MAG welding of 960QL quenched and tempered steel

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Abstract. The article presents research of the welding technology of S960QL quenched and tempered steel with the thickness of 10 mm. The main problem during welding heat-treated fine-grained steels is cold cracking. The aim of the research was to develop welding technology of tested steel to obtain high ductility and strength properties of the joint and to avoid the problem of crack formation after welding process. For the test the butt joint was welded. For this it was used MAG process in the flat position. Welding process was carried out based on preliminary tests and pre-prepared Welding Procedure Specification according to ISO 15609-1 standard. During welding the M21 mixture was used as the shielding gas. As the filler metal a solid wire G Mn4Ni2.5CrMo was used. The welded joint was tested in accordance with the ISO 15614 standard requirements. The research included non-destructive tests and destructive tests. The non-destructive tests included visual, magnetic particle and radiographic tests. The destructive tests included transverse tensile, root and face bend, impact, macroscopic, microscopic and hardness. Impact test was carried out in the temperature of -20°C. Hardness measurements were made using the Vickers method and the load of 9.80 N. All of the tests ended with the positive result. The results of research show that tested welding technology and pre-heating temperature equal to 80°C allow to obtain a welded joint meeting the high quality requirements and the international standards requirements.

1. Introduction
Over the past 70 years, the yield point of the structural steel has increased by more than five times. Starting with low-alloy steel (Re about 200MPa), by higher-strength normalized low-alloy steel (Re about 350MPa), steels produced with thermo-mechanical treatment, in this with higher cooling rate (Re about 450 ÷700MPa) and ending with quenched and tempered steels with yield point about 1300MPa. Fine-grained steels do not constitute a separate group due to production process, chemical composition or mechanical properties. This type of steel is characterized by fine-grained microstructure in delivery condition which is positive due to low grain growth in heat-affected zone during welding process. Fine-grained are steel types produced using normalising, thermo-mechanical treatment and quenching with tempering. Mechanical properties of fine-grained steels depend on chemical composition and production process. The main problem during welding quenched and tempered fine-grained steels is cold cracking. In order to optimize the steel strength and cracking resistance of welded joint, the strength of filler metal should be the same or slightly lower than base material. Using filler metal with higher strength is not recommended. Welds should also be made in such places of construction that have the lowest possible stresses in order to reduce the risk of cracking [1-17].
2. Experimental procedure
The aim of the research was to develop welding technology of 10 mm thick S960QL (Weldox 960) steel using MAG welding process with solid wire X96 (GMn4Ni2.5CrMo) and active shielding gas M21. Chemical composition and mechanical properties of tested steel are presented in the table 1, microstructure is shown in figure 1. Table 2 presents chemical composition and mechanical properties of filler metal.

Table 1. Chemical composition and mechanical properties of 10 mm thick S960QL steel.

| Chemical composition, wt.% | C   | Si  | Mn  | P   | S   | Cr  | Ni  | Mo  | Cu  | Al  | Nb  | V   | Ti  | N   | B   |
|---------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|                           | 0.17| 0.22| 1.26| 0.008| 0.001| 0.21| 0.05| 0.604| 0.01| 0.061| 0.015| 0.041| 0.003| 0.003| 0.001|

| Mechanical properties     | Yield point \(R_{p0.2}\) [MPa] | Tensile strength \(R_m\) [MPa] | Elongation \(A_5\) [%] | Impact energy \(K\) [J] \(-40^\circ\)C |
|---------------------------|----------------------------------|-------------------------------|----------------------|----------------------------------|
|                           | 1023                             | 1069                          | 14                   | 78                               |

Figure 1. S960QL tempered martensite microstructure.

Table 2. Chemical composition and mechanical properties of X96 – GMn4Ni2.5CrMo filler metal.

| Filler metal designation | Chemical composition, wt.% | C   | Si  | Mn  | P   | S   | Cr  | Ni  | Mo  | Zr  |
|--------------------------|-----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| X96                      |                             | 0.11| 0.77| 1.98| 0.010| 0.013| 0.43| 2.25| 0.50| 0.006|

| Yield point \(R_{p0.2}\) [MPa] | Tensile strength \(R_m\) [MPa] | Elongation \(A_5\) [%] | Impact energy \(K\) [J] \(-40^\circ\)C |
|-----------------------------|--------------------------------|----------------------|----------------------------------|
| 930                         | 980                            | 14                   | 40                               |

2.1. Welding technology
The welding process was carried out on the basis of preliminary tests and pre-prepared Welding Procedure Specification presented in the table 3.
Table 3. Welding Procedure Specification of tested technology.

| Manufacturer: Wojciech Grzegorczyk                  | Parent Material Designation: S960QL |
|----------------------------------------------------|-----------------------------------|
| Joint Number: P1                                    |                                   |
| Joint Type and Weld Type: butt weld (BW) / butt joint V | Material thickness (mm): 10 mm |
| Details of Sealing Run: Single-side welding         | Method of Preparation and Cleaning: Thermal cutting and machining |
| Welding Position: flat PA                            |                                   |

Weld Preparation Details (Sketch)

Parent Materials

| Welding joint | Material 1 | Material 2 |
|---------------|------------|------------|
| Type          | Steel      | Steel      |
| Designation   | S960 QL    | S960 QL    |
| Thickness [mm] | 10         | 10         |

Filler Material

| Filler Material | Welding Position | Welding Position |
|-----------------|------------------|------------------|
| Type            | Wire             | Wire             |
| Designation     | X96              | X96              |
| Diameter [mm]   | 1.2              | 1.2              |
| Comments        | --               | --               |

Shielding Gas

| Shielding Gas | Welding Technique |
|---------------|-------------------|
| Name          | Mixture           | Bead type | String |
| Mixture       | 82%Ar+18%CO₂      | Weave width | Do not use |
| Flow rate [l/min] | 15         | Number of passes | 7 |
| Preheat Temperature | 80°C     | Number of beads | 7 |

Welding Parameters

| Run | Welding Process | Filler Material Type | Size [mm] | Welding Current Polarity | Intensity [A] | Arc Voltage [V] | Travel Speed [cm/min] | Welding Energy [kJ/cm] | Time tₚ5 [s] |
|-----|-----------------|----------------------|-----------|--------------------------|--------------|----------------|----------------------|------------------------|-----------|
| 1   | 135             | X96                  | 1.2       | +                        | 120          | 17             | 12                   | 10                     | 10        |
| 2   | 135             | X96                  | 1.2       | +                        | 230          | 27             | 35                   | 11                     | 11        |
| 3   | 135             | X96                  | 1.2       | +                        | 230          | 27             | 35                   | 11                     | 11        |
| 4   | 135             | X96                  | 1.2       | +                        | 230          | 27             | 35                   | 11                     | 11        |
| 5   | 135             | X96                  | 1.2       | +                        | 230          | 27             | 35                   | 11                     | 11        |
| 6   | 135             | X96                  | 1.2       | +                        | 230          | 27             | 35                   | 11                     | 11        |
| 7   | 135             | X96                  | 1.2       | +                        | 230          | 27             | 35                   | 11                     | 11        |
2.2. Non-destructive testing of welded joints
Visual tests were carried out according to ISO 17637 standard. Because the results did not detect surface imperfections, welded joint was classified to quality level B according to ISO 5817 standard, figure 2. Magnetic particle tests were carried out using magnetization in two perpendicular directions in order to optimize detection of possible imperfections. The magnetic field intensity during tests was 38 kA/cm. The tests did not detect imperfections such as cracks or lacks of fusion. Radiographic tests were carried out according to EN 1435 standard using X-ray tube CERAM type 235 with X-ray beam diameter of 2 mm, voltage of 180 kV, current intensity of 3 mA and using intensifying screens OW - 0.15 mm. The tests resulted in classifying the welding joint to quality level B, figure 3.

![Figure 2. Face and back of weld view.](image2)

![Figure 3. Radiograph of welded joint.](image3)

2.3. Destructive testing of welded joints
In order to check the mechanical properties of welded joint there were carried out tests: root and face bend tests, transverse tensile tests and impact tests in the temperature of -20°C. The results of these tests are presented in table 4.
Table 4. The mechanical tests result.

| Bending angle, [°] | Tensile strength $R_m$, [MPa] | Impact energy, [J] -20 °C |
|--------------------|-----------------|-----------------|
| P1/1               | 999             | 69              |
| P1/2               | 989             | 113             |
| P1/S               |                 |                 |
| P1/FL              |                 |                 |
| P1/HAZ             |                 |                 |

Hardness measurements of welded joint were carried out using Vickers method according to ISO 6507 standard using Hardness Tester WILSON W WOLPERT Micro Vickers 401MVD, with load of 9.80 N. The hardness test results are presented on figure 4.

2.4. Metallographic tests

Metallographic tests of welded joint included macroscopic and microscopic observations. Results of macroscopic tests are presented on figure 5 (etching with Adler) and the microscopic test results are shown on figure 6 (etching with Nital).
3. Results and discussion
The aim of the research was to develop welding technology of quenched and tempered S960QL steel (Weldox 960) using MAG process with solid wire X96 (GMn4Ni2.5CrMo). For the research single-side butt joint with butt weld V, 10 mm thick was made in active shield M21. Welding parameters included in Welding Procedure Specification proved to be correct. The weld joint made using tested technology has met the requirements of international standards. The root pass was made using low welding parameters (low energy) in order to limit burn-through weld defects. The filler passes were made using higher welding parameters (high energy) in order to limit incomplete fusion. Selection of suitable welding conditions such as preheat and interpass temperature is important to receive appropriate quality of welded joint. Welding with too low energy can result with cold cracking, while welding with too high energy may cause decrease of mechanical properties, hardness and impact.
resistance. Visual, magnetic particle and radiographic tests did not detect imperfections in welded joint. During bend test with grinded root and face of the weld, 180° bending angle has been received. No cracks or tears appeared on any samples during this test which proves high plastic properties of weld joint. Tensile strength of tested joint reached value about 1000 MPa which is comparable to base metal. Impact energy of the weld, fusion line and HAZ were tested using impact test. Impact energy results in all tested areas was higher than the minimum limit value 30 J in -20°C. Maximum allowable hardness for multilayer welds of tested group of steel without the heat treatment is 420 HV. Hardness measurements proved that maximum hardness has not been exceeded in any area of the joint. Macroscopic metallographic test proved correct appearance of welded joint with all characteristic areas: weld metal, heat affected zone and base metal. It also proved that all the beads were made correctly in multilayer weld and that all characteristic areas were uniform without any imperfections. Microscopic metallographic tests proved that thermal cycle did not result in excessive grain growth in heat affected zone. The structure of weld and base metal is martensitic-bainitic.

4. Conclusions
The test results showed that considered MAG welding technology of S960QL 10 mm thick butt joint in flat position meets the international standards requirements. Destructive and non-destructive tests of the joint confirmed that preheating temperature of 80°C ensure high mechanical properties of the joint, that are similar to the base metal properties. Hardness did not exceed the admissible value of 420 HV in any area of welded joint. Macroscopic metallographic tests showed that base metal has martensitic-bainitic structure. In the heat affected zone found slight grain growth which do not decrease strength of welded joint. When designing welded structures made of high-strength steel, it is necessary to take into account the strength of the weld to calculate the bearing capacity of the structure, not the strength of the base metal as is usual. The strength of the weld can be slightly lower than the strength of base metal.

5. References
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