MECHANICAL PROPERTIES OF SUBMERGED ARC WELDMENTS OF HIGH STRENGTH STEEL S960QL

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https://doi.org/10.37904/metal.2024.4943

Abstract

Nowadays, high-strength steels (HS) and ultra-high-strength steels (UHS) are increasingly used, especially in welded structures. These types of steels are mainly used as material for heavily loaded structures such as bridges, cranes, and excavators, as well as for pressure vessels, various types of vehicles, ships, drilling structures, etc. operating at room temperature or below. Since the requirements for the above structures are specific, the use of high-strength and ultra-high-strength steels requires research into the factors affecting their weldability. According to the usual welding rules HS steels and UHS steels can be welded by all conventional welding methods. The S960QL steel studied in this paper falls into the group of high strength quenched and tempered fine-grained grain steels. This work presents results showing the influence of the welding gap on some mechanical properties of submerged arc weldments of the high strength steel S960QL.

Keywords: High strength steel, S960QL, mechanical properties, submerged arc weldments

1. INTRODUCTION

One of the goals of modern industry is to achieve economic efficiency by reducing the total mass of products, and this goal is one of the most important factors affecting production costs. To achieve this goal, metallurgists are developing structural steels with improved mechanical properties [1].

In the last 70 years, the yield strength of structural steels has been increased more than fivefold - from 200 MPa to 1100 (1300) MPa [2]. The use of these high-strength steels has two main advantages: 1) structures made of these steels can support much greater loads without increasing the mass of the structure than steels with lower mechanical properties, and 2) these steels allow a reduction in the mass of the products for the same load [3]. The reduction in mass of a structure made of S960 steel instead of S355 steel can be more than 60 % [4].

High-strength steels have been used in welded structures since the early years of the 21st century [3]. These steels are mainly used for heavy mobile cranes, heavy-duty trucks [5, 6], pipelines for oil and gas and other highly loaded components [4]. These steels are widely used in the automotive and shipbuilding industries [7, 8], nuclear power plants [9] and many other areas. Today, the use of high-strength steels is limited to some extent only by their high price.

High-strength steels are fine-grained and can be normalised (denoted by the letter N, like S460N), thermomechanically treated (denoted by M, like S460M) or quenched and tempered (denoted by Q, like S960Q) [2]. Structural steels with a yield strength of 900 MPa or more are called ultra-high strength steels (UHSS) - S960QL is an example of a UHSS [9]. The higher strength of S960QL results from the higher concentration of alloying elements and the lower tempering temperature. UHSS have an ultrafine-grained microstructure that includes martensite and bainite [1, 10]. The carbon concentration in these steels is low, not more than 0.2 %, and therefore they are suitable for welding. However, the mechanical properties of the weldments differ depending on the heating temperature [8]. In the area heated to A1, in the direction from the base metal to the heat-affected zone, the strength and hardness decrease, but the toughness is increased by recrystallisation processes. In the area of heating above A1, in the zone of partial recrystallisation, fine-grained phases can form which promote the formation of martensite with low hardness and therefore do not lead to a significant increase in hardness. In the region of overheating to above 1100 °C, the nitrides and carbides present in the steel structure dissolve and the austenite grains enlarge, leading to the formation of coarse-grained martensite and increased hardness, which can lead to the formation of cold cracks. To avoid this, preheating is carried out depending on the thickness of the welded part [11]. The allowable hardness values in the heat affected zone are in the range of 350 HV10, but for some steels with higher plasticity they can reach 400 HV10. Another point to consider is the softening of the heat affected zone.

Therefore, the preheat temperature and the interphase temperature play an important role in the welding of high-strength heat-treatable steels, together with the heat input, which must be controlled within a certain range [6]. The technical literature provides information on the influence of these factors on the mechanical properties of welds made of high-strength steels, but there is a lack of information on the influence of the welding gap, which does not comply with the standard EN ISO 9692.

The aim of the present work is to investigate the influence of the welding gap on the mechanical properties of welds made of high-strength steel S960QL produced by submerged arc welding.

2. METHODOLOGY

The welding methodology used here is borrowed from a methodology used in real production for welding S960QL steel.
The weldments investigated were made of high-strength, fine-grained, quenched, and tempered S960QL steel produced by Voestalpine Stahl GmbH Austria in a thickness of 6 mm. Information on the chemical composition and mechanical properties of the steel provided by the manufacturer can be found in **Table 1**. According to the manufacturer, the carbon equivalent is CEV = 0.6.

The weldments were made by submerged arc welding. Direct current with reversed polarity DC (+) was used. The welded parts had a size of 500 mm x 150x6 mm. After welding, test pieces were cut for the determination of the microstructure and hardness as well as for tensile tests and impact bending tests. The dimensions of the welded parts and the locations where the test pieces were cut off were in accordance with the requirements of EN ISO 15614-1:2017. The preparation of the welded parts followed EN ISO 9692-2:2001 except for the welding gap to be examined. The bevelling was done mechanically and was 30° (60° in total) without blunting.

The welding gaps examined were 0, 4, 6 and 8 mm (according to EN ISO 9692-2:2001, the thickness of the welded parts must not exceed 2 mm).

Table 1 Chemical composition and mechanical properties of S960QL steel (from the manufacturer)

Chemical composition, [wt%]															
C	**Si**	**Mn**	**P**	**S**	**Al**	**B**	**Cr**	**Cu**	**Mo**	**N**	**Nb**	**Ni**	**Ti**	**V**	**Zr**
0.175	0.249	1.075	0.009	0.001	0.084	0.0023	0.620	0.018	0.608	0.0039	0.029	0.039	0.003	0.002	0.001

Mechanical properties			
R_m [MPa]	**R_{eH} [MPa]**	**A_5 [%]**	**KV^{-40} (10x6) ?? [J]**
1028	1006	13	59

It was necessary to investigate the range of gaps studied because, in the manufacture of real structures, calibrating the workpieces to meet the requirements of EN ISO 9692-2:2001 is tedious, expensive, and not always possible. According to the manufacturer, the welding gap can be up to 8 mm. Low carbon steel backing strips of 500 mm x 25 mm x 3 mm and run-on and run-off strip were used. The filler material was a wire with a diameter of 1.2 mm, designated G 89 5 M Mn4Ni2.5CrMo according to EN ISO 16834:2012. The flux used was S A AB 1 56 AC H5 according to EN ISO 14174:2019 [12].

The modes used and the number of passes for the different welding gaps can be found in **Table 2**.

Table 2 Parameters of the welding modes used for the different welding gaps.

Welding mode/gap	Pass	Current, I	Voltage, U	Rate, V
	№	[A]	[V]	[mm/min]
Welding mode (WM1), gap = 0	1	240	31	280
	2	270	31	150
Welding mode (WM2), gap = 4	1	240	31	250
	2	240	31	180
	3	270	32	140
Welding mode (WM3), gap = 6	1	240	31	250
	2	240	31	180
	3	270	32.5	120
Welding mode (WM4), gap = 8	1	240	31	250
	2	240	31	180
	3	240	31	180
	4	270	32.5	100

The parts were welded in PA position according to EN ISO 6947:2019. During welding, the recommended temperature of 150 °C [7] or less was maintained. Two plates were made for each welding gap - a total of 8 for the steel under study.

The macrostructure was revealed with a reagent of 20.3 g $FeCl_3$, 12.5 ml HCl and dH_2O up to 200 ml. The hardness in the base metal (BM), heat-affected zone (HAZ) and weld metal (WM) was measured using the Vickers method according to ISO 6507-1:2018 with a load of 1 kg. The distance between the impressions was 1 mm and the measurements were taken in the middle of the weld thickness.

The tensile test was conducted in accordance with the general requirements of EN ISO 6892-1:2020 and the specific requirements of EN ISO 4136:2012. The dimensions of the working part of the specimens were: original width of the parallel length of a specimen b_0 - 25 mm; original thickness of a specimen a_0 - 6 mm and original gauge length (L_o) - 70 mm.

The Charpy pendulum impact test was conducted in accordance with EN ISO 148-1:2015 at a temperature of -40 °C. A V-notch (KV8) was used in the centre of the weld and in the transition zone between the weld and the heat-affected zone.

3. RESULTS AND DISCUSSION

Figure 1 shows the results of the hardness distribution in the different zones of the weldments. From **Figure 1** follows that the highest hardness in the heat-affected zone (HAZ) was recorded in welding mode WM1 and the lowest in welding mode WM4. This shows that the more passes performed, the lower the peak hardness in this zone. The change in hardness of the base metal towards the fusion zone follows a similar trend for welding modes WM1, WM 2 and WM3, but this trend does not hold for WM4. For welding modes WM1, WM2 and WM3, local extreme values of hardness are observed in the transition zones between SCHAZ and FGHAZ, FGHAZ/ CGHAZ and CGHAZ/WM. A detailed discussion of the reasons for these extreme values and the microstructure can be found in [12]. The hardness of the weld metal is the lowest and does not depend on the welding mode.

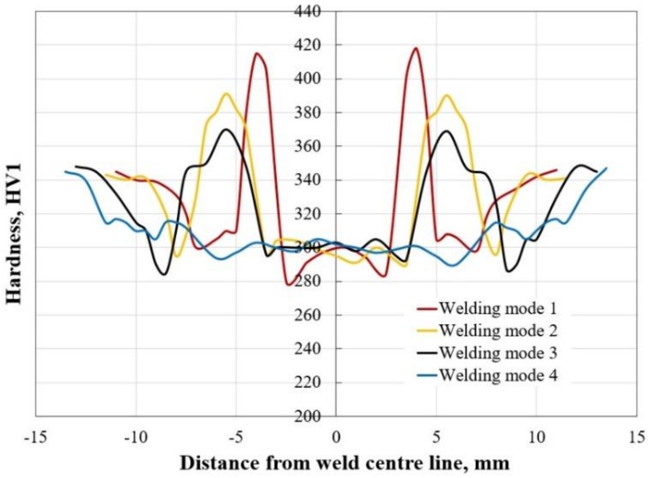
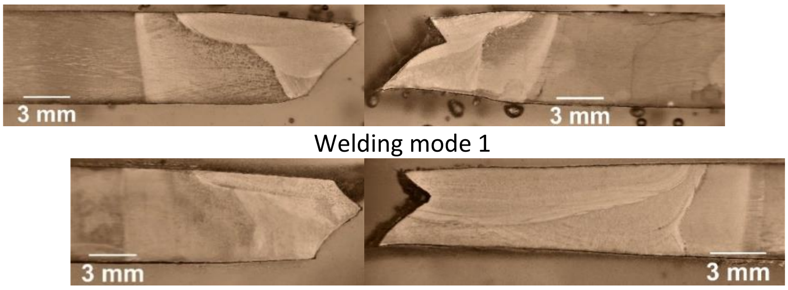


Figure 1 Hardness distribution in different welding modes

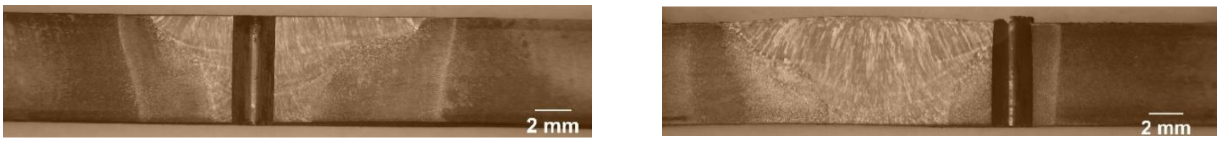


Welding mode 1

Welding mode 4

Figure 2 Macrostructure of specimens after tensile test

Figure 2 shows the fracture zone after the tensile test of the specimens produced with the welding modes WM1 and WM4. In all modes tested, the fracture occurred at the weld, and this makes sense when looking at the hardness distribution profile in **Figure 1**. After the tensile test and analysis of the results, the zones for impact toughness were selected. The notched impact strength was determined in the weld and in the transition zone from the fusion zone FZ to the HAZ, as shown in **Figure 3**.



a

b

Figure 3 Location of the V-notch for Charpy pendulum impact test: a – welding mode 1; welding mode 2

Figure 4 and **Figure 5** show the results obtained after the tensile test and the impact test. **Figure 4** shows that an increase in the welding gap or the number of passes is accompanied by a decrease in the strength properties. The effect of softening is more pronounced at $Rp_{0.2}$, which is associated with a decrease in the $Rp_{0.2}$/Rm ratio from 0.98 to 0.83. The effects of softening are also reflected in the relative elongation, as the highest values for this characteristic are observed for WM4.

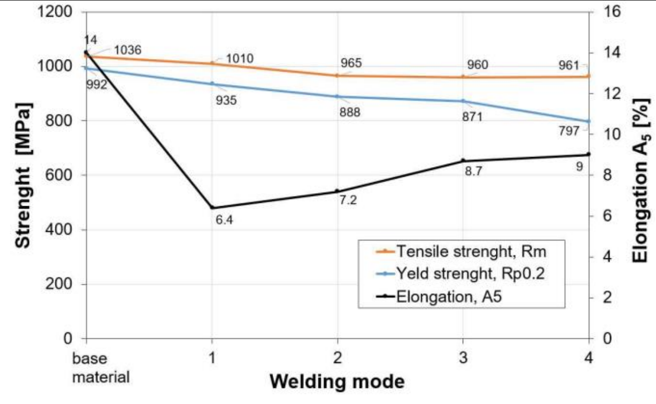


Figure 4 Tensile test results

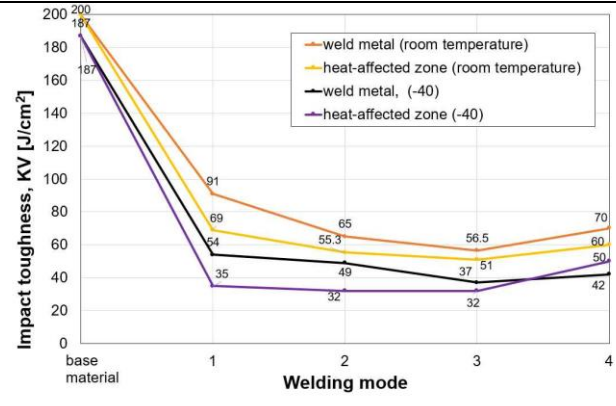


Figure 5 Charpy pendulum impact test results

The results for the notched impact strength (**Figure 5**) show that the notched impact strength values are lower in the transition zone than in the weld for all welding modes. Similar results were expected assuming the presence of a coarse-grained zone in the transition from the weld to the HAZ. The highest values of notched impact strength are observed for WM4, where no coarse-grained zone is observed because of repeated heating to realise a larger number of passes [12].

4. CONCLUSIONS

An increase in the number of welding passes (welding gap dimension) leads to a decrease in the hardness of the coarse-grained heat-affected zone from 420 HV_1 to 315 HV_1, while the hardness of the weld metal does not depend on the number of passes. The measured maximum hardness values for welding modes WM1 and WM2 are a prerequisite for the formation of cold cracks. For welding modes WM3 and WM4, the hardness is significantly lower, especially for WM4, where the hardness values are most evenly distributed.

The experiments presented show that increasing the welding gap leads to a more homogeneous grain size and a more uniform hardness distribution within the heat-affected zone. The operating properties of welded constructions could therefore be positively influenced by enlarging the welding gap.

The results from the tensile test show a decrease in the strength properties $Rp_{0.2}$ и R_m and an increase in the plasticity properties with the increase of the welding gap or the number of passes. This is related to the tempering that takes place with each additional pass. At the largest welding gap, the decrease in strength is 7 %, in yield strength 20 % and plasticity decreases by 35 %. For all welding, the fracture is in the weld, which reflects the hardness distribution well.

The notched impact strength results show that the notched impact strength values for all welding modes are above 30 J at -40 °C, which meets the requirements of EN 10025-6:2019 for minimum notched impact strength.

ACKNOWLEDGEMENTS

This study is financed by the European Union - Next Generation EU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project № BG-RRP-2.013-0001-C01.

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