INFLUENCE OF A WELDING DEFECT ON A HSLA S500MC STEEL PLATE: MICROSTRUCTURE AND RESIDUAL STRESS EVALUATION

Intissar Frih(*) , Pierre-Antoine Adragna¹, Guillaume Montay¹
¹ Université de Technologie de Troyes (UTT), Troyes, France
(*) Email: intissar.frih@utt.fr

ABSTRACT
This paper investigates the influence of a MIG-welding defect (porosity) on the microstructure, the hardness and the residual stress of a High Strength Low-Alloy (HSLA) steel plate. To determine the effect of a defect, local hardness and Young modulus around the porosity were measured using nanoindentation. The welding residual stresses, though the thickness, were measured using the contour method. A relationship between the grain size, the hardness and young modulus on the welded structure and around the porosity will be presented in this work.

Keywords: MIG-welding, HSLA steel, porosity, microstructure, residual stress, contour method.

INTRODUCTION
The welded constructions are widely used in various domains (transport, civil engineering, offshore …). High Strength Low-Alloy steel is among the nuances used for these applications due to their good weldability, high yield strength, and low carbon content [1]. However, the mechanical proprieties of HSLA steel can be modified due to the welding process that generates defect and residual stress in the structure. Tensile residual stresses are the most damaging and can accelerate many failure processes. Also, the failure of these structures is mainly due to pre-existing defect generally located in the toe of the weld [2]. Several studies have treated the harmfulness of crack defect on the behaviour of welded structure [3, 4].

However, the understanding of the effect of porosity with the presence of residual stress in the weld is still insufficient. In the context of the safe design the effects of the residual stresses and the porosity defect within the weld should be taken into account.

In this study, the microstructure of the weld and around the porosity is determined. In order to improve the design of components and to optimize their manufacturing, residual stresses induced during welding fabrication must be quantified using the contour method [5].

EXPERIMENTAL METHODS
Material and welding process
In this work, the base material used for the butt-welded plate is the S500MC HSLA steel. Its chemical composition is reported in Table 1. The equivalent carbon content (C_eq), which
indicates an excellent weldability for the S500MC steel, is 0.43 calculated according the following equation as mentioned by several authors among which Amer et al. [6]:

\[ C_{eq} = C + \frac{Mn+Si}{6} + \frac{Ni+Cu}{15} + \frac{Cr+Mo+V}{5} \]  

(1)

The mechanical properties of the base material are listed in table 2. Its ultimate tensile strength is about 520 MPa and its elongation is about 18%.

Butt welded joint of the HSLA steel plates is carried out, in our laboratory, using conventional manual metal arc welding technique. To complete the joining, two weld passes were performed by means of a MIG-fusion welding process. Wire electrode diameter is about 1mm and his chemical composition is detailed in Table 3. The current and the voltage of the welding are 128 A and 17 V respectively.

As shown in Fig. 1, arc welding was used for producing the joint of HSLA steel plates of dimension 130×100×10 mm³. The bevel angle of the joint was 30° on either side. The joint preparation consisted of a 2 mm root gap with a 2 mm deep root face. In the rest of the paper, x, y and z directions designate longitudinal, transverse and normal directions, respectively, as shown in Fig. 1-a.

![Fig. 1](image)

**Table 1** - Chemical composition of the S500MC HSLA steel (weight %)

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Nb</th>
<th>V</th>
<th>Al</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>0.12</td>
<td>0.03</td>
<td>1.6</td>
<td>0.025</td>
<td>0.015</td>
<td>0.09</td>
<td>0.2</td>
<td>0.015</td>
<td>0.15</td>
</tr>
</tbody>
</table>

**Table 2** - Mechanical properties of the S500MC HSLA steel

<table>
<thead>
<tr>
<th>Tensile strength, ( \sigma ) (MPa)</th>
<th>Yield strength, ( \sigma_y ) (MPa)</th>
<th>Elongation, ( \varepsilon ) (%)</th>
<th>Hardness HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>690</td>
<td>520</td>
<td>18</td>
<td>220</td>
</tr>
</tbody>
</table>

**Table 3** - Chemical composition of the filler material (weight %)

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>0.06 - 0.14</td>
<td>0.7 – 1.0</td>
<td>1.3 – 1.6</td>
<td>0.025</td>
<td>0.025</td>
</tr>
</tbody>
</table>
Microstructure
In order to evaluate the microstructure modifications caused by welding, a metallographic study has been performed on the specimen extracted from the butt welded plate. For the microstructural examinations, the welded plate was first sectioned and the cut sample was embedded into black epoxy resin. Sample tested was then polished by a standard metallographic technique (final polishing by an alumina paste). Then, the polished surface was etched in a solution of 2% of nital for 15s, to reveal their microstructure. In this study, microstructure of the welded joints was characterized using VHX-1000 digital microscopy (DM) and scanning electron microscopy (SEM).

Vickers hardness distribution
The measurements of micro hardness were performed on the mirror polished surface at room temperature. These measurements were carried out according to the FM-300e Microhardness Tester in Vickers HV scale using a 1.0 kg load. To obtain the distribution of the hardness along the whole area of the cross section transverse to the welding direction, the measurements were realized for different depths. To get a minimum dispersion of the measurements, the spacing between each horizontal line is 1mm (9 lines) and the spacing between each indent is 0.3 mm (50 points per line) as presented in Fig. 2.

Nanoindentation
Nanoindentation technique was conducted using Nano Indenteur® XP, in order to determine the local hardness and Young's modulus around the porosity in the welded joint of HSLA steel. In fact, nanoindentation method has proven to be a powerful procedure to obtain micro scale mechanical properties of materials from load-displacement measurements as demonstrated by Fischer-Crippes [7]. According the Oliver and Pharr [8] method, hardness and Young’s modulus can be extracted from the indentation curves. The technique consists to control the evolution of the indentation load with the displacement of the indenter. The maximum penetration displacement was 800 nm for each test. Nanoindentation procedure was performed on the longitudinal section of butt-welding joint.
Residual stress measurement: Contour Method

The contour method (CM) was developed by Prime [5] in order to measure the residual stress field over a cross-section. This technique offers higher spatial resolution for thin plates as was verified by Richter-Trummer et al. [9]. The measuring protocol consists of three main steps: (1) specimen cutting, (2) contour measurement and data processing, (3) numerical calculation based on the performance and quality of the cut.

Cutting process is the first step, and also is the most critical in the implementation of the method of measurement. Electrical Discharging Machining (EDM) method can effectively achieve the desired precision for work piece sectioning. As presented in Fig. 3, welding was performed in the longitudinal direction and the cutting was carried out in the transverse direction with a brass wire of 0.25 mm diameter and a cutting rate of 6 mm/min.

Measuring the displacements, due to the stress relaxation, is the second step. In the present study, the coordinate measurement machine (CMM) with a touch probe of 1 mm diameter was used for scanning the profile of the cutting surface, as presented in Fig. 4. The profile was scanned with an accuracy of 1.8 µm in volume. The scanning was realized for both halves of the cut. Each cut surface was measured with a dense point spacing of 0.03 mm in the transverse and depth directions. The average of the measured data, for both halves of the cut, is calculated in order to remove the effect of shear stresses or any asymmetric effects in the cut. Numerical treatments applied to the measured data are the filter firstly and then the smoothing which will also allow us to obtain a representative polynomial function of the measured values. This smoothing function represents our input in the finite element calculation.

The final step is the finite element analysis used to evaluate the residual stresses normal to the cut surface from the imposed displacements. Displacements imposed are those calculated by smoothing: the approximate polynomial function determined by the least squares estimates of the measured displacement value x in each node according to its coordinates y and z.

RESULTS

Microstructure overview

Fig. 5 shows the macrograph of a butt welding plate. Three distinct areas can be clearly identifiable: 1- the base metal (BM), 2- the heat affected zone (HAZ) and 3- the weld metal (WM). The average width of the HAZ region is about 1/1.5 mm. It is important to remember how important a role does the size of the fusion zone and the size of the HAZ in welded
assemblies. These areas contain the defects which are the starting point of any problem in welded joints. Macro defects can be visibly detectable in a digital macrograph. These defects are located at the boundary between the fusion zone and the HAZ but in the side of the WM as shown in Fig. 5. Two defects (porosity1, porosity2) were located at the right side of the WM and the third defect (porosity3) was located on the left side of WM. These defects were observed with a semi-major axis of about 150 µm, 50 µm and 30 µm respectively. In the following paragraphs, the porosity1 will be a center of interest because it is a tunnel defect and the largest porosity observed on the weld.

Digital micrographs of the weld regions are shown in Fig. 6. Significantly changes were observed while moving from the base HSLA metal to the fusion boundary especially the average grain size and the proportion of the phases.

As shown in Fig. 6, the HAZ region is divided into three areas: coarse grained zone, partially fine grained zone and fine grained zone. Microstructure characterization was carried out by SEM as observed in Fig. 7. The base plate has a typical microstructure of ferrite with average grain size of 15 µm. The coarse grained HAZ can be observed near the fusion boundary and contained 80% bainite and 20% coarse grained acicular ferrite.
In the middle HAZ region, as presented in Fig. 7-b, the average grain size is about 10 µm. The fine grained HAZ, next to the interface with the BM, has a ferritic microstructure with average grain size of 8 µm. Fine grain structure can be seen in the top of the weld centerline with average grain size of about 5 µm. The WM reveals a coarser solidification microstructure composed of 70% coarse grained bainite and 30% very fine grained acicular ferrite. By moving to the bottom of the weld centerline, the grain size increased gradually.

The microstructure around porosity1 was shown in Fig. 7-d. A coarse grain region can be observed around the porosity with average grain size of about 22 µm. These coarse grains are surrounded by extremely fine grains resulting in an obvious structural inhomogeneity. At the top of porosity1, local microstructure is composed of 68% acicular ferrite and 32% bainite. At the bottom of porosity1, acicular equiaxed ferrite (granular microstructure) was observed.

Fig. 7 Microstructures of the welded S500MC HSLA steel (a) The base steel (b) The HAZ area (c) The weld steel and (d) At the top of porosity1

**Hardness distribution**

Fig. 9 shows the distribution of Vickers micro-hardness in the whole area which is estimated according to the nine lines measuring strategy. In the base metal, the hardness remains at 220±10 HV. Fig. 8 presented the measurement results of line1 and line4 which are the lines located at 1 mm and 5 mm below the top of the weld respectively. As observed in Fig. 8-a, the
hardness reaches the peak value of about 312 HV at the weld metal according the line1 of measurement.

As shown in Fig. 8-b, according the line4 of measurement, the hardness rises as the HAZ is approached from the direction toward the center of the weld area. It reaches the peak value of about 260 HV at the boundary between the HAZ and the weld metal but in the side of the weld metal. Once the weld metal is crossed, the hardness drops down dramatically to 147 HV at the boundary between the weld metal and the HAZ but in the side of the weld metal due to the presence of the porosity1. Then, the hardness rises as the HAZ is approached from the direction toward the base metal.

![Fig. 8 - Distribution of Vickers micro-hardness](a) line1 of measurement, (b) line4 of measurement

The variation of Vickers hardness as a function of the grain size allows concluding that the Vickers hardness follows the Hall-Petch relation as detailed by Hall [10] according to the equation (2):

\[
HV = HV_0 + \frac{k}{\sqrt{D}}
\]  

(2)

Based on Fig.10, the parameters values are: \(HV_0 = 21.425 \text{ N.mm}^{-2}\), \(k = 20.963 \text{ N.mm}^{3/2}\) and D (mm) is the average diameter of the grain.

![Fig. 9 - Cartography of Vickers micro-hardness](a) Cartography of Vickers micro-hardness  
![Fig. 10 - Variation in hardness with d^{3/2}](b) Variation in hardness with \(d^{3/2}\)
Nanoindentation results

The load–displacement curves acquired during nanoindentation test were shown by Fig. 11. From the load–depth diagram, local elastic material parameter (elastic modulus and hardness) can be extracted using the Oliver and Pharr [8] method. The contact hardness \( H_C \) is defined as:

\[
H_C = \frac{P_{\text{max}}}{A_C}
\]

(2)

where \( P_{\text{max}} \) is the maximum applied load and \( A_C \) is the projected contact area between the substrate and the tip. The contact depth \( h_c \) is given by:

\[
h_c = h_{\text{max}} - \beta \frac{P_{\text{max}}}{S}
\]

(3)

where \( S \) is the unloading stiffness, \( \beta \) is a constant that depends on the geometry of the indenter (\( \beta = 1.034 \) for a Berkovich indenter) and \( E_r \) is the reduced elastic modulus calculated based on the elastic theory proposed by Sneddon [11]:

\[
E_r = \frac{S\sqrt{\pi}}{2\sqrt{24.5h_c}}
\]

(4)

According the Oliver and Pharr method, hardness and Young’s modulus can be obtained from the indentation curves presented by Fig. 11. Nonindentation results shows that maximum hardness (3.8 GPa) was obtained in the fusion zone at 1000 \( \mu \)m from the porosity1 and the corresponding microstructure was bainite and very fine grained ferrite of about 5 \( \mu \)m. In the vicinity of the porosity1, hardness decrease gradually. At the left of porosity1, the average micro hardness was 2.6 GPa and the corresponding microstructure was coarse acicular equiaxed ferrite of about 22 \( \mu \)m. Near the welding defect, but in the side of coarse grained HAZ, the hardness was about 2.7 GPa and the corresponding microstructure was bainite and coarse grained.
ferrite. At 1000 µm from the porosity, in the fine grained HAZ, a gradual increase in hardness (3.3 GPa) was observed and the corresponding microstructure was fine grained ferrite.

Fig. 12-b shows the variation of Young's modulus near the welding defect. The Young's modulus also decreases near the porosity (about 240 MPa) and increases by moving away. Young's modulus increases up to 285 MPa at the weld metal and it is about 265 MPa at the heat affected zone.

Experimental results on the HSLA welded joint are summarized in Fig. 13 as a plot of hardness vs. $d^{1/2}$, these allows concluding that the elastic modulus follows the Hall-Petch relationship according to the equation (5):

$$E = E_0 + \frac{k}{\sqrt{D}}$$

(5)

Based on Fig.13, the parameters values are: $E_0 = 195.76$ N.mm$^{-2}$, $k = 6.6335$ N.mm$^{3/2}$ and $D$ (mm) is the average diameter of the grain.

**Contour method results**

Fig. 14 shows that the measured raw data for the two cut faces. The alignment of measured data from both cut surfaces and the removing of noise were carried out using MATLAB.
software. The averaging of two cut faces measurements was performed and fitted smoothly as observed in Fig. 15. The three dimensional finite element model was presented in Fig. 17. The mesh was constructed using the three-dimensional 8 nodes C3D8R. The convergence was reached with 169,968 elements for a total of 183,855 nodes.

Then, displacements plotted in Fig. 16 were imposed to the finite element model in order to calculate the longitudinal residual stresses. Results given by numerical simulation were plotted in Fig. 18. The cartography of longitudinal stress, within the fusion zone, the heat affected zone and the base metal, was shown in Fig. 20. The distribution of residual stresses measured with the contour method shows that the weld region throughout the thickness is under tension and the base metal region is under compression.

Results given by numerical simulations were plotted in Fig. 17. The cartography of longitudinal stress, within the fusion zone, the heat affected zone and the base metal, were obtained. The distribution of residual stresses measured with the contour method shows that the weld region throughout the thickness is under tension and the base metal region is under compression. It is obvious that the longitudinal residual stress was not uniform throughout the thickness of the butt-welding joint. The peak tensile residual stress was obtained at weld centerline (244MPa). The peak measured stress was close to the yield strength of the filler material at room temperature.
As observed in Fig. 14, the HAZ is at most in residual compression where the high hardness ferrite grained weld metal is in tension. The weld metal is the most critical zone for cracking growth near porosity due to the presence of residual tension. The lowest hardness values were obtained at the highest compressive stress. Residual stresses are reduced near the porosity due to relaxation and it corresponds to the lowest hardness obtained across the weld.

CONCLUSION

The influence of a welding porosity on the microstructure, the hardness and the residual stress of a HSLA steel plate was studied. The main conclusions can be summarized as follows:

1. Microstructure study, across section of HSLA welded, exhibit five regions: very fine equiaxed grains at the weld metal zone, coarse grained HAZ near the fusion boundary, partially refine grained zone on the middle of HAZ, fine ferrite HAZ and the base metal zone. Very large grains are observed around the porosity which shows the lowest toughness and ductility in a welding structure.

2. Hardness tests shows that: the maximum value of hardness was attained at the weld metal region, sharply decreasing in hardness from fusion boundary to fine grained HAZ, gradually increase hardness at the base metal zone and the lowest hardness was obtained around porosity.

3. The Hall-Petch relationship is used to link the ferrite grained size and the micro-hardness results.

4. The cross-sectional residual stress profile was measured using the contour method. Results show that the peak tensile stress is located near the weld centerline in the fusion zone and the highest compressive stress is situated in the heat affected zone.

5. The relation between residual stress and hardness measurements instrumented is not obvious to demonstrate however it is clearly identified that the weld metal is the most critical zone for cracking growth essentially near porosity due to the presence of residual tension.

ACKNOWLEDGMENTS

The authors acknowledge the financial supports of Champagne-Ardenne region to implement this project.

REFERENCES


