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*Original Article*

# Butt welding of thin sheets of S960MC steel

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**Abstract:** The paper presents the application of MAG welding to TMCP steels (thermo-mechanically controlled processed) grade S960MC and 3 mm thick. In the analyzed joints, the research focused on their mechanical properties and changes in the heat-affected zone (HAZ) that occur in this type of steels. The hardness and tensile strength tests carried out showed a significant decrease in the properties of the joint compared to the declared values of the base material and the filler material used in the tests. In the case of hardness, it was a decrease of 34% in HAZ and by 15-21% in relation to the strength limit. Changes in HAZ properties of a joint correlate with changes in its structure.

**Keywords:** S960MC steel; HAZ; weldability

## Introduction

The use of high-strength low-alloy steels (HSLA) is associated with ensuring high strength of the structure while maintaining or reducing its weight. At the same time, good plastic properties and weldability are required. In the case of vehicles, for example, a reduction in weight leads to fuel savings and thus a reduction in pollutant emissions. The improvement of the mechanical properties of steel can be achieved by controlling the chemical composition and the production process. Both of these factors have a significant influence on the weldability of materials. In HSLA steels, methods to increase strength are used, mainly based on controlling the cooling process in rolling mills and controlling the microstructure of the steel. During the welding process, the material heats up very quickly, followed by rapid cooling. This temperature cycle changes the microstructure and mechanical properties in the heat-affected zone (HAZ), mainly changing the grain size and dissolving the carbides. These changes are then reflected in the mechanical properties, in particular in the values of hardness, ductility, yield point and tensile strength. The amount of heat input has the greatest influence on these changes [1,2] and the next important parameter is the cooling time $t_{8/5}$, which determines the obtained microstructure of the welded joint. For this reason, hybrid welding methods can be a good solution for welding steels sensitive to the amount of heat input [3,4]. By increasing the welding efficiency while reducing the amount of welding consumable, the effects of heat on the size and structure of the HAZ and the size of welding deformations can be minimized. The critical area is the HAZ, the sub-zones of which are defined by the welding heat cycle. There are different heat treatment conditions in each subzone depending on the distance from the heat source. This leads to the development of different microstructures and mechanical properties of the area in question. HAZ can be divided into four main sub-zones, namely coarse-grained heat-affected zone (CGHAZ), fine-grained heat-affected zone (FGHAZ), inter-critical heat-affected zone (ICHAZ) and sub-critical heat-affected zone (SCHAZ). The division of HAZ into particular sub-zones is shown in (Fig. 1) [5÷7].

After welding high-strength steels, the SWC softens. The term "SWC softening" is used for the sub-area of the HAZ where the hardness is lower than that of the base material. The microstructure of steels with a tensile strength close to 900 MPa usually consists of martensite or bainite, which is tempered below the transformation point $A_1$ during production. Due to the fact that the material is exposed to temperatures above $A_1$ temperature during welding, the HAZ microstructure changes irreversibly. During the subsequent cooling of the HAZ, it is not possible to achieve the same conditions as in the production of the base material [8,9], which leads to "softening" mainly in the ICHAZ and SCHAZ subzones. Research has shown that this sub-area has lower mechanical properties. This is also where most of the fatigue cracks begin. It was also confirmed that the width of the softened area increases with the increase of the amount of heat input, and the hardness decreases with the increase of the parameter $t_{8/5}$ [9÷12].

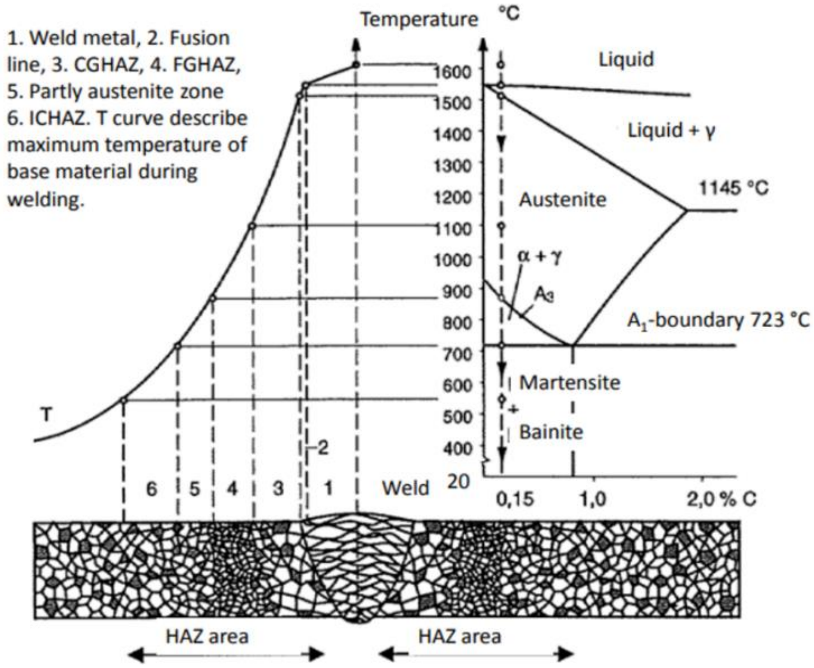



**Fig. 1.** Diagram of the relationship between the thermal cycle of welding, structural changes and the construction of a welded joint made of unalloyed steel [2]

Recent studies on welding high-strength steels (especially S960) describe the influence of processing parameters and technology on the obtained properties, but these studies mainly concern plates with a thickness of 8 mm and more. It is well known that welding thin sheets may reveal some differences in the obtained properties of the welded joint compared to thick sheets [13,14]. The aim of the work is to indicate changes in the microstructure and mechanical properties of a butt-welded joint of S960MC steel with a thickness of 3 mm, welded using the MAG method.

## Material and methodology of the research

The study used S960MC steel supplied in accordance with EN 10149-2 [15]. The required chemical composition according to this standard and the chemical composition according to the certificate of the tested steel are given in table I. The required mechanical properties according to EN 10149-2 and the mechanical properties according to the certificate of the tested steel are given in table II.

**Table I.** Chemical composition of S960MC steel

| According to | Chemical composition of S960MC steel, wt.% of S960MC steel | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | Al | Nb | V | Ti | Mo | B |
| EN 10149-2 * | 0.20 | 0.60 | 2.20 | 0.025 | 0.010 | 0.015 | 0.090 | 0.20 | 0.250 | 1.000 | 0.005 |
| SSAB Strenx S960MC ** | 0.12 | 0.25 | 1.30 | 0.020 | 0.010 | 0.015 | 0.05 | 0.05 | 0.07 | – | – |
| Inspection certificate *** | 0.087 | 0.18 | 1.11 | 0.009 | 0.001 | 0.030 | 0.002 | 0.01 | 0.022 | 0.128 | 0.001 |

* Maximum values except for Al. The Al value is minimal. The sum of the elements Nb, V and Ti may not exceed 0.22%
** Maximum values except for Al. The Al value is minimal. The sum of the elements Nb, V and Ti may not exceed 0.18%
*** Nb+V+Ti=0,034%

**Table II.** Mechanical properties of S960MC steel

| According to | Mechanical properties of S960MC steel, thickness 3 mm | | |
|---|---|---|---|
| | $R_{p0,2}$ [MPa] | $R_m$ [MPa] | A [%] |
| EN 10149-2 | min. 960 | 980÷1250 | min. 7 |
| SSAB Strenx S960MC | min. 960 | 980÷1250 | min. 7 |
| Certificate | 1031 | 1154 | 12 |
| | 1038 | 1147 | 11 |

The welded joint was configured as an I-weld butt joint with a 1.5 mm root gap. The size of the sheets was 150 × 300 mm with a thickness of 3 mm. Welding was performed with the MAG process using the Fronius TPS 2700 device, in accordance with the proposed welding parameters presented in table III. Welding parameters were selected on the basis of previous welding tests.

**Table III.** Welding parameters

| Welding process | Polarity | Current intensity I, A | Arc voltage U, V | Welding speed, mm/s | Electrode wire feed, mm/s | Gas flow, l/min | Heat input of welding, kJ/mm |
|---|---|---|---|---|---|---|---|
| 135 | DC+ | 130 | 18.5 | 7.8 | 4.5 | 16 | 0.25 |

The welding wire Carbofil 3NiMoCr by Oerlikon with a diameter of 1 mm was used as an additional material (EN ISO 16834-A: G 89 5 M21 Mn4Ni2.5CrMo) [16]. The chemical composition and mechanical properties of this wire are given in table IV. It is a binder where the minimum yield strength of the weld metal is lower than the yield strength of the base material. M21 (82%Ar+18%$CO_2$) shielding gas was used to cover the joint.

**Table IV.** Chemical composition (% by weight) and mechanical properties of the filer material

| | Chemical composition (% by weight) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | Cr | Ni | Mo | Cu | Al | V | Ti | Zr |
| EN ISO 16834* | 0.13 | 0.50÷ 0.80 | 1.60÷ 2.10 | 0.015 | 0.018 | 0.20÷ 0.60 | 2.3÷ 2.80 | 0.30÷ 0.65 | 0.30 | 0.120 | 0.030 | 0.100 | 0.1000 |
| Certificate | 0.11 | 0.66 | 1.77 | 0.009 | 0.007 | 0.41 | 2.43 | 0.46 | 0.17 | 0.007 | 0.007 | 0.069 | 0.0019 |

* Maximum values

| | Mechanical properties of the weld metal | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| EN ISO 16834 | $R_{p0,2}$ [MPa] | ≥ 890 | $R_m$ [MPa] | 940÷1180 | A [%] | ≥ 15 | KCV [J] | ≥ 47 / -50 °C |
| Certificate | $R_{p0,2}$ [MPa] | ≥ 930 | $R_m$ [MPa] | ≥ 980 | A [%] | ≥ 14 | KCV [J] | ≥ 47 / -50 °C |

After welding, the joints were cut in the transverse direction into test pieces with a minimum distance of 25 mm from the start of the welding. The following tests were performed:

- visual inspection,
- macroscopic and microscopic examinations,
- microhardness test,
- transverse tensile test.

The assessment of the mechanical properties of the welded joint was made in accordance with EN ISO 15614-1: 2017 [17], according to the following criteria:

- the tensile strength of the welded joint must be equal to or greater than the minimum required tensile strength of the base material ($R_m$ ZS ≥ 980 MPa),
- the maximum hardness of the welded joint (for the base material classified in group 2.2 according to EN ISO 15608 [18]) must not exceed 380 HV without post-weld annealing. In the case of steels above $R_{p0,2}$ ≥ 890 MPa, a critical value must be agreed.

In practice, the criteria values are often lowered. For example, for a welded joint made of S960MC steel, $R_{p0,2}$ ≥ 910 MPa is relatively required. They also set the upper and lower limits for the assessment of hardness in the joint, which for a joint made of S960MC steel must be in the range of 260÷450 HV without heat treatment.

## Results and discussion

### *Assessment of macro and microstructure*

The visual tests were carried out in accordance with the EN ISO 17637:2017 standard and the joint quality assessment in accordance with the EN ISO 5817:2003 standard for the B quality level. The visual tests performed did not reveal any imperfections and the geometric dimensions of the joint were within the EN ISO 5817 standard for the B quality level. The macro and microstructure evaluation was performed with a Zeiss Optical microscope. Samples were prepared according to standard metallographic sample preparation procedures and etched with 2% Nital. The macrostructure of the welded joint (Fig. 2) showed no cracks, bubbles and other internal defects with a smooth transition of the weld metal to the base material.

The microstructure of the base material is shown in figure 3a and consists of a mixture of tempered martensite and bainite. Microstructural assessment shows significant changes in HAZ.

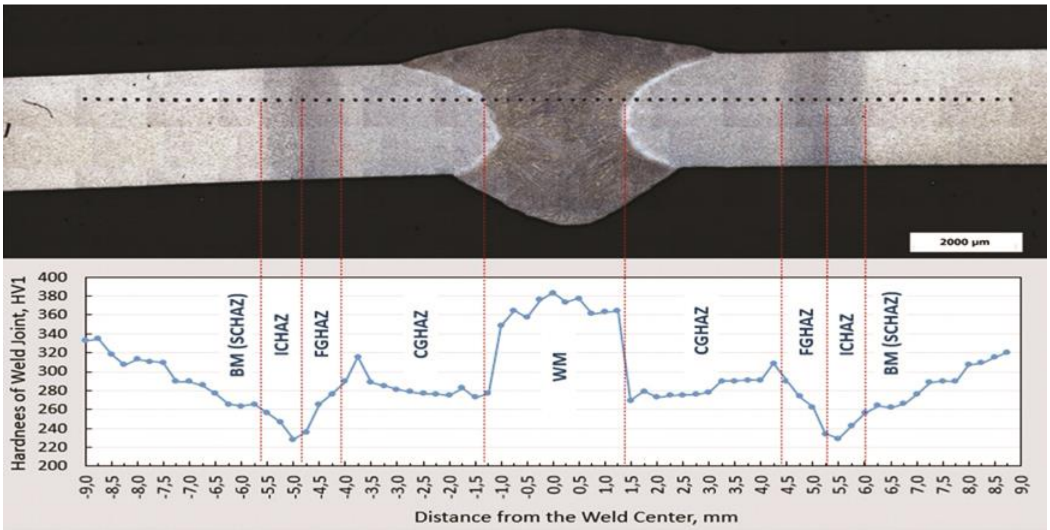



**Fig. 2.** Macrostructure of welded joint of S960MC steel and microhardness profile HV1 in individual subzones HAZ (BM – basic material, WM – weld metal)

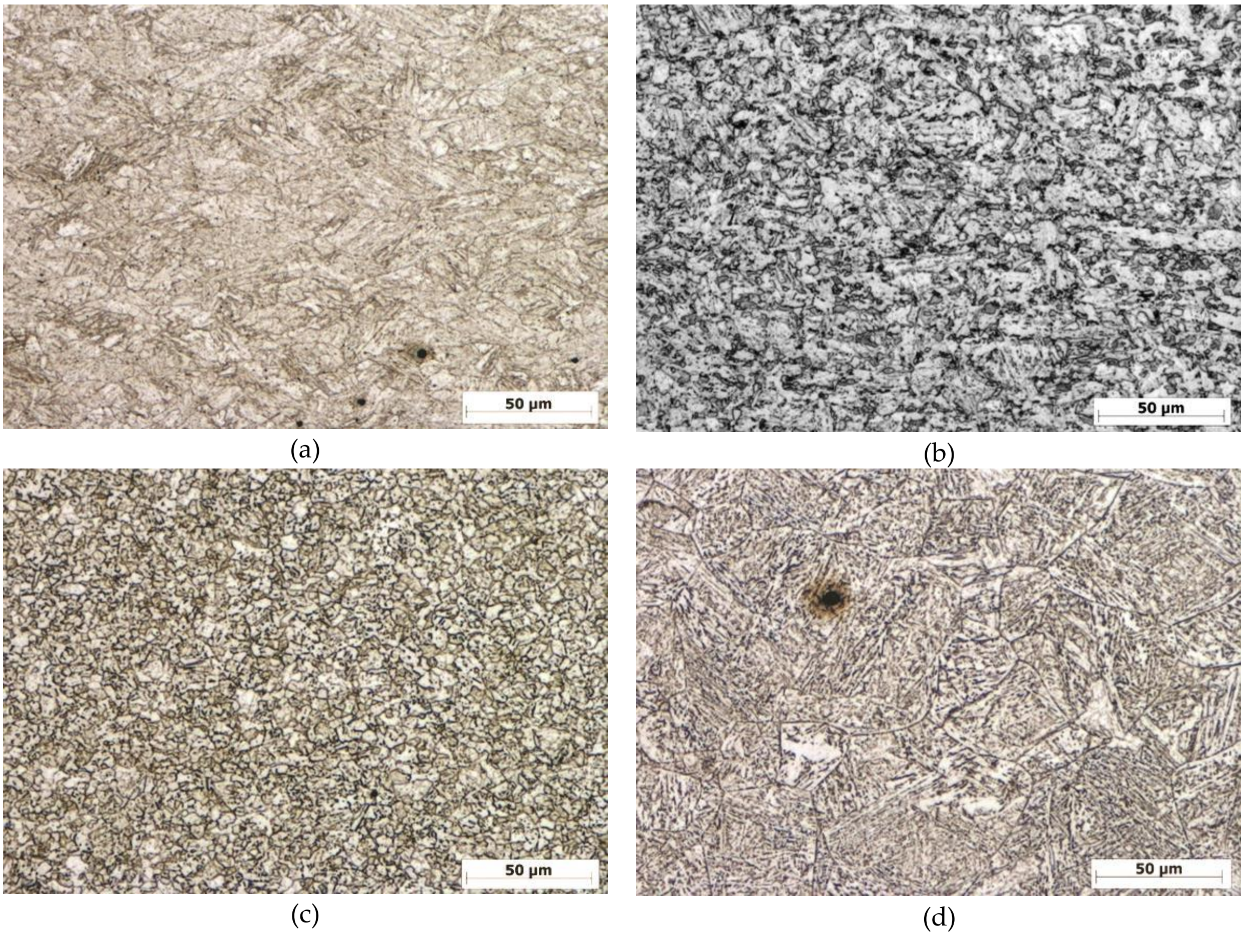



**Fig. 3.** Microstructure of the base material and individual sub-zones of the HAZ welded joint of S960MC steel a) basic metal, b) ICHAZ, c) FGHAZ, d) CGHAZ

In line with the observation of the microstructure, several structural sub-zones were recorded in the HAZ. HAZ phase transitions depend on the height of the maximum temperature and the time for which its individual parts were exposed. Closer to the weld metal and the melting zone, the area was exposed to higher temperatures, but at the same time there was a faster cooling rate. In the HAZ of the examined weld, three main sub-zones were distinguished (there were transition areas between these clearly separated sub-zones). Similar behaviour was described by the authors [19÷23]. In the direction from the weld metal to the base material, the first observed zone was the coarse-grained area (CGHAZ) (Fig. 3d). The CGHAZ is an area that has been heated well above the $Ac_3$ temperature, which has led to an increase in the grain size of the austenite and the transformation of the base material into austenite. After quick cooling, the enlarged austenite grains were transformed back into coarse martensite.

The second area of the HAZ is the fine-grained zone (FGHAZ) (Fig. 3c). This area was heated slightly above the $Ac_3$ temperature, but for a very short time. Despite the fact that it caused the transformation of the base material into austenite, due to the relatively low temperature and very short time as well as rapid cooling, it led to the fragmentation of the austenitic structure and its subsequent transformation into martensite. The last area of the HAZ is called the intercritical zone (ICHAZ) (Fig. 3b). This area was exposed to the temperature from $Ac_1$ to $Ac_3$, where the martensite was partially converted to austenite. This heating produced a mixture of martensite and austenite which, upon rapid cooling, transformed into martensite and ferrite, while the unconverted martensite was tempered. The resulting microstructure of this area is a mixture of martensite, ferrite and tempered martensite – similarly to other studies [19,22]. According to other authors, ICHAZ is the weakest area for welding high-strength steels [24]. The width of the ICHAZ was about 750 μm. Additionally, another area (SCCHAZ) was observed, where the temperature did not exceed the $Ac_1$ temperature, thanks to which no structure change took place, but only the tempering of the martensitic phase, which resulted in a slight decrease in hardness in this area.

## *Microhardness evaluation*

To describe the structural changes in the area of the welded joint, the hardness rating was used, which was measured on the line from the base material through the HAZ, the weld metal towards the base material on the other side. The load F = 9.8 N (HV1 method) was applied, the distance between the prints was 0.25 mm. The hardness of the base material was 359 HV1 (mean value after ten impressions). The hardness profile (Fig. 2) shows a gradual decrease in hardness from the base material to the ICHAZ sub-zone. This decrease is related to the tempering of martensite in the structure of the base material. Reduction of strength is common in high-strength steels (quenched and TMCP) when heated to a temperature in the range of 450°C-$Ac_1$ as a result of martensite tempering [25]. The lowest hardness values were measured in ICHAZ, where only 66% of the hardness of the base material was recorded. It is therefore evident and confirmed that ICHAZ is the most critical area even for materials with a thickness of 3 mm. In the FGHAZ region, the hardness measurement results showed an increasing tendency and reached their maximum in the entire HAZ. In the CGHAZ region, a slight decrease in the microhardness towards the weld metal was observed, which was related to the excessive grain growth in this zone. Figure 4 shows HAZ with HV1 values in the ICHAZ subarea with a minimum value of 228 HV1. The average hardness values in each HAZ sub-zone are given in table V.

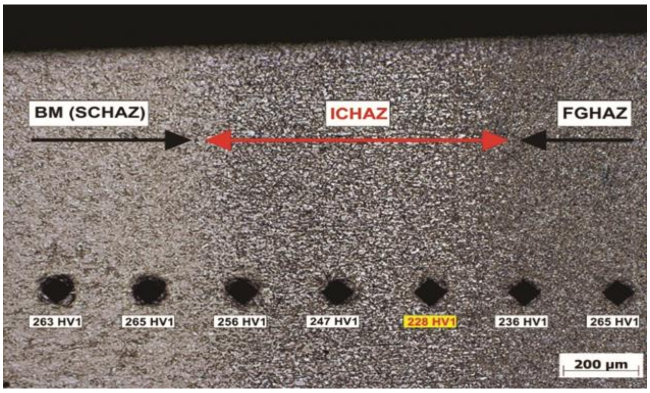



**Fig. 4.** Heat-affected zone with a specified ICHAZ zone along with microhardness values

**Table V.** Microhardness values of individual subzones in HAZ

| HAZ subzones | Left side of the welded material | | | | Center of the weld | Right side of the welded material | | | |
|---|---|---|---|---|---|---|---|---|---|
| | SCHAZ | ICSHAZ | FGHAZ | CGHAZ | WM | CGHAZ | FGHAZ | ICSHAZ | SCHAZ |
| Average value HV1 | 297 | 244 | 267 | 283 | 368 | 283 | 276 | 236 | 287 |

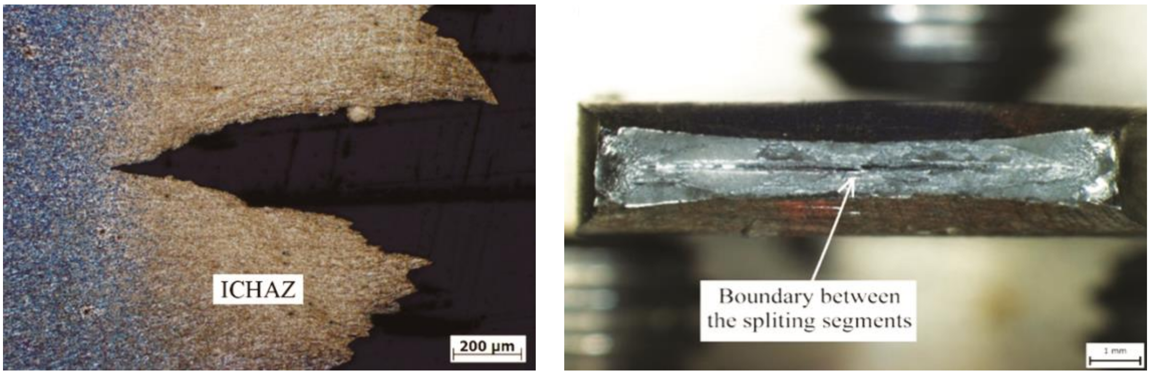
### *Joint strength evaluation*

The tensile test was performed according to EN ISO 6892-1 [26]. The test samples were prepared in accordance with EN ISO 4136 [27]. Two samples with an average value of $R_{p0,2}$ = 815 MPa and $R_m$ = 842 MPa were tested. The results of the tensile test of the welded joint are given in table VI.

**Table VI.** Results of tensile test in the transverse direction of the welded joint

| Sample No. | Mechanical properties | | | Comments |
|---|---|---|---|---|
| | $R_{p0,2}$ [MPa] | $R_m$ [MPa] | A [%] | |
| 1-1 | 794 | 826 | 5 | Crack in the HAZ |
| 1-2 | 836 | 858 | 3 | Crack in the HAZ |
| Average value | 815 | 842 | 4 | |

The tensile test showed a significant reduction in tensile strength and yield strength compared to the base material. The tensile strength of the welded joint has been reduced to 73% of the strength of the base material specified in the certificate. The yield point also decreased and reached 78% of the base material. The crack occurred approximately 6 mm from the center of the weld in both samples, which corresponds to the ICHAZ sub-zone in HAZ with the lowest hardness. Thus, it can be said that the fracture is in the narrow area of the ICHAZ. Figure 5a shows the fracture profile and Figure 5b shows the macroscopic refractive surface of one part of the specimen after the tensile test. These analyses also confirmed that the fracture was in the ICHAZ area. After the tensile test, the sample is divided into two segments, the boundary between the segments coinciding with the center of the sheet thickness. The authors [19] found that this specific splitting may be caused by the rolling and sheet metal production process, when the chemical composition may vary along the thickness. As plastic strain builds up, a crack may first arise parallel to the rolling direction before it begins to enlarge.




(a) (b)

**Fig. 5.** Fracture profile (a) and macrostructure of the fracture surface (b) of the sample after tensile test

## Conclusions

Based on the metallographic evaluation and mechanical tests of welded joints of S960MC steel, the following conclusions can be drawn:

- a welded joint made of S960MC steel with a thickness of 3 mm was successfully made using the additional material G 89 5 M21 Mn4Ni2.5CrMo without cracking and with the correct geometry of the weld;
- observations of the microstructure indicated several different zones in the HAZ. The CGHAZ, FGHAZ, ICHAZ, SCHAZ sub-areas are clearly identified;
- the hardness measurement shows that ICHAZ is the weakest area of the entire joint, with a hardness of only 66% of that of the base material;
- the hardness of the base material (in the SCHAZ zone), even at a distance of 9 mm from the center of the weld, does not reach its original value;
- the weld has a hardness (368 HV1) similar to the base material (359 HV1);
- the results of the static tensile test showed a significant reduction in mechanical properties compared to the base material. For the critical (minimum) values according to EN 10149-2, the tensile strength was 85% of the base material, the yield point was 86% and the elongation was less than 65% compared to the base material values. According to the certificate, the tensile strength was 79% of the base material, the yield strength was 73% and the elongation was less than 33% of the base material.

**Author Contributions:** conceptualization, M.M. and J.W.; methodology, M.G. and L.T.; software, M.F and L.S.; validation, M.M. and M.G.; formal analysis, M.G.; investigation, M.F and L.S.; resources, J.W.; data curation, M.F., L.S and L.T.; writing—original draft preparation, M.G and L.S.; writing—review and editing, M.G., J.W. and L.S.; visualization, M.F and L.T.; supervision, J.W.; project administration, J.W. and M.M.; funding acquisition, M.G. and J.W.,
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**Conflicts of Interest:** The authors declare no conflict of interest.

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[16] EN ISO 16834-A Welding consumables - Wire electrodes, wires, rods and deposits for gas shielded arc welding of high strength steels – Classification

[17] STN EN ISO 15614-1:2017 Specification and qualification of welding procedures for metallic materials - Welding procedure test - Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys.

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