Luumi, Lauri; Santos Vilaca da Silva, Pedro; Sato, Yutaka S.; Hänninen, Hannu; Kokawa, Hiroyuki

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EFFECT OF SECOND PASS IN 2-SIDED FSW OF HIGH-STRENGTH STRUCTURAL STEEL

Lauri Luumi, Aalto University, Espoo, Finland

Pedro Vilaça, Aalto University, Espoo, Finland
Yutaka S. Sato, Tohoku University, Sendai, Japan
Hannu Hänninen, Aalto University, Espoo, Finland
Hiroyuki Kokawa, Tohoku University, Sendai, Japan

ABSTRACT

Friction stir welding (FSW) of high-strength steels shows promise over traditional fusion welding methods because it is an autogenous solid-state process with low heat input. Technical and financial requirements for the tool and welding machine can become limiting with increasing plate thickness and 2-sided welds are an option. It can also result in better mechanical properties.

Low-alloyed low-carbon high-strength complex phase steel was friction stir welded to investigate the difference in microstructure and mechanical properties between 1-sided and 2-sided welds and compared them to the base material and fusion welding methods. The 2-sided welds achieved tensile properties comparable to fusion welding methods and about 85 % of values for the base material. Only the 1-sided specimen with lack of penetration in tension failed the bending test. Second pass mostly increased the properties in the plastic region but elastic properties improved only slightly.
INTRODUCTION

Friction stir welding (FSW) of high-strength steels shows promise over traditional fusion welding methods [1-9] because it is an autogenous solid-state process with low heat input. Technical and financial requirements for the tool and welding machine can become limiting with increasing plate thickness and 2-sided welds are an option. This reduces the needed probe length and rigidity and strength of the machine. 2-sided welding can also avoid imperfections such as lack of penetration and root defect or allow the use of a weaker anvil. It can also result in better mechanical properties [9, 10].

Most studies on FSW of high-strength steels have been done with pipeline [1, 7, 11-13] or shipbuilding [2-4, 9, 14] steel. The advantage of low heat input in FSW becomes greater with increasing hardness and complexity of the steel since it is more easily affected by welding.

In this study, low-alloyed low-carbon high-strength complex phase steel was friction stir welded to investigate the difference between 1-sided and 2-sided welds. Post-weld microstructures are determined with optical microscopy and mechanical properties through hardness, tensile and bend testing. The values of 1- and 2-sided welds are compared to base material and fusion welding methods.

EXPERIMENTAL

Low-alloyed low-carbon high-strength steel was friction stir butt welded with a Q60 composite tool consisting of 60 % PCBN and 40 % W-Re alloy (geometry in Figure 1). The base material is direct quenched to a microstructure of ferritic-bainitic matrix with carbon-rich second phase microconstituents having nominal yield strength of 700 MPa [15]. Chemical composition is presented in Table 1. Plate thickness was 6 mm and probe length 4 mm. Traverse speed was 1 mm/s and weld length 150 mm in all welds. The surfaces to be welded were ground before welding and argon shielding gas was used. The welding machine was operated on position control and plunge depth of 4 mm was used. Rotation speed during plunge was 400 RPM and during the 30 second dwell time was reduced to the target speed. Figure 2 shows the welding machine, clamping and backing plate.
Table 1. Chemical composition of the studied steel in weight-% based on melt analysis.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Nb</th>
<th>V</th>
<th>Ti</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0,059</td>
<td>0,205</td>
<td>1,79</td>
<td>0,007</td>
<td>0,0022</td>
<td>0,083</td>
<td>0,013</td>
<td>0,113</td>
<td>0,0003</td>
</tr>
</tbody>
</table>

Figure 1. Geometry of the Q60 tool.

Figure 2. Welding machine and clamping.

A partially penetrated 1-sided weld (denoted as M13) is compared with 2-sided welds produced with different conditions. In specimen M23, both sides are welded using 300 RPM and no machining in between passes. Specimen M223 was first welded with 300 RPM, machined flat and the second pass welded with 200 RPM. Machining reduced the thickness by 0,2 mm. Both 2-
sided welds were flipped along the longitudinal axis for the second pass. The influence of the different conditions is investigated by metallographic analysis, tensile testing, hardness measurement and bend testing. Table 2 contains the rotational speeds producing the studied welds.

<table>
<thead>
<tr>
<th></th>
<th>RPM of first pass</th>
<th>RPM of second pass</th>
<th>Max Z-force [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M13</td>
<td>300</td>
<td></td>
<td>33</td>
</tr>
<tr>
<td>M23</td>
<td>300</td>
<td>300</td>
<td>33</td>
</tr>
<tr>
<td>M223</td>
<td>300</td>
<td>200</td>
<td>37</td>
</tr>
</tbody>
</table>

Optical microscopy was used with Nital etchant to characterize microstructure. Hardness measurements were performed using Vickers-hardness with a load of 9,8 N.

Tensile test used standard SFS-EN ISO 4136 except for specimen dimensions. Gauge length was 70 mm and specimen width 14 mm. Cutting was done by EDM without additional machining. An extensometer was used up to the ultimate tensile stress for strain measurement. This data was used for determining tensile parameters. Location of the tensile specimen is shown in Figure 3.

Global Efficiency of Tensile Strength (GETS) [16] was used to evaluate the performance of the welds in a tensile test. GETS combines tensile properties to a single value utilizing weight factors for individual properties. Each tensile property is normalized by that of the base material. GETS is calculated with equation (1).
Figure 3. Locations of specimens in the plate.

\[
GETS = \left( C \sigma_y \frac{\sigma_{yi}}{\sigma_{yBM}} + C \sigma_{UTS} \frac{\sigma_{UTSi}}{\sigma_{UTSBM}} + CA \frac{A_i}{ABM} + CU_T \frac{U_{Ti}}{U_{TBM}} \right) \times 100\% \tag{1}
\]

Weight factors for yield strength \( C \sigma_y \), ultimate tensile strength \( C \sigma_{UTS} \), elongation \( CA \) and toughness \( CU_T \) are all 0.25.

Transverse face and root bend tests were performed according to standard SFS-EN ISO 5173 + A1 except the specimen width was reduced from 24 mm to 16 mm for lack of material. Cutting was done by EDM without additional machining. Global Efficiency of Bending (GEB) was used to evaluate the welds. It is defined by equation (2).

\[
GEB = \left( CF \frac{F_i}{F_{BM}} + Cd \frac{d_i}{d_{BM}} + CU_B \frac{U_{Bi}}{U_{B_{BM}}} \right) \times 100\% \tag{2}
\]

Weight factors for maximum force \( CF \), displacement at maximum force \( Cd \) and energy \( CU_B \) are 0.25, 0.25 and 0.5 respectively to balance strength and ductility.
RESULTS

Macrographs are shown alongside hardness profiles in Figures 4, 6 and 8. Locations for the micrographs (Figures 5, 7 and 9) are indicated in the macrographs.

Figure 4. Macrograph and hardness of specimen M13 with lack of penetration, fracture location and the locations of micrographs.

The hardness profile of specimen M13 is quite stable from HAZ to HAZ. The area of increased hardness is the hard zone (HZ) as described in [11]. The average hardness over the lower plateaus is 259 HV1. The lowest measured hardness was 231 HV1. M13 fractured from the root flaw as expected. The average hardness of the base material is 287 HV1.
Figure 5. Micrographs from specimen M13. The scale bars in pictures 1 and 3 are 100 µm while in the others 10 µm.

Figure 5-2 is a micrograph of the SZ of the 1-sided weld. Microstructure consists of equiaxed ferrite grains with bainite. Grain size is larger than in the base material. Figure 5-4 shows the HZ and it is mostly bainite laths in ferrite grains. Figure 5-5 is taken from the HAZ which has recrystallized but does not
include bainite. Figure 5-6 is indistinguishable from the base material with elongated grains and bainite laths with carbides.

![Image](image_url)

**Figure 6. Macrograph and hardness of specimen M23 with fracture location and the locations of micrographs.**

Specimen M23 had clear difference in hardness between stir zone and HAZ as can be seen in Figure 6. The average hardness values on the lower plateaus in the HAZ were 230 and 224 HV1. The lowest measured hardness was 220 HV1. The upper plateau in the stir zone had an average hardness of 315 HV1. The tensile test specimen necked and fractured on the retreating side of the first pass and propagated to the advancing side of the second pass.
The SZ of M23 (Figure 7-1) shows similar microstructure to the SZ of M13 but with more bainite. Figure 7-3 shows the area where the HAZ of both passes overlap. It does not show bainite laths like the HAZ of M13. Figure 7-4 is from right next to where the heat affected zones overlap which shows the microstructure of the base material with grain growth. Figure 7-5 shows the
base material further away from the SZ. It has relatively fine elongated grains with some bainite. Figure 7-6 shows the area which was in the SZ of the first pass and in the HAZ of the second. It has a fine microstructure without bainite.

![Image]

Figure 8. Macrograph and hardness of specimen M223 with fracture location and the locations of micrographs. Pass on the top is with 200 RPM and 300 RPM on the bottom.

Specimen M223 had the lowest measured hardness at 209 HV1 where the HAZ of both passes overlap. The lower plateaus had average hardness values of 222 and 233 HV1. The lower being on the left side in Figure 8 which coincides with the advancing side of the 300 RPM pass. Micrographs showed no cause for the hardness drop. The tensile specimen necked and fractured at the HAZ overlap on the right side as showed in Figure 8.
Figure 9. Micrographs from specimen M223. The scale bar in picture 1 is 100 µm and in the others 10 µm.

Figure 9-2 shows the SZ of M223. It is similar to the stir zones of other stir zones but with smaller grain size. HAZ overlap area of M223 (Figure 9-3) is comparable to that of the M23. Figure 9-4 is taken from the SZ of the first pass and shows strong discoloration even in the macrograph and is believed to be rust instead of a relevant microstructural zone.

Tensile test curves are presented in Figure 10 in engineering stress and strain. Data is taken from the extensometer which was removed prior to fracture. Table 3 contains pertinent values from tensile tests next to fusion weld techniques for comparison.
Figure 10. Engineering stress-strain curves for the welds and base material from extensometer data.

Table 3. Results of tensile tests of the welds compared to base material and metal active gas welding (MAG), plasma arc welding (PAW) and submerged arc welding (SAW) [17].

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_y$ [MPa]</th>
<th>$\sigma_{UTS}$ [MPa]</th>
<th>A [%]</th>
<th>$U_T$ [J/mm$^3$]</th>
<th>GETS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>765</td>
<td>846</td>
<td>17</td>
<td>38,9</td>
<td>1</td>
</tr>
<tr>
<td>M13</td>
<td>580</td>
<td>607</td>
<td>8</td>
<td>18,9</td>
<td>0,61</td>
</tr>
<tr>
<td>M23</td>
<td>620</td>
<td>763</td>
<td>12</td>
<td>40,5</td>
<td>0,87</td>
</tr>
<tr>
<td>M223</td>
<td>590</td>
<td>730</td>
<td>12</td>
<td>40,3</td>
<td>0,84</td>
</tr>
<tr>
<td>MAG</td>
<td>670</td>
<td>770</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAW</td>
<td>600</td>
<td>720</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAW</td>
<td>630</td>
<td>770</td>
<td>11</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Results of bend tests and calculated GEB are tabulated in Table 4. In specimens marked with B1, the side of the second pass is on the top. So, in M13 B1, the side with lack of penetration is in tension and in M223 B1, the side welded with 300 RPM is in tension. B2 denotes that the opposite side is in tension.
Table 4. Results of 3-point bend tests with GEB. M13 B1 fractured but the others showed no cracking.

<table>
<thead>
<tr>
<th></th>
<th>F [N]</th>
<th>d [mm]</th>
<th>U_B [J]</th>
<th>GEB</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>10340</td>
<td>25,9</td>
<td>231822</td>
<td>1</td>
</tr>
<tr>
<td>M13 B1</td>
<td>4635</td>
<td>6,4</td>
<td>26053</td>
<td>0,23</td>
</tr>
<tr>
<td>M13 B2</td>
<td>9593</td>
<td>30,1</td>
<td>243375</td>
<td>1,05</td>
</tr>
<tr>
<td>M23 B1</td>
<td>9497</td>
<td>28</td>
<td>225312</td>
<td>0,99</td>
</tr>
<tr>
<td>M23 B2</td>
<td>9466</td>
<td>29</td>
<td>242873</td>
<td>1,03</td>
</tr>
<tr>
<td>M223 B1</td>
<td>8815</td>
<td>29,5</td>
<td>222285</td>
<td>0,98</td>
</tr>
<tr>
<td>M223 B2</td>
<td>8381</td>
<td>21,3</td>
<td>149289</td>
<td>0,73</td>
</tr>
</tbody>
</table>

DISCUSSION

The 1-sided weld resulted in undermatching in both stir zone and heat affected zone but the 2-sided welds exhibited increased hardness in the stir zone. However, the hardness in the heat affected zones decreased further creating more hardness gradients. Additional hardness differences are created by hard zones in the stir zones.

The ferritic-bainitic microstructure of the base material was retained in the SZ after recrystallization but grain size was increased leading to the hardness decrease in M13. The HZ with was the most notable in M13 but in all specimens the presence of bainite was required to match the hardness of the base material. The HAZ underwent recrystallization to form larger equiaxed ferrite grains without bainite which lead to lower hardness compared to the base material. In the 2-sided welds, the HAZ overlap had an even lower hardness due to the heat of the second pass.

In the tensile tests, necking and consequent fracture occurred in the HAZ overlap in the 2-sided welds which is the softest region. Tensile results indicate that yield strength is improved by less than 10 %, tensile strength by over 20 %, elongation by 50 % and toughness by over 100 % by the second pass compared to the 1-sided weld. The 2-sided welds show comparable results to fusion welding methods with values about 85 % of those of the base material. Most notably, toughness surpassed base material.

Bend tests and the calculated GEB value indicate that 2-sided welds behave as well as the base material. The values are lower only for M223 B2 in which
the 200 RPM pass is in tension. Expectedly, the 1-sided weld with the lack of penetration in tension behaved poorly, but the welded side in tension gave the best result of all specimens.

**CONCLUSIONS**

Low-alloyed low-carbon high-strength steel was friction stir welded in 1 and 2 passes to study the effect of the second pass and compare to the base material and other welding methods.

The fine grained ferritic-bainitic microstructure of the base material was coarsened in the stir zone but cooling rate was sufficient to produce some bainite. Previously reported hard zone was observed. The HAZ did not include bainite and had the lowest hardness values. Second pass lowered the hardness further.

The 2-sided welds achieved tensile properties comparable to fusion welding methods and about 85 % of values for the base material. Tensile specimens of 2-sided welds fractured in the HAZ. Only the 1-sided specimen with lack of penetration in tension failed the bending test. Second pass mostly increased the properties in the plastic region but elastic properties improved only slightly.

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