 \) for which the graph of the function \( \sigma_3b(n) \) approaches the one of the our points \( b_3 = (12390; 30680; 153510) \) and the force vector is \( f = (14; 9; 6) \). The shape of this curve is also shown in figure 7, with the blue line continues.

![Figure 7](image-url)  
*Figure 7. Plotting the durability curves. n-number of cycles, \( \sigma_1b(n) \), \( \sigma_2b(n) \), \( \sigma_3b(n) \)-the durability curves.*

4. Conclusions
As can be seen in figure 7, for the three sets of specimens, the durability curves are not asymptotic to the horizontal axis. This means that practically we cannot talk about the fatigue resistance \( \sigma_0 \) according to the classical Wohler curve.

Also in figure 7, it is observed that at a certain value of stress variation \( \Delta\sigma \), the specimens with “WIG remelting weld toe” resist the largest number of cycles, and the specimens without rehabilitation, resist the smallest number of cycles. The intermediate place is occupied by the specimens with “grinding weld toe”. We can conclude that we have an increase of approximately 40% in the number of cycles up to fatigue failure in case of “grinding weld toe” specimens, respectively with 195% case of “WIG remelting weld toe” specimens.

5. References
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