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PROPERTIES AND WELDABILITY OF HIGH-STRENGTH LOW-ALLOY S1100QL STEEL

SVOJSTVA I ZAVARLJIVOST NISKOLEGIRANOG ČELIKA VISOKE ČVRSTOĆE S1100QL

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Abstract

The high-strength low-alloy steel S1100QL is used in the most demanding mechanical engineering applications. Typical structures made of this steel are hydraulically extendable pallet cranes in mobile lifting machinery, which require high strength-to-weight ratio. The high yield strength and toughness of S1100QL steel is achieved through proper chemical composition, hot rolling, and heat treatment. Those factors also have a strong effect on the weldability of this steel: the welded joint should have the properties required by EN ISO 15614-1. In this paper, the main properties of the S1100QL steel are shown. In addition, WPQR was performed on a 15 mm thick plate using the GMAW process. Analysed properties such as tensile test, impact toughness, hardness and microstructure are compared to the requirements of the international standards from the field of arc welding.

Rezime

Niskolegirani čelik visoke čvrstoće S1100QL koristi se u najzahtevnijim aplikacijama mašinstva. Tipične konstrukcije izrađene od ovog čelika uključuju hidraulički izvlačne paletne dizalice u pokretnim mašinama za podizanje koje zahtevaju veliki odnos čvrstoće i težine. Visoka granica tečenja i žilavost čelika S1100QL postiže se pravilnim hemijskim sastavom, toplim valjanjem i termičkom obradom. Ovi faktori takođe imaju snažan uticaj na zavarljivost ovog čelika: zavareni spoj treba da ima svojstva koja zahtevaju EN ISO 15614-1. U ovom radu su prikazana glavna svojstva čelika S1100QL. Pored toga, WPQR je izveden na ploči debljine 15 mm primenom MAG procesa. Analizirana svojstva kao što su ispitivanje zatezanjem, žilavost, tvrdoća i mikrostruktura, upoređuju se sa zahtevima međunarodnih standarda iz oblasti elektrolučnog zavarivanja.

1. Introduction

Steel S1100QL is a high-strength low-alloy (HSLA) steel with yield strength of 1100 MPa. According to some authors it is also called fine-grained or micro-alloyed steel [1]. Civil and mechanical engineering are two main fields of use where high strength-to-weight ratio of structures is required. HSLA steels with relatively high impact toughness were developed in order to lower mass of structures. To fulfil mechanical properties such as yield and tensile strength, elongation and impact toughness, the S1100QL is produced with special chemical composition.

Microalloying elements such as titanium, niobium, vanadium and boron are typically used during steel making process. Titanium addition is used for boron protection as well as austenite grain refinement. Microalloying is used to achieve fine ferritic grains in the microstructure. As a result, the yield strength and impact toughness of the steel increases. The phenomenon is defined with Hall-Petch equation [2]. Petch was also the first researcher who defined correlation between impact toughness and grain size. With the increase of temperature, during the austenitisation annealing, grains increase due to the grain boundary migration. Austenite grains are increasing with quadratic relation to temperature. As a result of grain coarsening, the yield strength, tensile strength, elongation, contraction and impact toughness decrease.

Ferrite is formed from austenite during continuous cooling through *Ar3* temperature. In order to have control over austenite grain size, it is necessary to take care during heating before hot rolling process and also during hot processing. Two main mechanisms are known that have effect on grain size coarsening. Alloying elements dissolved in steel matrix cause additionally resistance to mobility of high-angle grain boundaries [3]. The second one, Zenner drag effect, is correlated to attachment of fine precipitates along austenite grain boundaries. Small precipitates lower the surface energy between austenite grains and thus additional energy is necessary for grain coarsening.

Beside microalloying elements (V, Nb, Ti) high-strength low-alloy steels are typically alloyed with Cr, Ni and Mo. With the increases of those elements the curve of CCT diagram is moved to right, to longer transformation times, and as a result through thickness hardening effect increases. Homogenous microstructure over the thickness of the plate is necessary to fulfil mechanical requirements. Non-metallic inclusions have negative effect on impact toughness and thus content of phosphorus, sulphur, nitrogen, oxygen and hydrogen must be as low as possible.

Manufacturing process of S1100QL steel consists of following steps:

- **Steel making process in the melt shop**: Scrap metal is melted using electric arc furnace (EAF). Degasation and final alloying is done on vacuum-degasation unit (VD). Liquid metal is cast into slabs using continuous caster.

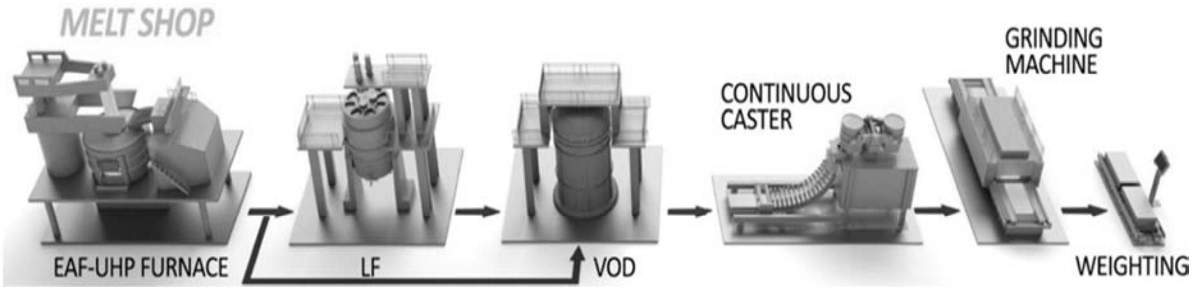

Figure 1. *Steel making process in SIJ Acroni melt shop [4]*

Slika 1. *Proces proizvodnje čelika u čeličani SIJ Acroni [4]*

- **Hot-rolling mill:** Slabs made of S1100QL steel are reheated into austenite region using pusher type furnace. Four-high rolling mill with capacity of 600 tons is used for rolling of the slabs into the final plates with the maximum width of 2500 mm.

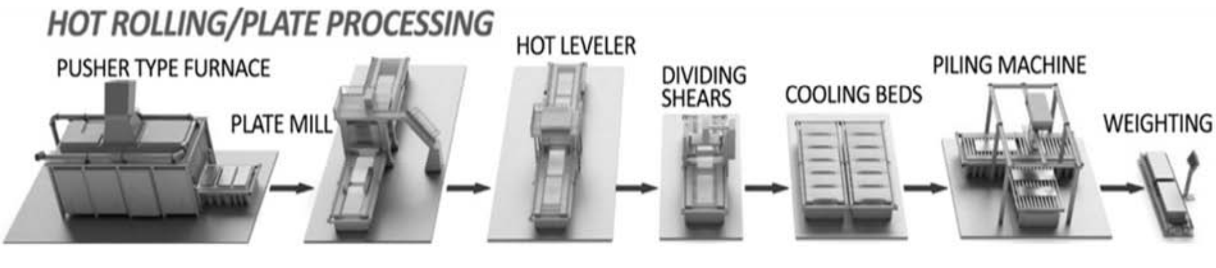

Figure 2. *Hot rolling process in SIJ Acroni [4]*

Slika 2. *Proces toplog valjanja u SIJ Acroni [4].*

- **Heat treatment and finalisation:** Quenching of steel plates from the austenite region is the first step of heat treatment. Steel in a form of a quarto plates is heated into austenite region, 30 – 50 °C above Ac3 temperature. Holding time between 15 – 30 minutes, depending on the plate thickness, is necessary for complete transformation of ferrite into austenite all over the plate thickness. After austenitization annealing the plates are quenched using Multi-Flex quench heat treatment line. Cooling speed directly defines microstructural evolution in the steel plate and is thus defined as the crucial technological parameter. Critical cooling speed is required in order to get homogenous martensitic microstructure all over the plate thickness.

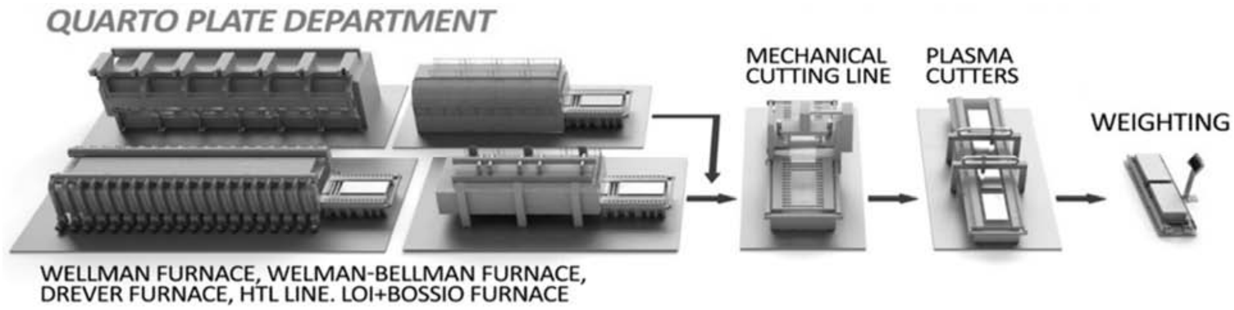

***Figure 3.** Heat treatment process in SIJ Acroni quarto plate department [4]*

***Slika 3.** Proces termičke obrade u odeljenju kvarto ploča SIJ Acroni [4]*

As a result of chemical composition and high cooling speed during quenching process the S1100QL steel plate have high hardness but low impact toughness and ductility. Additional step of low temperature tempering is required after quenching to increase impact toughness and ductility. In final quenched and tempered condition, the microstructure consists of tempered martensite.

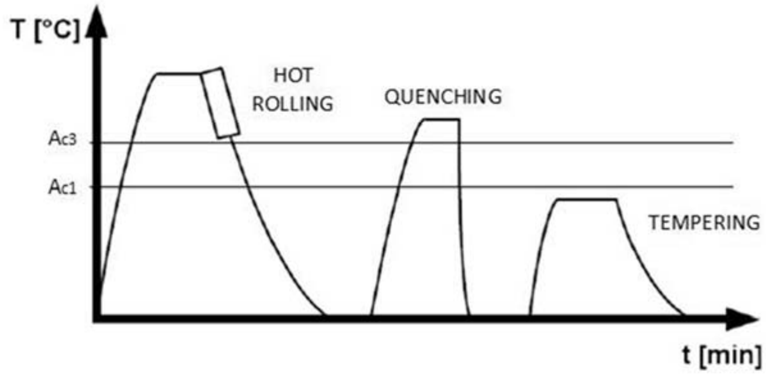

***Figure 4.** Heat treatment process of S1100QL steel in SIJ Acroni [5]*

***Slika 4.** Proces termičke obrade čelika S1100 QL u SIJ Acroni [5]*

Grade S1100QL is not conventional construction steel due to relatively high carbon content and consequently carbon equivalent value CEV. Additionally, S1100QL is a non-standard grade due to the yield strength over 960 MPa, which is the highest yield strength range included into EN ISO 10025-6 [6]. According to ISO/TR 15608 this grade can be included into the steel group 3.2 which covers quenched and tempered (QT) fine grained steels with a specified yield strength ReH > 690 MPa [7].

Welding is the main technological operation during manufacturing process of high strength structures made of construction steel. Due to the heat input during arc welding microstructural changes occur in the material and hence also degradation of mechanical properties in the HAZ is to be expected.

According to above mentioned details the aim of this work was to investigate the properties of butt weld joint made of S1100QL steel in a form of a 15 mm thick plates using GMAW process. Characterisation was done according to EN ISO 15614 [8].

2. Experiment

Base material used for welding procedure test was produced by SIJ Acroni Jesenice with commercial name SIMAXX 1100QL. Chemical composition with maximum mass content of alloying elements is defined in the Table 1. Weld edges of 15 mm thick plates were prepared in a form of letter V – 60° as seen on the Figure 5.

Table 1. *Maximum content of alloying elements (in mass %) for SIMAXX 1100QL [9]*

Tabela 1. *Maksimalni sadržaj legirajućih elemenata (u mas. %) za SIMAXX 1100QL [9]*

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	B
0,19	0,50	1,60	0,012	0,002	1,20	1,20	0,60	0,30	0,005

SIMAXX 1100QL is a HSLA steel with the mechanical properties that are not specified in EN ISO 10025-6 standard. Before order the mechanical properties should therefore be agreed between customer and producer. European producers of HSLA steels with yield strength over 1100 MPa guarantee the properties according to the datasheets [10-14].

Table 2. *Mechanical properties of SIMAXX 1100QL steel produced by SIJ ACRONI [9]*

Tabela 2. *Mehanička svojstva SIMAXX 1100QL čelika proizvođača SIJ ACRONI [9]*

Yield strength Granica tečenja $R_{p0,2}$ [MPa]	Tensile strength Zatezna čvrstoća R_m [MPa]	Elongation Izduženje $A_{5,65}$ [%]	Impact toughness Energija udara *KV2* at -40 °C [J]
≥ 1100	≥ 1150	≥ 10	27 transverse / 30 longitudinal

Welding parameters which were used for all eight weld passes were set according to the Table 3. Heat input varied between 0,6 kJ/mm to 1,3 kJ/mm. Selected welding parameters shall be used when welding HSLA steels due to two main reason. Extremely low heat input could result in high hardness in HAZ. On the other side high heat input could have negative effect on grain coarsening in the HAZ close to the fusion line. Welding was done using GMAW with massive wire with diameter of 1,2 mm. Wire designation was G 89 6 M21Mn4Ni2CrMo. Before welding both plates of the welded joint were preheated to 150 °C. Mixture of 18 % CO2 with 82 % Ar with volume flow of 17 l/min was used as a shielding gas.

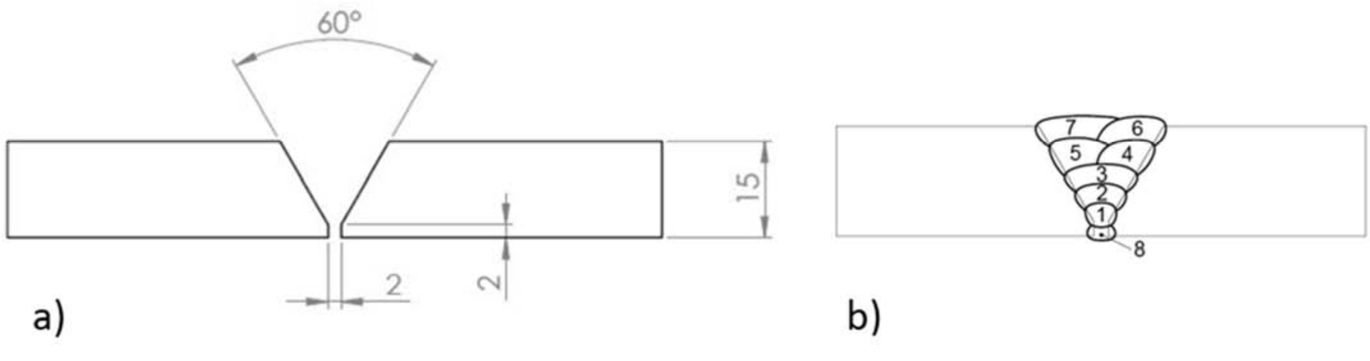

Figure 5. *a) butt joint (BW) edge preparation, b) weld passes position*

Slika 5. *a) priprema ivice sučeonog spoja (BW), b) redosled polaganja zavara*

Table 3. *Welding parameters*

Tabela 3. *Parametri zavarivanja*

Weld bead/ Prolaz	Arc voltage/ Napon [V]	Welding current/ Struja zavarivanja [A]	Welding speed/ Bzina zavarivanja [mm/s]	Preheated/ Predgrevanje *Tp/Ti* [°C]	Heat input Q *Efficiency factor k= 0,8 included* / Unos toplote Q *Koeficijent efikasnosti k= 0,8 uključen* [kJ/mm]
1	17,4	137	2,84	150	0,67
2	21,4	205	3,29	150	1,07
3	21,4	214	2,80	150	1,31
4	21,7	216	5,59	170	0,67
5	23,2	217	4,89	175	0,82
6	20,3	201	3,08	185	1,06
7	22,6	209	3,10	190	1,22
8	22,7	206	2,92	180	1,28

3. Results

The welded joint was analysed according to the requirements of EN ISO 15614-1. The focus of experimental work was on determination of mechanical properties. Therefore, yield strength, tensile strength, impact toughness and hardness were measured. Additionally, also microstructure of the weld and HAZ was analysed.

3.1 Tensile strength

Two tensile specimens were cut in transverse direction of the welded joint. Results of the testing are shown in the Table 4.

Table 4. *Tensile testing results and fracture location of the welded joint*

Tabela 4. *Rezultati ispitivanja zatezanjem i položaj preloma zavarenog spoja*

Tensile specimen/Uzorak za zatezanje	Yield strength/ Granica tečenja $R_{p0,2}$ [MPa]	Tensile strength/ Zatezna čvrstoća *Rm* [MPa]	Fracture location [base / HAZ / weld metal] Lokacija preloma [osnovni / ZUT / metal šava]
1	959	1012	Weld metal Metal šava
2	957	1009	

As seen from the results, the weld joint efficiency factor is lower as 1. Yield strength and also tensile strength of the weld joint is lower as it is specified for the base metal plate made of SIMAXX 1100QL steel. This under matching in mechanical properties was already expected according to the specification of the welding wire. Joint efficiency factor η can be calculated according to the equation 1.

$$\eta = \frac{Rp_{0,2}\ weld\ joint}{Rp_{0,2}\ base\ metal} \qquad (1)$$

Joint efficiency factor η = 0, 87 was determined for both tensile specimens.

3.2 Impact toughness

According to EN ISO 9016 two sets of specimens were machined from the butt joint [15]. Three specimens were machined with notch at the weld centreline (VWT) and three specimens with the notch in the HAZ (VHT). Testing was done on instrumented Chirpy impact tester. For each specimen energy of crack initialisation (Eli) and energy of crack propagation (Up) was determined. As seen from the Table 5 impact toughness of all specimens at -40 °C was higher as 27 J. What can also be observed is that energy of crack initialisation of VWT specimens is higher as energy for crack propagation. Specimens from the HAZ zone show only minor difference between Eli and Ep.

Table 5. *Impact testing results of the welded joint*

Tabela 5. *Rezultati ispitivanja energije udara zavarenog spoja*

Specimen/ Uzork	Impact toughness/ Energija udara *KV2* [J]	Average impact toughness/Srednja vrednost energije udara *KV2* [J]	Energy of initialisation/ Energija stvaranja E_{li} [J]	Energy of propagation/ Energija širenja U_p [J]
VWT-1	37	37	27	10
VWT-2	35		26	9
VWT-3	40		29	11
VHT-1	76	89	43	33
VHT-2	97		45	52
VHT-3	94		51	43

3.3 Hardness of the welded joint

Hardness was measured according to EN ISO 9015 [16]. Due to the relatively high CEV of the base material with the value of 0, 67 % care must be taken during welding. Limited maximum hardness value in as-welded condition for steels from a group 3.2 from ISO 15608 is 450 HV. In order to exactly determine hardness distribution over the welded joint we made detailed hardness mapping. As seen from the Figure 6 the highest value of hardness was measured in the HAZ close to the weld bead eight, which was the last bead welded. The maximum hardness was measured at the position highlighted with an arrow on Figure 6 with the value of 416 HV5.

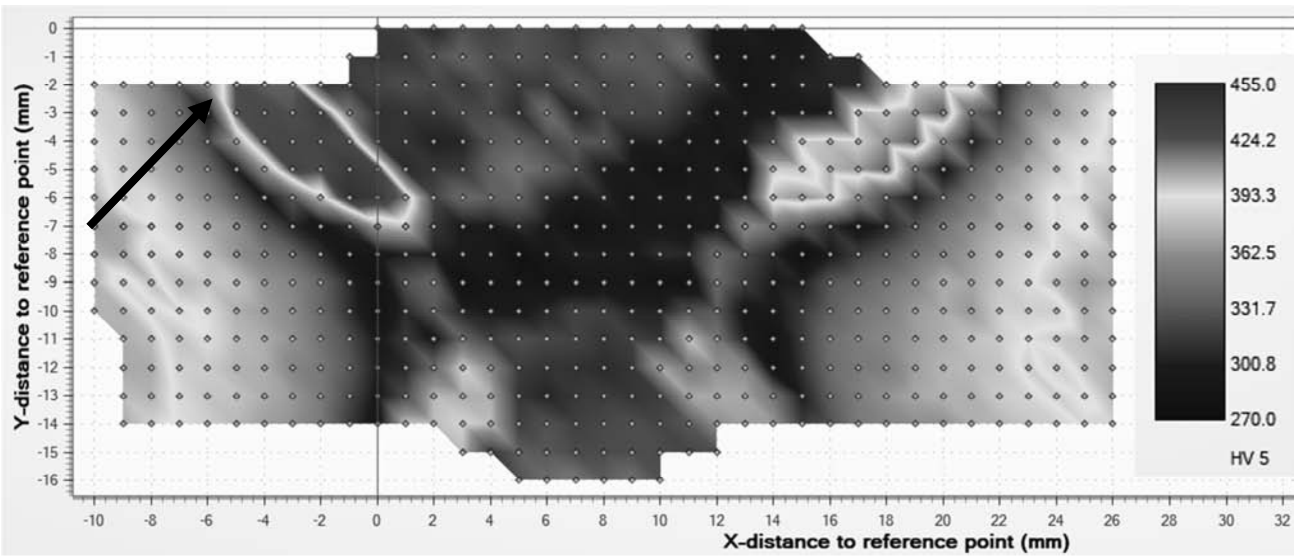

Figure 6. *Hardness mapping on the cross section of the welded joint*

Slika 6. *Mapirana raspodela tvrdoće na poprečnom preseku zavarenog spoja*

3.4 Microstructure of the welded joint

Metallographic samples were etched using 2 % Natal etchant. As seen from the Figure 7. no undercuts or incomplete penetrations were observed on the macro-cross section.

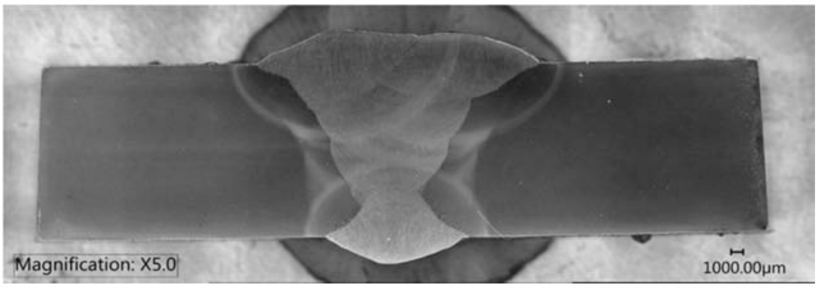

Figure 7. *Macro-photo of the butt weld joint*

Slika 7. *Makro fotografija sučeonog spoja*

Additionally, we also analysed microstructure of the weld metal as shown on the Figure 8. Microstructure in the weld metal consists mostly of the acicular ferrite, which improves the impact toughness of the weld matrix.

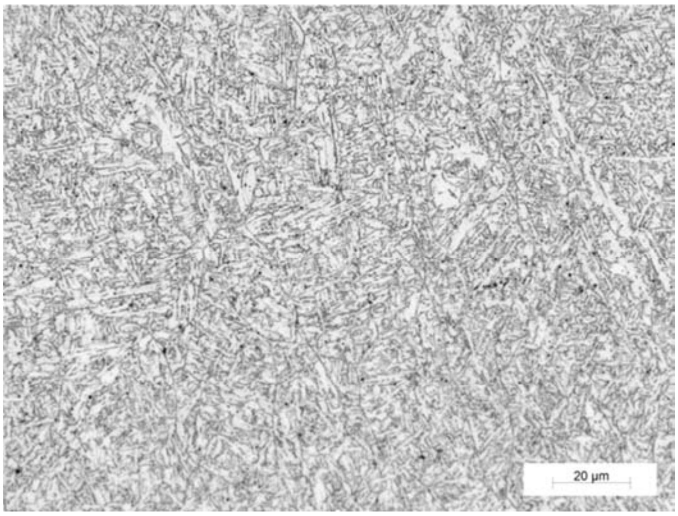

Figure 8. *Microstructure in the weld metal, magnification 500 times*

Slika 8. *Mikrostruktura metala šava, uvećanje 500 puta*

Microstructure in the HAZ is shown on the Figure 9. As seen, the microstructure in this region is martensitic. Due to the effect of heat input also grain coarsening was observed. The largest grains with the diameter up to 100 μm were observed close to the fusion line.

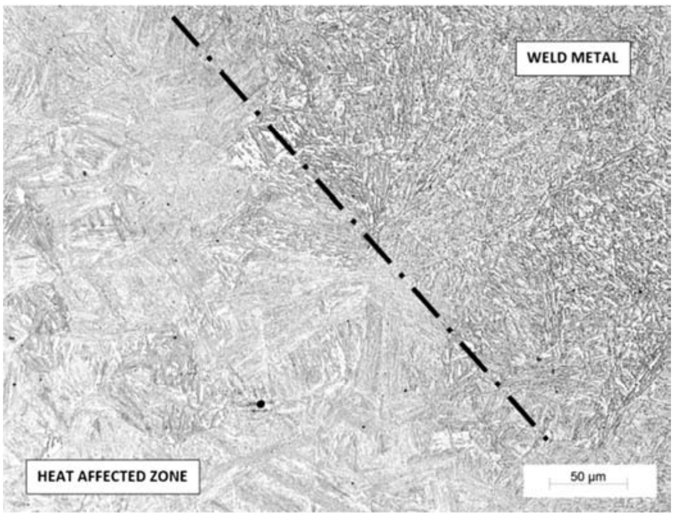

Figure 9. *Microstructure in the HAZ near the fusion line (dashed line), magnification 200 times*

Slika 9. *Mikrostruktura ZUTa u blizini linije topljenja (isprekidana linija), uvećanje 200 puta*

4. Conclusion

With this experimental work the mechanical properties of the welded joint made form SIMAXX 1100QL steel were analysed. Tensile testing showed that due to the under matching in mechanical properties the joint efficiency factor is 0, 87. Additionally, it was observed that hardness across the weld joint is in safe region, approximately 30 HV under the limit defined by EN ISO 15614-1. Impact toughness in the weld metal and in the HAZ of the joint completely fulfils requirement of international standard. As seen from this experimental work the tensile testing is the only test in which testing of the welded joint failed. Yield strength measured on the BW joint was lower as specified for base metal steel. Due to the under matching in mechanical properties the requirements of the welded joints made from S1100QL steel should be defined separately as an annex of the next edition of the standard EN ISO 15614-1. The minimum value of joint efficiency factor should therefore be specified.

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