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WELDABILITY INVESTIGATION OF FINE-GRAINED S1100QL STEEL

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This paper presents the results of weldability investigation on welded joints made of fine - grained high-strength S1100QL steel. The investigations are performed on two welded plates by HV 10 hardness measuring and by Charpy V notch testing at different test temperatures. Mechanical properties of welded joints are overviewed, along with welded parameters, all of which enable obtaining of high-quality welded joints.

Key words: weldability, fine-grained steel S1100QL, hardness, impact energy

INTRODUCTION

High-strength steels are used in manufacturing of lighter structures, especially for transport industry and in production of other mechanical equipment. Application of those steels increases the capacity of welded structures and improves their service efficiency. Large structures, such as bridges, cranes, hoists, pressure vessels, parts of ships, which are exposed to changing loads and low temperatures, shall be produced of new types of high-strength steels, which are resistant to brittle fracture, with good weldability properties and low costs of manufacture. Referring to the welded structure load, an important property of steel is its resistance to shape change under load. Unfortunately, high-strength steels are not frequently used or are even forbidden to be applied in some welded products. Such steel has unfavorable ratio of conventional yield stress $R_{p0,2}$ and tensile strength R_m. Higher value of yield stress shall result in reduced weight of a welded structure or a product. Greater ratio of conventional yield stress $R_{p0,2}$ and tensile strength R_m indicates less ”reserve” in cases of overload and shorter time until possible fracture [1]. In available literature, this relationship is presented as Yield Point / Tensile Point, being usually $Y/T = R_{p0,2}/R_m \approx (0,7 – 0,9)$ [2].

RESEARCH OBJECTIVE

Within welding, material is exposed to relatively large amount of heat, resulting in rapidly increased temperature in the welded joint, followed by cooling period. The consequence of weld thermal cycle is visible in changed mechanical properties and microstructure of the welded joint. In general, welded joint is weakened if compared to the initial properties of base material. Thermodynamic processes during welding of improved fine-grained high-strength S1100QL steel are extremely complex, and their impact on structure and properties of the investigated steel is still to be studied in details. Such studies are usually directed towards understanding of processes that occur in material structure, towards improving of welded joints quality, as well as to develop new welding technology. The most of research into improved high - strength steel S1100QL is focused on explanation of failures that occur in welded joints, primarily of cold cracks, which are nowadays one of the most common problems in the welding [3]. Cold cracks develop at a temperature below 200 °C and may appear immediately after cooling of welded joint, or even several days after welding. The risk of cold cracking increases with increased strength of the material. Although cold cracks are studied for decades, they still represent major issue in the integrity of welded structures, especially of high-strength steels. Previous studies have shown that hydrogen content in welded joint was the most dominant factor for occurrence of cold cracks. It was found that hydrogen atoms were able to pass through the crystal lattice of material and they could cause formation of cold cracks in welded joints by interacting with residual stresses and with microstructure prone to hardening. Hydrogen path and occurrence of cracks in high-strength steels is greatly influenced by the material microstructure and its imperfections [4]. The authors of presented paper studied the parameters of true welding of ultra-high strength steel in order to obtain a weld with acceptable mechanical properties without cold cracks. Experimental research presented in this paper was performed on improved micro alloyed ultra-high strength steel S1100QL [5]. Diagram of relationship between true stress and strain at various temperatures for S1100QL steel is presented in the Figure 1.

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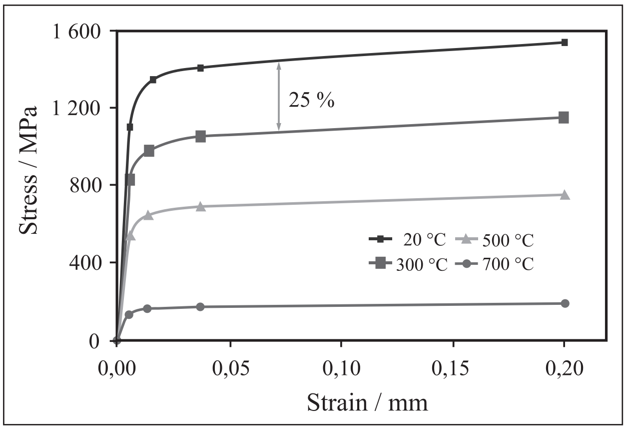

Figure 1 Relationship of true stress - strain at various temperatures for S1100QL steel [3]

Chemical elements contained in the examined steel are presented in the Table 1, and its mechanical properties are overviewed in the Table 2.

Table 1 **Compositions of S1100QL steel [4]**

Base materials		HRN EN 10025-6	Measured values
Elements content, cwt / %	C	max. 0,20	0,17
	Si	max. 0,50	0,25
	Mn	max. 1,70	0,88
	P	max. 0,02	0,005
	S	max. 0,005	0,002
	Cr	max. 1,50	0,49
	Mo	max. 0,70	0,41
	Ni	-	1,28
	Nb	-	0,02
	V	-	0,02
	Co	-	0,03
	B	-	0,003

Table 2 **Mechanical properties of S1100QL [4]**

Mat.	Yield strength R_e / MPa	Tensile strength R_m / MPa	Elon-gation A_5 / %	Impact energy K_V / J
HRN EN 10025	min. 1 100	1 200 - 1 500	min. 8	-40 °C ≥ 30
Measured value	1 120	1 430	12,5	55

Weld thermal cycle

The tendency of cold cracking in welded joint of high-strength steel depends on many factors, such as chemical composition of the base material, welded material thickness, content of hydrogen in the welded joint, preheating temperature (T_o) and temperature between passes (T_m), heat input during welding, welding process, geometry of the weld, and the level of residual stresses after welding. All mentioned factors can be addressed through the cooling time and heat affected zone in the temperature interval from 800 to 500 °C ($t_{8/5}$). In that temperature interval, there are the most important structural changes occurring in the welded joint, which directly affect final mechanical properties of the weld.

Weld thermal cycle is defined by two levels of cooling time ($t_{8/5\,min}$) and ($t_{8/5\,max}$). Lower values of cooling time than minimum allowed cooling time ($t_{8/5\,min}$) cause high strength and hardness in the heat affected zone (HAZ), which can cause cold cracks. Higher values of cooling time than maximum allowed cooling time ($t_{8/5\,max}$) cause too low values of impact toughness and high transient temperature from ductile to brittle condition. Between minimum and maximum value of cooling time ($t_{8/5\,min}$) and ($t_{8/5\,max}$), there is a favorable zone providing satisfactory mechanical properties within HAZ. Previous researches into S1100QL steel resulted in acceptable mechanical properties in HAZ by cooling time ($t_{8/5}$) from 6 to 15 s and from 8 to 12 s [2]. The risk of cold cracks in HAZ was avoided. Furthermore, the risk of impact toughness decline and transient temperature increase in the HAZ was also reduced. Calculation of cooling time ($t_{8/5}$) depends on the heat transfer model that is applied during welding. Cooling time ($t_{8/5}$) can be calculated for two-dimensional and three-dimensional heat transfer, and is described by the equations 1 and 2. [4]

$$t_{8/5} = \frac{(430 - 0{,}43 \cdot T_o) \cdot F_2}{\delta^2} \cdot \left(\frac{q}{v}\right)^2 \cdot \left[\left(\frac{1}{500 - T_o}\right)^2 - \left(\frac{1}{800 - T_o}\right)^2\right] \ldots (1)$$

$$t_{8/5} = (6{,}7 - 5 \cdot 10^{-3} \cdot T_o) \cdot F_3 \cdot \left(\frac{q}{v}\right) \cdot \left[\left(\frac{1}{500 - T_o}\right) - \left(\frac{1}{800 - T_o}\right)\right] \ldots (2)$$

where:
T_o - preheating temperature / °C
I – welding amperage / A
U – welding voltage / V
v – welding speed / cm/min
F_2 and F_3 – factors of heat transfer
($E=q/v$) – heat input / J/mm
d – material thickness / mm

The equation 3 expresses marginal thickness between two- dimensional and three- dimensional 3 heat transfer, [4]

$$\delta_{gr} = \sqrt{\frac{(430 - 4{,}3 \cdot T_o) \cdot \frac{q}{v} \cdot \left(\frac{1}{500 - T_o} + \frac{1}{800 - T_o}\right)}{6{,}7 - 5 \cdot 10^{-3} \cdot T_o}} \ldots (3)$$

where $d < d_{gr}$ refers to two- dimensional heat transfer, and $d > d_{gr}$ refers to three- dimensional heat transfer.

PERFORMED EXPERIMENTS

Two plates (P_1 and P_2) of dimension ≠ 12 x 300 x 300 mm were welded as of the parameters presented in the Table 3.

Welding of plates was performed in the direction of rolling, with the V groove preparation for welding. Filler material was a solid wire Union X 96 (EN 12634), Ø1,2 mm. Chemical composition and mechanical properties of the filler material are overviewed in the Table 4. Shielding gas was a mixture of 12 % Ar + 82 % CO_2

Table 3 **Parameters of welding of plates to specimen P_1 and P_2**

P_1	I / A	U / V	T_o /°C	T_m /°C
Base	140	16	100	100
Filler	250	28	100	100
P_2	I / A	U / V	T_o /°C	T_m /°C
Base	170	21	100	100
Filler	285	30	100	100

Table 4 **Chemical composition and mechanical properties of filler material [5]**

<table>
<tr><th rowspan="2">Filler mat.</th><th colspan="6">Chemical composition in mass / %</th></tr>
<tr><th>C</th><th>Si</th><th>Mn</th><th>Ni</th><th>Cr</th><th>Mo</th></tr>
<tr><td>Union X 96</td><td>0,12</td><td>0,80</td><td>1,90</td><td>2,35</td><td>0,45</td><td>0,55</td></tr>
<tr><td colspan="7">Mechanical properties at room temperature</td></tr>
<tr><td>$R_{p0,2}$ / MPa</td><td colspan="2">R_m / MPa</td><td colspan="2">A_5 / %</td><td colspan="2">K_V / J -50°C</td></tr>
<tr><td>≥ 930</td><td colspan="2">≥ 980</td><td colspan="2">≥ 14</td><td colspan="2">≥ 50</td></tr>
</table>

(HRN EN 439). Temperature of preheating was T_o = 100 ° C, and temperature between passes was T_m = 100 ^{0} C.

Plates were welded according to MAG procedure by an automatic welding machine. Plates were cut by water jet into segments ≠ 12 x 100 x 100 mm, out of which there were test tubes made for measuring of hardness, impact toughness, tensile strength and yield strength.

Testing of hardness

The Figure 2 presents locations of true welded specimens at which hardness was measured.

Diagram of hardness values after true welding (in three measurements) is presented in the Figure 3.

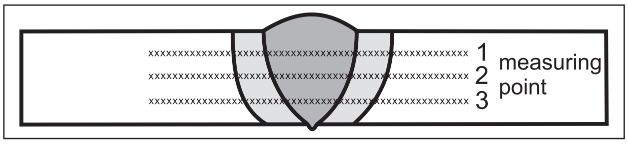

Figure 2 Locations on true welded specimens for hardness measurements

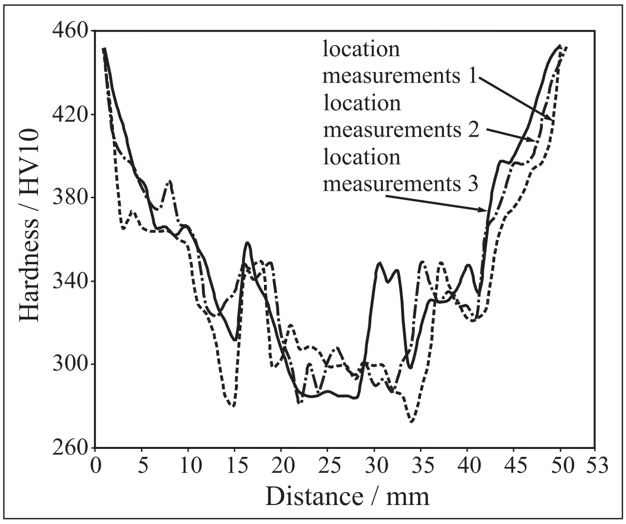

Figure 3 Diagram of hardness values depending on the distance

Results of testing the impact energy

Results of testing the impact energy at temperatures of 20, 0, - 20, - 40 and - 60°C are shown in Figures 4 and 5 (plates 1 and 2), while dependence of impact energy on the same temperatures is shown in the Figure 6. As expected, the Figures 4, 5 and 6 show that impact energy is smaller at lower temperatures.

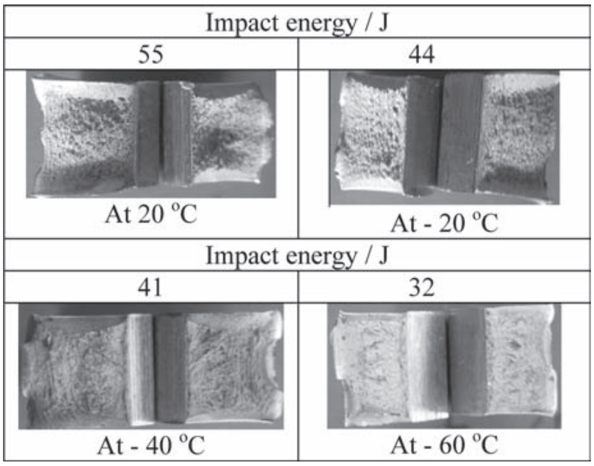

Figure 4 Fracture zone and results of impact energy testing depending on the temperature (average of three measurements – plate 1)

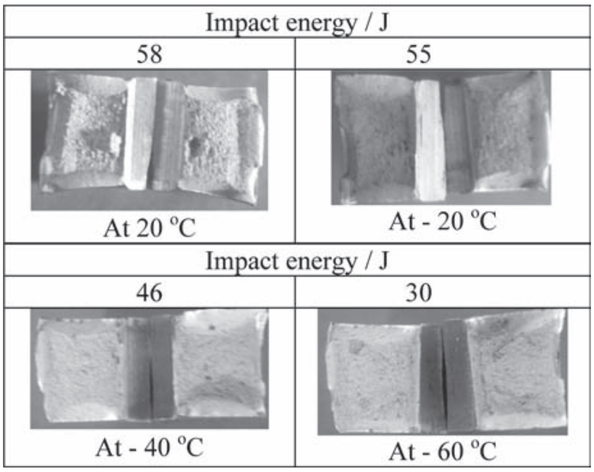

Figure 5 Fracture zone and results of impact energy testing depending on the temperature (average of three measurements, plate 2)

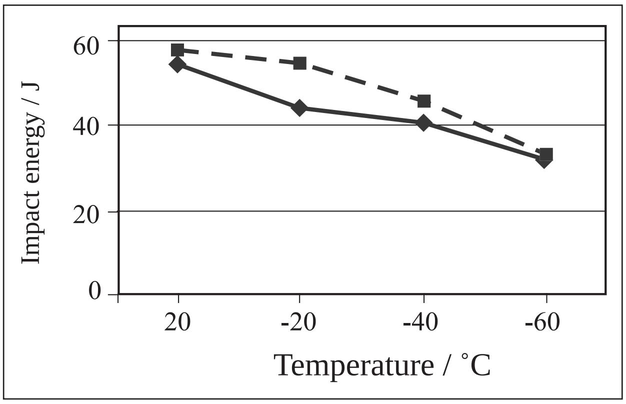

Figure 6 Dependence of impact energy of true welded specimens on temperature (specimens of plate 1 – solid line and of plate 2 – dashed line)

Testing of yield strength ($Rp_{0,2}$) and tensile strength (R_m)

Testing of yield strength and tensile strength of welded joints were carried out according to the EN 895 standard. Results of measurements are overviewed in the Table 5, and fractured test tubes are visible on Figure 7.

Table 5 **Mechanical properties of welded joint (average of 3 specimens)**

Mechanical properties	R_m / MPa	$R_{p0,2}$ / MPa	A_5 / %	Z / %
Plate P_1	1 205	955	11,5	58
Plate P_2	1 204	976	10,5	59,5

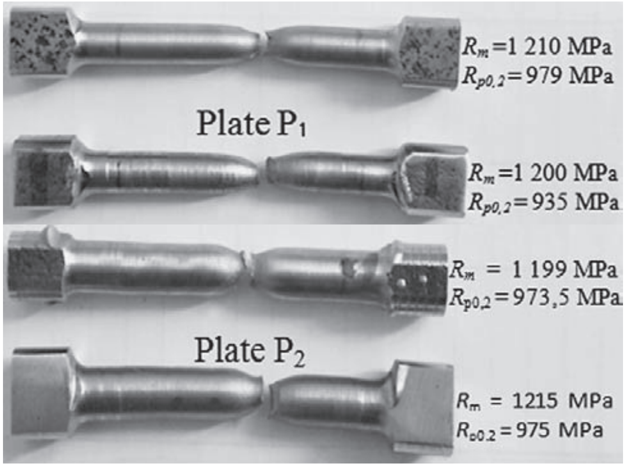

Figure 7 Fractured test tubes in tensile testing of weld properties

CONCLUSION

Performed experiments proved that it was possible to achieve high-quality welded joint by applying appropriate welding parameters (T_o, T_m, $t_{8/5}$ and E). Welding of S1100QL steel requires control and exact application of selected welding parameters, because even minor deviations can have negative effects on the quality of welded joints. The lowest values of impact energy in true welded specimens were obtained by test temperature of - 60 °C and were related to grain tempered martensite, which occurred due to hardness measured in the range of 280 to 320 HV.

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