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Fatigue behavior of MAG welds of thermo-mechanically processed 700MC ultra high strength steel

Teemu Lahtinen¹, Pedro Vilaça¹, Virgínia Infante²

¹Department of Mechanical Engineering, School of Engineering, Aalto University, 02150 Espoo, Finland

²LAETA, IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

Abstract

The present work analyzes the weldability of 8 mm thick plates of commercially available modern high strength steel with minimum yield strength of 700 MPa. The weldability is improved by modeling the welding conditions to evaluate and support the extensive analysis of the mechanical and the metallurgical properties of the welds. Materials were welded by a two-pass MAG process with four different heat inputs. All the welds and respective base materials underwent fatigue tests, tensile tests and hardness measurements. In tensile tests, the strains were measured using digital image correlation (DIC) equipment. Fatigue fracture surfaces were investigated for the highest and lowest loads tested using scanning electron microscopy. The failures in tensile and in fatigue tests occurred in the recrystallized HAZ. DIC measurements revealed that in tensile tests the strain localized in the domain of minimum hardness. The accumulative effect of both welding passes lowered the strength and hardness at the root side, making the root side more sensitive to weakening, as shown by hardness profiles. In addition, increasing the heat input lowered the fatigue strength of the welds. The welds had 150–300 MPa lower maximum fatigue strength (R=0.1) than the base material.

Keywords
Ultra high strength steel; Fatigue; MAG; Welding parameters; Heat affected zone
1. Introduction

Weight reduction in steel structures has been a point of interest due to the environmental aspects and improvement in efficiency. This has led to an increased interest in using high strength steel grades in various applications made of steel plates, namely, in building cranes, ships and different kinds of containers. Fusion welding is the most common way to produce joints in all kinds of steel structures. The weldability of the steel is therefore an important aspect when considering the usability of the steel. During the last decades, a remarkable improvement has been achieved via low alloying and thermomechanical controlled processing, enabling the production of steels with fine grain size combining high strength and good toughness [1]. Typically, the weldability is also improved compared to steel of the same level of strength produced by conventional methods [2]. Anyway, modern examples of steel are very sensitive to cooling rate and possible tempering after cooling [3], and due to the high heat input during fusion welding, their structure undergoes severe changes in fusion line and heat affected zone (HAZ), which needs to be well understood. In addition to strength and hardness, impact toughness can also be deteriorated at the fusion line and HAZ. When considering weldability of high strength steel, fatigue properties are an important aspect as well. Due to structural gradients in the HAZ, the fatigue behavior of the weldment can change considerably compared to the behaviour in the base material. Even though high strength steel with outstanding mechanical properties in terms of strength and toughness in comparison to conventional structural steel can be produced, still the fatigue life is comparable to the fatigue life of medium strength steel [4,5]. Fatigue is significant because cyclic stresses occur in several applications, such as machine components, ship structures, bridges and other constructions. Therefore, fatigue is related to most mechanical material failures in practice [6,7]. The most significant factor determining the resistance to cyclic load is the geometry [8,9]. Surface roughness is an important factor, because a rough surface provides more possibilities for crack initialization [10,11]. Another important aspect is the purity of the steel. Large non-metallic inclusions act as fatigue initiators and decrease the resistance against fatigue [8]. Residual stresses also have an impact on fatigue behavior. Tensile stresses reduce fatigue life, whereas compressive stresses improve it [12]. Microstructural effects are also important in some cases, as high hardness gradients may occur [13]. Notable mismatches promote crack initiation, which may be the case at the interface between the weld metal and heat affected zone (HAZ) [14]. Costa et al. [15] investigated the effect of weld overfills on fatigue life of thermomechanically processed high strength steel with yield strength of 670 MPa. The results showed clearly that the as-welded condition was significantly weaker in terms of fatigue life, based on stress localization due to geometrical effects. When overfills were removed, the crack was initiated at internal defects. In welded structures the facture is commonly initiated at the vicinity of the weld toe. The stress concentrates to that area because of the geometrical changes (in as-welded condition). Usually near the weld toe, large inclusions also occur, which leads to early crack initiation. Therefore, the propagation part is the most crucial part of fatigue life. In that case fatigue life is controlled by crack growth resistance instead of the capability to hinder crack initiation [15]. Increasing heat input has been noted...
to be detrimental to the fatigue properties as reported by Ghazvinloo et al. [16] in their report concerning MIG welding of aluminum with different welding parameters. Lowered fatigue properties are the results of more dramatic changes in microstructure due to increasing heat input [16]. Higher heat input promotes formation of coarse inclusions at the vicinity of the weld, which further decreases the fatigue strength. For example, titanium nitrides come into play if titanium is present [17].

This work investigates the influence of different welding conditions, in terms of heat input, on the fatigue behavior of MAG welds of thermo-mechanically processed 700MC modern ultra high strength steel. The objective is to provide information based on scientific methods, of the possibility of improving the fatigue properties without the need of post-weld heat and/or mechanical treatment of the weld zone. The welding procedure uses a double pass applied from the same side as that which is applied in the most realistic industrial condition for heavy and large structural components. Statistical analysis is applied to the results based on standard ASTM E739-91 [18]. Besides the focus on the fatigue properties, the weldability analysis in this work is carried out by assessing and integrating the results from other measuring techniques including tensile tests, hardness measurements and metallographic analysis.

2. Base material characterization

The base material in this study is micro alloyed high strength steel with fine grained ferritic-bainitic structure produced by a thermo-mechanically controlled process. The base material meets the requirements of the grade S700MC according to the standard EN 10149-2 [19]. The plate thickness is 8 mm. Figure 1 represents optical and SEM micrographs of the base material. In addition, an EBSD image of the base material is introduced. Grain size calculated by equivalent circle diameter method (ECD) is 2.370 µm. Grains smaller than 100 pixels are ignored in the calculation. The chemical composition of the steel is presented in Table 1. Mechanical properties are given in Table 2.
Figure 1. Optical micrograph, SEM micrograph and EBSD image of base material. Average grain size is 2.370 µm calculated by ECD method from the EBSD image.

Table 1. Limits for the chemical composition of the base material.

<table>
<thead>
<tr>
<th></th>
<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></td>
<td>&lt; 0.12</td>
<td>&lt; 0.25</td>
<td>&lt; 2.1</td>
<td>&lt; 0.02</td>
<td>&lt; 0.01</td>
<td>&gt; 0.015</td>
<td>&lt; 0.091*</td>
<td>&lt; 0.201*</td>
<td>&lt; 0.151*</td>
</tr>
</tbody>
</table>

*Sum of Nb, V and Ti < 0.22 %

Table 2. Mechanical properties of the base material.

<table>
<thead>
<tr>
<th></th>
<th>Yield strength (min MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Elongation A5 (min %)</th>
<th>Charpy V 10x10 mm (min J @ -60 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>700</td>
<td>750–950</td>
<td>13</td>
<td>40</td>
</tr>
</tbody>
</table>

3. Welding procedure

Material was welded with a Kemppi Promig 530 automatized system using a Böhler X 70-IG wire. The groove was V shaped with a 50° angle. Two weld passes were applied to each plate in weld beads of about 1000 mm deposited parallel to the final rolling direction, joining plates 200 mm wide before welding. The root pass was always made with the same heat input: 0.7 kJ/mm. A second pass was made with 4 different values of heat input, namely: 0.7 kJ/mm; 1.0 kJ/mm; 1.2 kJ/mm; and 1.4 kJ/mm. These four different heat input
values resulted in four different cooling rates, expressed as $t_{8/5}$ [s] cooling times. The 4 different $t_{8/5}$ values obtained were: 5 s; 10 s; 15 s; and 20 s respectively. Figure 2 presents joint design and welding sequence schematically. All dimensions are in millimeters [mm]. Figure 3 presents macrographs of the cross sections of each welding condition.

![Joint design and welding sequence](image)

**Figure 2.** Schematic presentation of joint design and welding sequence.

![Macrographs of welds](image)

**Figure 3.** Macrographs of welds with different heat inputs.
4. Experimental procedure

In this work, the specimens for fatigue tests were manufactured according to the requirements in the standard E 466 – 96 [20]. The dimensions and the geometry of the specimens is presented in Figure 4. The weld overheads were not removed from the specimens.

Figure 4. a) Dimensions of the fatigue test specimens; b) Scheme with the extraction plan for all specimens, where the initial and final transient state domain of the weld beads were discarded from the weldability analysis.
The tests were carried out with an Instron 8502 servo-hydraulic testing machine with a load cell of 250 kN. The frequency ranged between 7–10 Hz and the stress ratio R was 0.1. Figure 5 presents the experimental setup.

As the study objective is to obtain a design Wohler curve, the fatigue tests were carried out in a load-controlled mode using sinusoidal axial loading with constant amplitude. The temperature was the ambient room temperature in the laboratory. Tests were performed with maximum stress levels ranging from 300–650 MPa, in order to determine the S-N curves and the fatigue limit \( \sigma_f \). The specimens were tested until their complete failure or to an endurance of 2 million cycles if there was no evidence of fatigue cracking. The DIC equipment was not used in the fatigue tests because the duration of the tests was between 40 000 and 2 000 000 cycles making the capture, storage and processing of these measurements too expensive. Therefore, future work will be performed using DIC equipment to measure the strain field in the different welding zones, allowing the identification of “hot spots” where the fatigue cracks begin to propagate. These results could also be compared with the strain field obtained in the tensile tests, hardness measurements and confirmed with the fractography images.

In addition to fatigue tests, tensile tests with digital image correlation (DIC) measurements were also carried out for each welding condition. For DIC measurements, a Lavision Imager pro X camera system was used. In DIC measurement, pictures of the specimens were taken at the frequency of 2 Hz during the tensile test. A specific pattern was attached...
to the specimen by tattoo paper. Assessing the pattern changes using the DaVis software, the behavior of the strain and its localization was established. The test setup for DIC measurements is presented in Figure 6.

![Figure 6. DIC measurement.](image)

Hardness profiles were determined using a Vickers hardness test with an indentation load of 5 kg, HV5. Face side and root side hardness profiles were measured separately, so that the distance from the face side measuring line to the top of the plate was 1.5 mm and the respective distance from the root side measuring line to the bottom of the plate was 1.5 mm. Distances between the points were 0.5 mm.

5. Fatigue test results

Seven specimens for each welding condition and eight specimens for the base material were tested. Fatigue test results and characteristics of load conditions for each specimen are presented in Table 3. In some cases, infinite fatigue life was obtained and some of the specimens fractured at the base material instead of HAZ. These peculiarities are mentioned in the column “Comments”. The testing of the specimen 4 from the welding condition t8/5–20 s was aborted and the specimen was removed because of a grip failure.
Table 3. Fatigue test results.

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<th>Welding condition</th>
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<th>$\Delta\sigma$ [MPa]</th>
<th>$\sigma_{max}$ [MPa]</th>
<th>$\sigma_{min}$ [MPa]</th>
<th>$\sigma_m$ [MPa]</th>
<th>Frequency [Hz]</th>
<th>Number of Cycles</th>
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<td>220</td>
<td>10</td>
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</tbody>
</table>
In Figure 7, fatigue test results are presented by S-N curves on a log-log scale. In the graphical display of the S-N curves, $\sigma_{\text{max}}$ was used, and not the $\Delta\sigma$, because given the value of $R = 0.1$, then $\Delta\sigma = \sigma_{\text{max}} - \sigma_{\text{min}} = 0.9\sigma_{\text{max}}$ and the graph $\Delta\sigma$ versus N is close to $\sigma_{\text{max}}$ versus N. Each point represents a value from the experimental test and the fitted lines were obtained by fitting a linear regression equation (1) assuming $\sigma_{\text{max}}$ as the dependent variable. Arrows at the measured values denote infinite life.

$$\sigma_{\text{max}} = K_0 N_f^{-m} \tag{1}$$

where $\sigma_{\text{max}}$ is the maximum stress, $N_f$ is the number of cycles causing the failure. The symbols $m$ and $K_0$ are empirical constants, namely the exponent and the coefficient of the S-N curve, respectively. The values for the empirical constants $m$ and $K_0$ for each welding condition are presented in Table 4.

Table 4 Values for empirical constants $m$ and $K_0$.

<table>
<thead>
<tr>
<th>Welding condition</th>
<th>$m$</th>
<th>$K_0$</th>
</tr>
</thead>
<tbody>
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<td>BM</td>
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</tr>
<tr>
<td>t8/5=5s</td>
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<td>2.01·10¹⁵</td>
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<td>t8/5=10s</td>
<td>4.7862</td>
<td>1.39·10¹⁸</td>
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<td>t8/5=15s</td>
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</tr>
<tr>
<td>t8/5=20s</td>
<td>7.0719</td>
<td>9.73·10²³</td>
</tr>
</tbody>
</table>
Statistical analyses for determining 95% confidence bands for the fatigue test results were carried out according to the standard E739–91 [21]. Figure 8 displays the results of the statistical analysis for each welding condition and for the base material. Figure 9 represents all lower 95% confidence bands in the same graph for making the comparison easier. Below the line, specimens do not fail at the probability of at least 95%. In Figure 9, the vertical axis is not logarithmic.
Figure 8. S-N curves from the fatigue test results in 95 % confidence bands for the base material and for each welding condition.
Given the same maximum nominal stress level, higher fatigue crack initiation periods were obtained for condition $t_8/5=5$ s, as reflected by $K_0$ value presented in Table 4. From the analysis of Figure 7 it is also possible to verify that in welds, the $K_0$ value increases with the decreasing yield strength of the material, as expected. However, with a higher number of cycles and lower maximum loads, the differences between the specimens from different welding conditions dissipate. In most cases, the crack nucleated at the interface of the weld metal and the HAZ and the crack propagated along the soft region at the HAZ. As denoted by Table 3, a few exceptions occurred in which the crack was observed at the base material, close to the grip. Due to the large amount of specimens, only some of them were selected for further analysis. From each condition, two of the specimens having the fracture at the HAZ were selected: one with the lowest number of cycles and another with the highest number of cycles before the fracture. Figure 10 presents images of these selected fracture surfaces. The initiation zone, the propagation zone and the final rupture zone are clearly visible in each specimen. The fracture was nucleated at the face side weld metal and HAZ interface. Exceptionally, in specimen 2 (with the lowest number of cycles) from the condition $t_8/5=20$ s, the nucleation occurred at the root side, and the final rupture occurred partly at the weld metal.
It can be noted, that the main difference between the specimens with the highest and the lowest number of load cycles is the relative size of the crack propagation zone. This confirms that the propagation stage is the most critical stage in determining the fatigue life of the specimen. As an example, Figure 11 presents an SEM image of the propagation zone of specimen 3 (N=40583, $\sigma_{\text{max}}=650$ MPa) from the welding condition t8/5=15 s. From Figure 11, striations, secondary cracking and the direction of the crack propagation can be recognized, as marked into the image.

Figure 10. HAZ fracture surfaces of the specimens with the lowest and the highest number of cycles within each welding condition.
6. DIC measurements

With DIC measurements, localization of the strain was analyzed during tensile tests. A summary of DIC results is presented in Figure 12. The specimens used in DIC measurements were removed from the stationary zone and at the same location along the weld line with each other. The images has been taken at two points for each heat input, namely at the ultimate tensile stress and at the point just before the fracture. By increasing heat input, the strain localizes more clearly. In addition, the total absorbed energy decreases by increasing heat input, because of the strain localization. The domain, where the strain localizes, is the recrystallized zone.
7. Hardness measurements

The complete face and root side hardness profiles for the welds of all four different heat inputs are established in Figure 13.
Figure 13. Hardness profiles of the welds for all of the heat inputs.

Figure 13 shows that the root side is more prone to critical softening than the face side. The increasing heat input widens the HAZ and decreases the minimum hardness. When comparing the hardness profiles to the DIC measurements, it can be noticed that the strain localizes in the softest region of the HAZ. The welds exhibit an increased hardness domain next to the softest region, when moving further from the weld (tempered zone). The effect is visible on both face and root side and the maximum hardness is about 280-290 HV5.

8. Conclusions

A comprehensive analysis was conducted concerning the influence of the heat input during MAG welding, on fatigue properties and overall weldability of 700 MPa high strength steel. The specimens were welded with four different levels of heat input, resulting in four distinct $t_{8/5}$ cooling times: $t_{8/5}=5$ s, 10 s, 15 s and 20 s. The main conclusions of this study are:

- The combined results from the microstructural analysis, tensile tests with DIC measurements, and hardness profiles revealed that the most problematic domain in terms of strength/hardness is the recrystallized zone.

- Both high hardness gradients and geometrical features were shown to be the main controlling factors of the fatigue properties. Also, the welding parameters were shown to influence the gradient, value and position of absolute minimum of hardness, as well as the geometric features, such as the shape of the weld bead at face and root zones. This confirms that the welding parameters do influence the fatigue properties.

- Fatigue crack initiation was commonly observed at the weld metal / HAZ interface at the face side (near the toe of the weld bead) due to the geometrical effect, but in some specimens from the high heat input weld, crack initiation was observed at the root side, which brings out the effect of the hardness gradient on crack nucleation.

- The fatigue resistance of all the welds is lower than the base material, and is reduced by increasing the heat input.

- The detrimental effect of the heat input becomes more significant within the increase of the maximum load.

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References


Highlights

- Fatigue behavior of MAG welds of thermo-mechanically processed 700MC ultra high strength steel is investigated;
- Results are compared between different welding conditions in terms of heat input;
- Statistical analysis for determining 95% confidence bands for the fatigue test results were carried out;
- With DIC measurements, localization of the strain was analyzed during tensile tests.