Fatigue behaviour of butt welded joints in a high strength steel

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Abstract

Modern technological processes make it possible to produce high strength steel with up to 1200 MPa yield strength. This high yield strength gives potential for considerable improvements in performance and reduction in weight, which are of increasing importance in the transport sector and in vehicles used in the construction industry. However, data found in literature show that welded structural parts using these high and ultra-high strength steels have a fatigue resistance not very different in comparison with those obtained in conventional steels with a much lower yield stress.

In this work a fatigue study was performed in a high strength steel in order to evaluate the influence on fatigue strength of the following factors: stress concentration at weld toe, internal defects and welding process method. The material used in this study was a steel sheet called DOMEX 600 DC from SSAB with 5 mm of thickness. This is a high strength steel with a yield stress of 670 MPa and a tensile strength of about 750 MPa.

Butt welded specimens using MAG welding process were submitted to cyclic loading in servo hydraulic machine. Three welding conditions of transverse butt joints and base material were investigated in this fatigue study: as welded; welds overfill removed by grinding; welds overfill and first weld root removed by grinding.

The overfill removing by grinding promotes a significant improvement of the fatigue resistance in comparison with the as welded condition. The removing of the root of the first weld by disc grinding improves significantly the weld quality by reducing the level of internal defects, leading to a further increasing on fatigue strength close to the parent material.

The comparison of characteristic curves obtained for each welding condition and the fatigue class (FAT) indicates that, in general, fatigue strength of DOMEX 600 DC steel is significantly higher than fatigue strength recommended by IIW for conventional steels. The higher difference was found for welds with overfill removed and the first weld root submitted to a disc grinding operation.

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Keywords: high strength steel, fatigue, welded joints, characteristic curves

1. Introduction

During the last decades, steel industries had developing great efforts in order to produce steels products with higher strength and toughness, better weldability, using less expensive elements. These modern technological processes make it possible to produce high strength steel with up to 1200 MPa yield strength. This has been possible by introducing a thermo thermo-mechanically controlled process (TMCP) which combines controlled rolling with...
on-line accelerated cooling. The microstructures of TMCP steels are greatly refined as compared to those of conventional processed steels, resulting in a significant improvement in strength and toughness [1]. This high yield strength gives potential for considerable improvements in performance and reduction in weight, which are of increasing importance in the transport sector and in vehicles used in the construction industry.

However, when introducing high strength steels into fatigue loaded structures it is important to note that the fatigue strength does not follow the trend of the increasing base metal strength. Data found in literature about the fatigue resistance of high and ultra-high strength steels shows that fatigue resistance of welded structural parts is similar as compared to that of conventional steels with a much lower yield stress [2]. The possible reason for this is that the stress concentration and weld defects near weld toe, result in a short fatigue crack initiation period. Therefore, crack propagation will be the major part of the fatigue life. Since the crack growth resistances of mild steel and high strength steel are similar, the fatigue strength of the welded joints will not change too much with steel strength.

In this work a fatigue study was performed in a high strength steel in order to evaluate the influence of some factors on fatigue strength. Several fatigue test series were performed in order to analyse the effect of weld toe stress concentration, internal defects level and welding method. The characteristic curves will be obtained for each welding condition and a comparison with the correspondent fatigue class (FAT) for the fatigue strength recommended by IIW for conventional steels will be done.

2. Experimental details

The material used in this study was a steel sheet DOMEX 600 MC from SSAB Tunnplat AB in Sweden. The chemical composition and the mechanical properties of this high strength steel are indicated in tables 1 and 2, respectively.

Table 1. Chemical composition of DOMEX 600 MC steel (w/%)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>Nb</th>
<th>V</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.12</td>
<td>&lt;0.10</td>
<td>&lt;1.90</td>
<td>&lt;0.025</td>
<td>&lt;0.010</td>
<td>&lt;0.015</td>
<td>&lt;0.09</td>
<td>&lt;0.20</td>
<td>&lt;0.90</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties of DOMEX 600 MC steel

<table>
<thead>
<tr>
<th>Yield Strength, (\sigma_{YS}) [MPa]</th>
<th>Tensile Strength, (\sigma_{UTS}) [MPa]</th>
<th>Elongation up to rupture, (\varepsilon) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>670</td>
<td>750</td>
<td>13-16</td>
</tr>
</tbody>
</table>

Butt specimens were welded using MAG-welding process without edges preparing (I shape) but giving 1 mm of distance between them. The welding direction was normal to the rolling direction of the base material. Before welding the edges were cut in a guillotine shear machine. To protect the welding process, a combination of 85% Ar and 15% of CO₂ was used, surrounding the arc and the weld. As filler material was used 1mm diameter wire ESAB OK Autrod 13.13. The parameters used during welding were: 200A of current and 22V of voltage. The MAG-welding method used was the two beads bottom welding position, which has the advantage of a less heat input, less deformation and better mechanical properties, in comparison with the one bead welding method. After the welding the specimens were machined with geometry shown in figure 1. Both lateral edges were grinded to make them smoother. The fatigue strength of base material (un-notched specimens) of high strength steels is strongly related to the surface roughness. Domex grades normally have a surface roughness \(Ra \approx 2 \mu m\) [2].
Fig. 1. Specimens geometry for fatigue strength testing (dimensions in mm)

Microhardness tests were performed to characterize the Vickers hardness profile in the vicinity of the weld area using a 4.9 N load. Measurements were performed along three lines (figure 2): 1 mm far from both surfaces and at the specimen middle thickness, in successive positions with 0.25 mm of distance.

Fig. 2. Cross-section of weld joint with hardness measurement indentations.

Welded specimens were submitted to cyclic loading in servo hydraulic machine. A sinusoidal wave load with a stress ratio R=0 and a frequency of 20 Hz was applied. Four test series were performed in order to analyse the effect of weld toe stress concentration, internal defects level and welding process: BM, from the base material; AW, in the as-welded condition; WA and WB, with the overfill removed by grinding. Before performing the second weld in WB specimens the root of the first weld was removed using a grinding disc with 3 mm thickness. In WA specimens the two welds were performed without this intermediate operation. Fatigue results were plotted as S-N curves, presenting the stress range against the number of cycles to fracture. Life was defined as the number of cycles to failure and a total of 66 specimens were tested. Fatigue data were statistically analysed accordingly ASTM E739-91 Standard [3] and characteristic curves were determined according to the International Institute of Welding [4].

3. Results

Figure 3 shows clearly a hardness decrease in the heat affected zone and that the fusion zone average hardness is similar to the parent material hardness. Measurements at 1 mm far from both surfaces reveal that hardness typically ranged between 280-290 HV$_{0.5}$ in the both parent and fusion material and 240-250 in the heat affected zone, while at middle thickness hardness values are a little lower: 270-280 HV$_{0.5}$ in the fusion material and 230-240 HV$_{0.5}$ in the thermo-mechanically affected zone. In general, in the case of conventional normalized high strength steel the HAZ is hardened after welding especially at the region adjacent to the fusion line. However, the softened zone of welds performed in TMCP steels is often generated in the HAZ adjacent to the base material, which is contrary to the case of conventional normalized high strength steel.
Fig. 3. Hardness profiles measured along three lines.

Fig. 4. Weld microstructures (etching with Nital at 2%): a) Parent material, b) heat affected zone, c) area where grain growth has occurred, d) fusion zone.
Figure 4 shows the typical microstructures observed in the different zones of the welds. The microstructure of the parent material is shown in figure 4a). Grain size in this zone was 3.3 \( \mu \text{m} \) measured according ASTM E112 Standard [5]. By moving inwards to the HAZ a change of microstructure is seen, figure 4b); the grains become smaller with about 2 \( \mu \text{m} \) and more equiaxed (equal dimensions in both directions), due to recrystallization. In this zone the material is less resistant but more ductile. When moving further in the HAZ (figure 4c), the size of the grains becomes larger because the material in this zone has been heated sufficiently long time for grain growth to occur. Figure 4d) shows the microstructure in the middle of the weld joint (fusion zone) where an average grain size of about 60 \( \mu \text{m} \) was observed.

By putting the results of all fatigue tests we can get a picture of the fatigue strength. Figure 5a) shows the fatigue results obtained for the four conditions studied: BM, from the base material; AW, in the as-welded condition; WA and WB, with the overfill removed by grinding. Mean curves are also superimposed to permit a better comparison between the several series.

![Fig. 5. S-N curves: a) fatigue results obtained for the four conditions studied, R=0; b) statistical analyses according to ASTM E739-91 for the base material, R=0.](image)

Figure 5b) shows, as example, the statistical analyses, accordingly ASTM E739-91 Standard, for the base material. Table 3 summarizes the S-N curve parameters including both life and stress standard deviations, \( \sigma_N \) and \( \sigma_V \), derived from the referred statistical analyses performed for all specimen series. Constant \( C \) and exponent \( m \) are defined in equation 1 (S-N relationship)

\[
N \cdot \Delta \sigma^m = C \tag{1}
\]

Table 3. S-N mean curve parameters for the four testing conditions

<table>
<thead>
<tr>
<th>Series</th>
<th>( m )</th>
<th>( C )</th>
<th>( \Delta \sigma \text{ (N=2x10^6), [MPa]} )</th>
<th>( \sigma_N )</th>
<th>( \sigma_V )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>10.34</td>
<td>2.75E34</td>
<td>520</td>
<td>0.24</td>
<td>0.02</td>
<td>0.89</td>
</tr>
<tr>
<td>AW</td>
<td>5.16</td>
<td>2.34E18</td>
<td>250</td>
<td>0.27</td>
<td>0.05</td>
<td>0.63</td>
</tr>
<tr>
<td>WA</td>
<td>5.60</td>
<td>3.39E20</td>
<td>360</td>
<td>0.42</td>
<td>0.07</td>
<td>0.50</td>
</tr>
<tr>
<td>WB</td>
<td>9.70</td>
<td>2.09E32</td>
<td>475</td>
<td>0.29</td>
<td>0.03</td>
<td>0.66</td>
</tr>
</tbody>
</table>
The overfill removing by grinding performed in the WA specimens promotes a significant improvement of the fatigue resistance in comparison with the as welded (AW) specimens: for a fatigue life of $2 \times 10^6$ cycles the stress range is 250 and 360 MPa for AW and WA series, respectively, meaning a improvement of 44% in the fatigue strength. The exponents of series BM and AW are $m=5.16$ and $m=5.6$, respectively. These lower values of the exponent $m$ reveal that crack initiation period of these series is relatively low. As is well known welded components are less tolerant to fluctuating loads than their non-welded counter-parts for three reasons: a) welds contain internal flaws which act as the initiation site for crack propagation; b) welds create external stress raisers which act as the initiation site for crack propagation; c) the process of welding introduces residual stresses in the region of the weld exacerbating the applied fluctuating stress. Figure 6 shows typical pictures of the fracture surfaces observed in AW and WA specimen series. Fatigue crack initiation of AW specimens occurred always at the weld toes (figure 6a) while in the case of the WA specimens fatigue crack initiation occurs mostly from internal defects placed at the root of the welds (figure 6b).

As referred before, WB series was submitted to an intermediate operation between the two welding pass, consisting in the removing of the root of the first weld by disc grinding. This operation improves significantly the weld quality by reducing the level of internal defects. Figure 5a shows that fatigue strength of the WB series is significantly above the S-N curve for the WA series, being close to the parent material: for a fatigue life of $2 \times 10^6$ cycles the stress range is 475 MPa for WB series, meaning a further fatigue strength improvement of 32% in comparison with WA series. The fatigue strength of the base material for a fatigue life of $2 \times 10^6$ cycles was slightly higher, $\Delta \sigma=520$ MPa. The exponent $m=9.72$ is significantly higher than the exponent of WA series, indicating that crack initiation will be the major part of the fatigue life. This is in accordance with the small difference observed between the exponents $m=9.72$ for the WB series and $m=10.34$ for the base material.

When it comes to lower number of cycles the mean curves for all the welding conditions and the base material becomes closer. This is the influence of the tensile strength that has a low dependence with the welding condition. As the number of cycles increase we can see an increasing difference between S-N curves.
Fig. 7. S-N characteristic curves for a survival probability of 97.7%: a) Base material, b) As welded specimens, c) WA series, with the overfill removed by grinding, d) WB series, with the overfill and first weld root removed by grinding.

Figures 7a) to 7d) present the characteristic curves of the four specimen series obtained according IIW recommendations for a survival probability of 97.7%. The following four statistical effects were considered: i) variance of data, ii) variance of the mean value, iii) difference of the distribution of the whole data (population) and the distribution of the sample (Gaussian versus t-distribution) and iv) deviation from the assumed Gaussian distribution. Each figure present the fatigue results data, the mean curve calculated through the least squares method considering fatigue life as the dependent variable, scatter band defined by lines with 10% and 90% of survival probability. For clarity, each figure is only for one specimen series. The IIW characteristic curve of the fatigue class (FAT) for the correspondent classified structural detail is also superimposed for comparison. The scatter TV is calculated by equation 2 and can be related with standard deviation $s_V$ using equation 3.
Figures 7 shows that scatters in AW (as welded) and WA (welds overfill removed by grinding) conditions, \(1/T=1.34\) and \(1/T=1.53\), respectively, are higher than in the BM (base material) and WB (overfill and first weld root removed by grinding) conditions, \(1/T=1.14\) and \(1/T=1.18\). This is an expected result taking in account that stress concentration factor is greatly influenced by the weld toe radius in the case of as welded condition. Besides, the presence of internal defects with variable size will produces also an important scatter in both crack initiation and propagation lives for the case of WA specimen series. The comparison of characteristic curves obtained for each welding condition and the FAT class indicates that, in general, fatigue strength of DOMEX 600 DC steel is higher than fatigue strength recommended by IIW for conventional steels. In the case of transverse butt weld joints in the as welded condition and a toe angle <30º (FAT 100) the superiority of DOMEX 600 DC steel (figure 7b) is only observed for lives above \(10^6\) cycles. For a fatigue life of \(2\times10^6\) cycles the characteristic curve stress range of the AW series is 154 MPa, meaning a superiority of 54% of fatigue strength in comparison with FAT 100. For transverse butt welds ground flush to plate, 100 NDT (FAT 125), which correspond to our WA and WB conditions, the fatigue strength of DOMEX 600 DC steel is clearly higher than that indicated by IIW recommendations: for a fatigue life of \(2\times10^6\) cycles the characteristic curve stress ranges of WA and WB series is 220 and 390 MPa, respectively, meaning a superiority of 76% and 210% of fatigue strength in comparison with FAT 125.

\[
\frac{1}{T_\sigma} = \frac{\sigma(P_\sigma = 10\%)}{\sigma(P_\sigma = 90\%)}
\]

\[
S_\sigma = \frac{1}{2.56} \log \left( \frac{1}{T_\sigma} \right)
\]

Figure 8 compares the characteristic curves of the four specimen series obtained according IIW recommendations for a survival probability of 97.7%. The characteristic curves show that WB welding condition gives the better fatigue resistance between the three welding conditions and that WA welding condition characteristic curve is still above the as welded condition (AW). Comparing characteristic curve stress ranges of the several welding conditions for \(2\times10^6\) cycles we observe that removing the welds overfull by grinding leads to an increase of fatigue resistance.
from 154 to 220 MPa, meaning an improvement of about 40%. In the case of WB welding condition, where, besides the removing of the welds overfill, the weld root of the first weld pass was also subjected to a disc grinding operation, the characteristic curve stress range for 2x10^6 cycles is 390 MPa, meaning an improvement of about 150% relatively to the as welded condition. Therefore, we can conclude that the stress concentration at weld toe and internal defects near weld toe and weld root are the main factors that promotes fatigue strength decrease. Residual stresses were not measured in this work. However, taking in account that fatigue tests were conducted at a stress ratio R=0, maximum stress during most of the fatigue tests are close to yield stress of this steel. Therefore, residual stresses did not increase significantly the effective mean stress in these tests. The lower fatigue strength of WB welding condition relatively to base material can be partially explained through the decrease of hardness observed in the heat affected zone, previously shown in figure 3. Another factor that contributes to this trend is the presence of some small defects type pores, from which crack initiation occurs in some tests, contributing to a decrease of the mean curve.

4. Conclusions

Three welding conditions of transverse butt joints and the base material of a high strength steel were investigated in this fatigue study: i) as welded; ii) welds overfill removed by grinding; iii) welds overfill and first weld root removed by grinding; iv) base material. Stress concentration at weld toe and internal defects near weld toe and weld root are the main factors responsible by the fatigue strength decrease.

The removing of welds overfill by grinding promotes a significant improvement of the fatigue resistance in comparison with the as welded condition.

The removing of the root of the first weld by disc grinding improves significantly the weld quality by reducing the level of internal defects, leading to a further increasing on fatigue strength close to the parent material.

The comparison of characteristic curves obtained for each welding condition and the fatigue class (FAT) indicates that, in general, fatigue strength of DOMEX 600 DC steel is significantly higher than fatigue strength recommended by IIW for conventional steels. The higher difference was found for welds with overfill removing and first weld root submitted to a disc grinding operation.

References