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OCCURRENCE OF COLD CRACKS IN WELDING OF HIGH-STRENGTH S960 QL STEEL

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Preliminary notes

The paper presents the study of weldability of micro-alloyed high-strength S960 QL steel with the application of experimental methods and mathematical models from the aspect of cold cracks occurrence. In the experimental part of the research RD (Research Department) test was applied to estimate the steels susceptibility to the occurrence of cold cracks. For the analysis of the impact of heat input on the mechanical properties of the welded joint the test steels were welded with one, two or more runs, out of which samples were made for the production of specimens in order to measure the hardness and impact strength in HAZ (heat affected zone). Based on the obtained results an estimate was provided regarding the weldability of S 960 QL steel as well as the proposal for further research.

Keywords: *cold cracks, high-strength S 960 QL steels, mathematical model, RD test, weldability*

Pojava hladnih pukotina pri zavarivanju visokočvrstog čelika S960 QL

Prethodno priopćenje

U ovom radu provedeno je istraživanje zavarljivosti mikrolegiranog čelika visoke čvrstoće S960 QL uz primjenu eksperimentalnih metoda i matematičkih modela s aspekta pojave hladnih pukotina. U eksperimentalnom dijelu istraživanja primjenjen je RD test za procjenu sklonosti čelika na pojavu hladnih pukotina. Za analizu utjecaja unosa topline na mehanička svojstva zavarenog spoja zavarene su ispitne ploča s jednim, dva i više prolaza od kojih su načinjeni uzorci za izradu epruveta za mjerenje tvrdoća i udarne radnje loma u ZUT- u. Na osnovi rezultata dana je ocjena zavarljivosti čelika S 960 QL .

Ključne riječi: *hladne pukotine, matematički model, RD test, visokočvrsti čelici S 960 QL, zavarljivost*

1 Introduction
Uvod

The occurrence of cracks on welded structures made of high-strength S960QL steel which are installed in the cranes of the world leading manufacturers (Fig. 1) was the reason to carry out the study of the weldability of high-strength S960QL steel. The performed analysis at the production plants indicated that the cracks primarily occur during spring and winter, i.e. when air humidity is maximal and the temperature the lowest which may lead to the conclusion that high cooling rate and increased quantity of diffused hydrogen represent the risk factors. As may be seen in Fig. 2 these are longitudinal and transversal cracks that occurred in the heat affected zone (HAZ) and the weld. Since the welding production is performed the whole year round, and since during their exploitation the cranes are exposed to high loads, in order to achieve the required high quality of the welded joints in this steel it is necessary to define the field of technological parameters that will minimize the

Figure 1 *Welded structure forms made of S 960 QL steel where cracks appeared*
Slika 1. *Zavarene konstrukcije od čelika S 960 QL s uobičajenim pukotinama*

Figure 2 *Cracks on welded structures made of S 960 QL steel*
Slika 2. *Pukotine na zavarenim konstrukcijama od čelika S 960 QL*

conditions for crack occurrence. In order to determine the optimal interval of heat input and other technological requirements, it was decided to carry out the experimental trials and, using the existing mathematical models, to evaluate the weldability of high-strength S960 QL steel so as to fully avoid the possible damages of the welded structures.

2 Weldability of Micro-Alloyed Steels
Zavarljivost mikrolegiranih čelika

The S960 QL steel is a micro-alloyed fine-grained high-strength steel. The micro-alloyed steels are mainly applied for the construction of bridges, vehicles, cranes, ships, etc. In order to improve the weldability of micro-alloyed steels the carbon content in the majority of cases is lower than 0,1 % [1]. The micro-alloyed elements with carbon and nitrogen create and discharge carbides, nitrides and carbonitrides, facilitate the creation of fine-grained structure and by their discharge increase the strength (e.g. AlN, TiC, TiCN, TiN, V_4C_3, VC, NbC, NbCN). Niobium and vanadium are added to steel in order to increase the strength of steel without increasing the content of carbon and/or manganese. The increase in the content of carbon and/or manganese has harmful effect on the weldability and impact toughness [1, 5].

The weldability of materials cannot be tested directly by single standardized methods but rather tests are carried out which test certain properties of materials based on which conclusions can be made about the weldability regarding:

- cold crack initiation,
- hot crack initiation,
- lamellar separation,
- brittle fracture,
- increase in hardness,
- ageing of material,
- crack initiation in high-strength material.

In welding high-strength steels the biggest problem is the occurrence of cold cracks [7]. The susceptibility to cold crack initiation may be determined by carbon equivalent C_{ekv} which determines through chemical composition the mentioned susceptibility.

For the microalloyed steels the expression according to Itto and Bessyo is used [2]:

$$P_{cm} = C + \frac{Mn}{20} + \frac{Mo}{15} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{V}{15} + \frac{Cu}{20} + \frac{Si}{30} + 5B \qquad (1)$$

P_{cm} – carbon equivalent according to Itto and Bessyo, %.

The value of P_{cm} parameter should not exceed 0,25 % [2]. There are also different formulas for the estimate of the maximal hardness in the welded joint which are used to estimate the steel susceptibility to the cold cracks initiation. In the majority of structure steels the strength values up to 350 HV10 do not initiate the occurrence of hard phases yet, which are susceptible to the occurrence of cold cracks [4, 16]. According to Boothby and Cottrell the expression for maximum hardness takes into consideration also the cooling rate $t_{8/5}$ [2, 17]:

$$HV10_{max} = 2019 \cdot \left(1 - 0{,}5 \cdot \lg t_{8/5}\right) \cdot C + 0{,}3 \cdot \left(C_E \cdot B - C\right) + 66 \cdot \left(1 - 0{,}8 \cdot \lg t_{8/5}\right) \qquad (2)$$

where the carbon equivalent according to Boothby and Cottrell is:

$$C_E \cdot B = C + \frac{Si}{11} + \frac{Mn}{8} + \frac{Cu}{9} + \frac{Cr}{5} + \frac{Ni}{17} + \frac{Mo}{6} + \frac{V}{3}. \qquad (3)$$

Welding of enhanced microalloyed steels is very sensitive regarding to the heat input and decline of impact strength in HAZ due to grain roughening and occurrence of Widmannstäten structure. Therefore, in welding of this type of steel the pre-heating temperature T_0 is determined as well as the interpass temperature T_m, where the heat input has to be exactly within the defined limits ($E_{min}<E<E_{max}$). It is therefore necessary to determine the heat input for the upper and bottom value of time $t_{8/5}$ where the mean value $t_{8/5}$ represents the optimum. The optimal value $t_{8/5}$ is the most significant parameter in welding of steels of higher and high strength. The values lower than the bottom limit mean too fast cooling and forming of brittle structure whereas values higher than the upper limit result in coarse grains and decrease in toughness in HAZ which in turn causes increase in the transition temperature. The cooling time $t_{8/5}$ for the enhanced microalloyed steels should be from 8 to 12 s [8, 9]. In microalloyed steels the increase in strength and hardness can cause the occurrence of cold cracks in production and/or occurrence of cracks due to corrosion with stress in the conditions of aggressive medium during exploitation. In literature the pre-heated zone of HAZ for steels of higher and high strength is emphasised as the especially sensitive zone of HAZ. These are temperature ranges from 1100 °C to solidus line. In this range it comes to intensive grains coarsening. The cause of grain increaseing is complete dissolution of precipitates and their transition into solid solution which means also termination of the limiting action on the increase of austenitic grain.

During cooling the homogenised austenite dissolves into several unbalanced products which can have favourable and unfavourable impact.The favourable impact is dissolution of austenite into ferrite-perlite structure with needle-like ferrite and bottom bainitic structure in this range of HAZ. The unfavourable influence is the occurrence of martensite and Widmannstäten's ferrite structures.

The transformation of the material structures is accompanied by different solubility of hydrogen. Upon completion of structure transformations, the resulting bainitic or martensitic structure has lower solubility of hydrogen and other gases compared to austenite structure. If the excess of hydrogens is diffused into still non-transformed austenite, and by further transformation of austenite into martensite, martensite becomes hydrogen-saturated. The cooling increases the residual stresses, which leads to the possibility of the occurrence of cold cracks.

In welding of microalloyed steels it is necessary to:

- avoid the creation of brittle constituents in the weld and HAZ, which means that the cooling time $t_{8/5}$ should not be too short so that there would be no occurrence of any brittle needle-like martensites;
- avoid the creation of polygonal ferrite in the weld and HAZ, and $t_{8/5}$ should not be too big; minimize the reduction in hardness in the part of HAZ which cannot

be avoided but its width can be affected by lower volume of input heat, and its depth by the selection of steel more resistant to tempering. Ferrite is unfavourable since in impact load it is susceptible to crack initiation which continues to propagate through bainite and/or martensite and /or perlite. In practice the welding is almost always done in several runs. In multi-run welding almost every point passes through various thermal cycles, so that the total cooling time of every run is longer. The impact strength of every subsequent run is higher, the temperature of conversion into the brittle condition is lower and of hardness along the fusion line is lower. In multi-run welding there will be single heat affected zones around each run. Fast cooling of HAZ and weld metal influence the hardening and poor mechanical properties, and slow cooling affects the growth of grains and discharge of other undesired phases. Fig. 3 shows the thermal cycle during multi-layer welding [2].

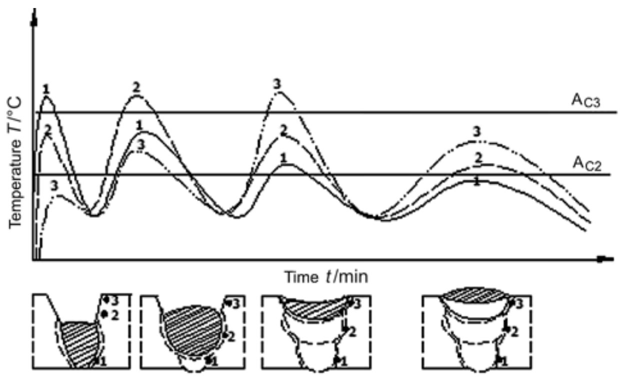

Figure 3 *Thermal cycle during multi-layer welding* [2]
Slika 3. *Toplinski ciklus tijekom višeslojnog zavarivanja* [2]

3 Mathematical Models for Determining Pre-Heating Temperatures and Heat Input
Matematički modeli za određivanje temperature predgrijavanja i unosa topline

3.1 Pre-heating temperature
Temperatura predgrijavanja

For the calculation of pre-heating temperature in the welding of microalloyed high-strength steels the expression according to Itto and Bessyo is applied. The pre-heating is used to achieve the reduction in the HAZ and weld metal cooling rate, enabling the exit of diffusion hydrogen, reduction in the intensity of residual stresses, increase in the cooling time $t_{8/5}$ and reduction of the possibility of the occurrence of cold cracks in HAZ and the weld. The pre-heating temperature in the welding of high-strength microalloyed and low-alloyed steels must be kept within strict limits T_{0min} and T_{0max}. The inter-transition temperature T_m is in fact maximally allowed pre-heating temperature $T_m = T_{0max}$ [3]. The too low pre-heating temperature can produce a too hard and brittle structure, and too high rough-grained and brittle structure, with softening of certain zones. The pre-heating temperature depends on the chemical composition of the material, which is expressed through carbon equivalent, material thickness, number of directions of heat removal, structure tension, as well as content of diffusion hydrogen. According to Itto and Bessyo the pre-heating temperature is calculated according to the expression [5]:

$$T_0 = 1440 \cdot P_w - 392 \ °C \tag{4}$$

where:

$$P_w = P_{cm} + \frac{H}{60} + \frac{K}{40} \times 40^4 \ \% \tag{5}$$

P_w – crack susceptibility parameter, %
H – the content of diffusion hydrogen in filler material, ml/100 g of weld metal
P_{cm} – carbon equivalent according to Itto and Bessyo (1), %
$K = K_0 \cdot d$ – stiffness intensity, K_0= 69 N/mm - constant
d – base material thickness, mm.

For the crack parameter $P_w > 0{,}24$ the steel is considered to be susceptible to the occurrence of cold cracks [4, 5]. Temperature T_0 represents minimal pre-heating temperature T_{0min}, and for maximum temperature T_{0max} 10 % higher value is taken [3]. Since T_0 is within the interval between T_{0min} and T_{0max} during the pre-heating temperature calculation the mean value is used: $T_0 = (T_{0max} + T_{0min})/2$.

3.2 Heat input
Unos topline

The heat input is determined by applying the expressions according to [6, 15].

For two-dimensional cooling (2D):

$$E_{ef} = \frac{q}{v} = U \cdot I \cdot \frac{\eta}{v} = \sqrt{\frac{d^2 \cdot t_{8/5}}{(430 - 0{,}43 \cdot T_0) \cdot F_2 \left[\left(\frac{1}{500 - T_0} \right)^2 - \left(\frac{1}{800 - T_0} \right)^2 \right]}} \text{, J/mm} \tag{6}$$

For three-dimensional cooling (3D):

$$E_{ef} = \frac{q}{v} = U \cdot I \cdot \frac{\eta}{v} = \frac{t_{8/5}}{(6{,}7 - 5 \times 10^{-3} \cdot T_0) \cdot F_3 \left(\frac{1}{500 - T_0} - \frac{1}{800 - T_0} \right)} \text{, J/mm} \tag{7}$$

From expressions (7) and (8) one can calculate the cooling time $t_{8/5}$ in the interval from 800 to 500 °C for two-dimensional (2D) and three-dimensional (3D) cooling [6]:

$$\text{For 2D: } t_{8/5} = \left(\frac{430 - 0{,}43 \cdot T_0}{d^2}\right) \cdot F_2 \left(\frac{q}{v}\right)^2 \cdot \left[\left(\frac{1}{500 - T_0}\right)^2 - \left(\frac{1}{800 - T_0}\right)^2\right], \text{ s} \quad (8)$$

$$\text{For 3D: } t_{8/5} = \left(6{,}7 - 5 \times 10^{-3} \cdot T_0\right) \cdot F_3 \cdot \left(\frac{q}{v}\right) \cdot \left[\left(\frac{1}{500 - T_0} - \frac{1}{800 - T_0}\right)\right], \text{ s} \quad (9)$$

where:
T_0 - pre-heating temperature, °C
I – welding current, A
U – welding voltage, V
v – welding rate, mm/s
η – efficiency level of electric arch,
$t_{8/5}$ – cooling time in heat interval from 800 to 500 °C, s
F_2 and F_3 – heat removal factors (F_2=F_3=0,9) for butt multi-run welding [14]
d – steel thickness, mm
E_{ef} – effective heat input, J/mm.

The heat removal model during welding is determined by the expression of determining the marginal material thickness:

$$d_{gr} = \sqrt{\frac{\left(430 - 0{,}43 \cdot T_0\right) \cdot \left(\frac{q}{v}\right) \cdot \left[\frac{1}{500 - T_0} + \frac{1}{800 - T_0}\right]}{6{,}7 - 5 \times 10^{-3} \cdot T_0}}. \quad (10)$$

d_{gr}, mm

If the actual material thickness is less than the marginal value ($d<d_{gr}$) the 2D cooling model is used, otherwise the 3D cooling model is used.

4 Experimental Work
Eksperimentalni rad

4.1 Estimate of S960 QL steel crack susceptibility based on the mathematical model
Procjena zavarljivosti čelika S960 QL na temelju matematičkih modela

The estimate of S960 QL steel susceptibility to the occurrence of cracks is determined by applying expression (5).

The chemical composition and the mechanical properties of the material have been taken from the attest of the basic material steel for the batch under number 653409 [10], Tab.-s 1 and 2.

Table 1 *Chemical composition of S960 QL steel (batch 653409)* [10]
Tablica 1. *Kemijski sastav čelika S960 QL(šarža 653409)*[10]

Mass content, %														
C	Si	Mn	P_{max}	S_{max}	Cr	Mo	Al	B	Cu	N	Nb	Ni	Ti	V
0,17	0,41	1,42	0,009	0,0004	0,63	0,46	0,038	0,002	0,030	0,0043	0,023	0,040	0,005	0,020

Table 2 *Mechanical properties of S960 QL steel (batch 653409)* [10]
Tablica 2. *Mehanička svojstva čelika S960 QL(šarža 653409)*[10]

R_m, N/mm^2	$R_{p0.2}$, N/mm^2	A_5, %	Z, %	KV, J (–40 °C)	HV10
1070	1025	15	55	> 40	350; 355

By inserting the percentages of chemical elements of S960QL steel (Tab. 1), the values of the test material thickness (d = 30 mm) and content of the diffusion hydrogen (according to the attest of the welding consumables and selection of GMAW welding procedure H= 1,2 ml/100 g_{weld} according to Itto and Besyo (expression (5)) the crack parameter value P_w = 0,31 was obtained. It is considered that the steel is susceptible to the occurrence of cold cracks if P_w > 0,24 [4, 5], which shows that S960 QL steel is susceptible to the occurrence of cracks.

In order to avoid the occurrence of cold cracks it is necessary to pre-heat the steel before welding, as well as to control the inter-pass temperature T_m, in multi-layer welding. By using the expressions (4) and (5) the pre-heating temperature T_0 = 150 °C was calculated. The temperature was determined to be $T_m = T_0$ = 150 °C.

4.2 Experimental determination of S960 QL steel susceptibility to the occurrence of cold cracks
Eksperimentalno određivanje osjetljivosti čelika S960 QL na pojavu hladnih pukotina

The S960 QL steel susceptibility to the occurrence of cold cracks has been experimentally evaluated by the application of RD (Researsh Department)-test [4], and by welding the experimental plates, with single-run, double-run and multi-run welding. Welding was done using the GMAW procedure, with the application of welding consumables Fliess ED-FK1000 (EN 12534) and ED-SG3 (EN 440) of 1,2 mm diameter [11, 12]. The chemical composition and the mechanical properties of the used

Table 3 *Chemical composition of welding consumables* [12]
Tablica 3. *Kemijski sastav dodatnog materijala* [12]

Type of wire	Mass content, %					
	C	Si	Mn	Ni	Cr	Mo
ED-FK1000	0,09	0,80	1,80	2,20	0,31	0,55
ED-SG 3	0,09	0,95	1,67	-	-	-

welding consumables are presented in Tables 3 and 4.

Table 4 *Mechanical properties of welding consumables* [12]
Tablica 4. *Mehanička svojstva dodatnog materijala* [12]

Type of wire	R_m/ N/mm^2	$R_{p0,2}$/ N/mm^2	A/ %	KV/J
ED-FK1000	≥940	≥885	≥14	≥47 (–60)
ED-SG 3	≥560	≥450	≥22	≥47 (–20)

welding consumables are presented in Tables 3 and 4.

The shielding gas used was a combination of M21 82 %Ar +18 %CO_2 (EN 439). The samples were welded manually with strict control of T_0, T_m, $t_{8/5}$ and E_{ef}. For S960 QL steel the cooling time $t_{8/5}$ has been determined experimentally. According to the recommendation of the manufacturer of the basic material the cooling time $t_{8/5}$ for S960 QL steel is $t_{8/5}$ = 6 to 12 s [11]. During the experiment the cooling time $t_{8/5}$ was strictly kept as close as possible to the mean value of 9 s. The pre-heating was done by a gas burner. The impact strength was measured on the instrument CHARPY-PW 30/15 WOLPERT, and hardness on the instrument ROCKWEL - OTTO - HT-8000R manufactured by WOLPERT.

4.2.1
RD – test
RD – test

The RD-test is one of the methods used to determine the high-strength steels susceptibility to the occurrence of cold cracks. The shape and dimensions of RD test are presented in Fig. 4 [4]. The steels are welded to the thicker basic plate, thus preventing angular deformations and dilatation. The prepared groove is welded (Fig. 4); after welding the samples are cut out and the mechanical properties tested. After having welded the S960QL steel and after 48-hour waiting, the sample was cut into 6 segments. The detection of cracks was performed on the macro cross section of specimens. The root weld on the test, and the remaining weld layers were made with wire ED-FK1000 Ø1,2 mm diameter. In welding the influencing parameters T_0, T_m, $t_{8/5}$ and E_{ef} were strictly controlled (Tab. 5).

Since the marginal value d_{gr} is less than the sheet thickness of the test specimen d it means that the heat removal is three-dimensional. Based on the upper and lower cooling time values $t_{8/5}$ = 6 to 12 s, the minimal and maximal allowed value of heat input has been determined.

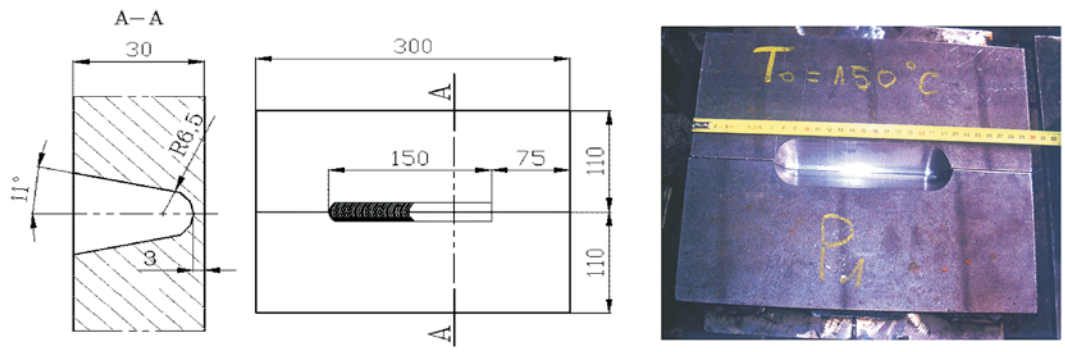

Figure 4 *Plate dimensions for RD test and prepared groove for welding*
Slika 4. *Dimenzije ploča za RD test i pripremljeni žlijeb za zavarivanje*

Table 5 *Welding parameters of RD test*
Tablica 5. *Parametri zavarivanja RD - probe*

Run	I/A	U/V	V/ mm/s	E_{ef}/kJ/mm	T_0/° C	T_m/° C	$t_{8/5}$/s	η
Root pass	140	18	2,16	0,93	150	150	7,5	0,8
Filler pass	220	28	3,33	1,43	150	150	10,5	0,8

According to (7) the calculated minimal and maximal value of heat input is E_{ef} = 0,8 -1,5 kJ/mm. This means that the heat input as well as the cooling time $t_{8/5}$ is within allowed limits. The efficiency level of electric arch is (η = 0,8) according to [11, 18].

The welded plate is cut into segments by means of a mechanical saw with constant cooling. From the segments the specimens for macro analysis and hardness measuring are made. Fig. 5 shows a macro cross section of the RD-test specimen.

The weld is homogeneous with clearly emphasised weld runs and no traces of initial micro cracks. The specimen 1-5 was used to perform the hardness testing along the cross-section at three levels according to Fig. 6. The measured values of hardness are presented in Tab. 6. The hardness values were measured in the base material,

Figure 5 *Macro cross section of RD-test (specimen 1-2)*
Slika 5. *Makropresjek RD - probe (epruveta 1-2)*

Table 6 *Results of measured hardness on specimen 1-5*
Tablica 6. *Rezultati izmjerenih tvrdoća na epruveti 1-5*

Specimen 1-5	Measure point	HV10		
		1	2	3
Base material	1	345	345	345
	2	352	352	345
HAZ Fusion line	3	352	360	360
	4	360	368	360
Weld	5	300	300	300
	6	301	300	290
Fusion line HAZ	7	360	368	360
	8	352	368	345
Base material	9	345	352	360
	10	345	352	345

***Table**7 Welding parameters of tests S 1 and S 2*
***Tablica** 7. Parametri zavarivanja proba S 1 i S 2*

Run	I/A	U/V	v/cm/min	E_{ef}/KJ/mm	$t_{8/5}$/s	T_0/° C	T_m/° C	η
First run	140	18	15	0,80	9	120	120	0,8
Seco. run	220	28	40	0,73	7,5	120	120	0,8

weld and heat affected zone. Based on the obtained results one may conclude that the minimum hardness values are obtained in the weld, and maximal in the heat affected zone.

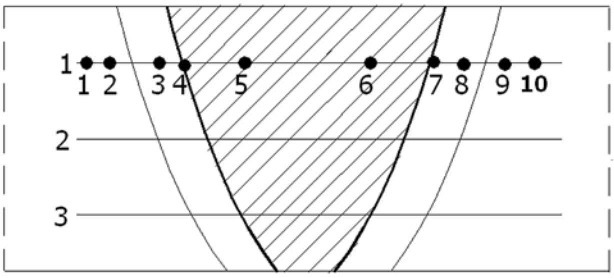

***Figure 6** Points of measuring hardness*
***Slika 6.** Mjesta mjerenja tvrdoća*

RD test was used to check the parameters obtained by the mathematical model. The homogeneous structure without any cracks indicates that strict compliance with and control of the technological process minimizes the risk of the occurrence of cold cracks.

4.2.2 Influence of welding parameters on hardness and impact toughness
Utjecaj parametara zavarivanja na tvrdoću i udarnu radnju loma

In order to determine the influence of welding parameters on the mechanical properties of the welded joint made of S960 QL steel, several samples have been welded with a single-run, double-run and multi-run welds according to Tab. 7. On the plates of dimensions 10×120×300 mm the "V" preparation of the joint was made with opening of 60º. Strict attention was paid to the welding parameters to insure the cooling time $t_{8/5}$ within the mean time limits, so as to avoid the marginal cooling time values. The welding parameters for test probes S1 and S2 are presented in Tab. 7. The calculated pre-heating temperature for the sheet thickness of 10 mm amounted to 120 °C. The welding was performed with wire type ED-FK1000 of Ø1,2 mm diameter.

The heat input for the first run amounted to E_{ef} = 0,80 kJ/mm, and for the second run E_{ef}= 0,73 kJ/mm. Based on the input heat and temperature pre-heating the heat removal model has been determined. In this case it is two-dimensional heat removal, since the calculated marginal value d_{gr} is greater than the test sheet thickness ($d_{gr} > d$). The cooling times $t_{8/5}$ for 2D model of heat conduction are in the range between the bottom and upper values of the experimentally determined cooling time i.e. $t_{8/5}$= 6 to 12 s. After welding the plates were cut into segments with dimensions of 10×10×100 mm which were used to make the specimens for the macro analysis and hardness measurements. The macro cross sections of tests S1 and S2 are presented in Fig. 8.

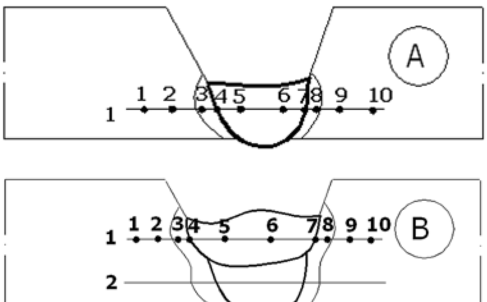

***Figure** 7 Points of measuring hardness*
***Slika** 7. Mjesta mjerenja tvrdoća*

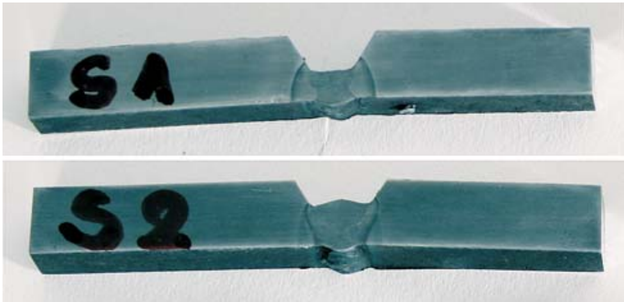

***Figure 8** Macro cross section of tests S1 and S2*
***Slika 8.** Makropresjek proba S1 i S2*

Macro cross section S1 represents single-run, and S2 double-run welding. It is clear that there are no cracks, porosity, inserts, etc. The hardness in the base material, weld and heat affected zone were measured. The measuring points are presented in Fig. 7. Symbol A in Fig. 7 designates

***Table 8** Measured hardness on test S1*
***Tablica 8.** Izmjerene tvrdoće na probi S1*

S1	Meas. point	Hardness HV10
		1
B.M.	1	349
	2	355
HAZ	3	380
Fusion line	4	400
Weld	5	364
	6	370
Fusion line	7	403
HAZ	8	382
B. M.	9	356
	10	356

***Table 9** Measured hardness on test S2*
***Tablica 9.** Izmjerene tvrdoće na probi S2*

S2	Meas. point	Hardness HV10	
		1	2
B.M	1	345	356
	2	356	356
HAZ	3	380	356
Fusion line	4	382	362
Weld	5	361	349
	6	356	334
Fusion line	7	383	369
HAZ	8	373	364
B.M	9	349	345
	10	356	347

Table 10 *Welding parameters of test specimen P3*
Tablica 10. *Parametri zavarivanja probe P3*

P3	I/A	U/V	v/cm/min	E_{ef}/KJ/cm	$t_{8/5}$/s	T_0/° C	T_m/° C	η
Root	140	18	13	0,93	6,53	150	150	0,80
Filling	220	28	20	1,43	10,2	150	150	0,80

the measuring method of hardness in single-run welding and symbol B designates double-run welding.

The calculated value of hardness in the heat affected zone both from the left and the right side of the specimen in single-run welding is approximately 400 HV10. Such hardness values represent the potential risk of the occurrence of cracks in the heat affected zone. This is an indicator that the HAZ structure contains micro-structural constituents which are susceptible to the occurrence of cold cracks. In double-run welding the measured values of hardness in HAZ are lower, and this especially refers to the measured hardness in the cross-section 2 (Fig. 7B), where the hardness value is about 360 HV10, whereas in cross-section 1 (Fig. 7B) higher hardness values of about 380 HV10 were measured. In order to analyze the impact of multi-layer welding which is most represented in practice, and in order to estimate the HAZ properties at low temperatures, an experimental test P_3 on the sheet thickness of 20 mm was made. The dimensions of test after welding were 20×250×300 mm. For this thickness the pre-heating temperature T_0=150 °C was calculated. The test has been welded manually with strict control of parameters T_0, T_m, E_{ef} and $t_{8/5}$. Heat conduction is three-dimensional (3D), since the calculated marginal value is lower than the test plate thickness ($d_{gr}<d$). The welding parameters of the P3 sample are presented in Tab. 10.

"V" preparation of joint was made. The root weld on the test was designed with wire ED- SG3 Ø1,2 mm, and the remaining weld layers were made with wire ED-FK1000 of the same diameter. The welding parameters (I, v, U) are determined so that together with the pre-heating temperature and inter-pass temperature they insure cooling time $t_{8/5}$ within allowed limits from 6,5 to 10,2 s. For the measuring of the impact toughness in HAZ the specimens were prepared according to EN 875 [13]. The impact in HAZ was tested at four temperature levels (+20, 0, –20, –40) °C, and the base material at +20 °C. The results obtained by measuring the impact toughness in HAZ on test P_3 and on the base material are presented in Table 11. Based on the obtained results a graphical presentation of the dependence of the impact toughness of fracture on the testing temperatures was made, Fig. 9.

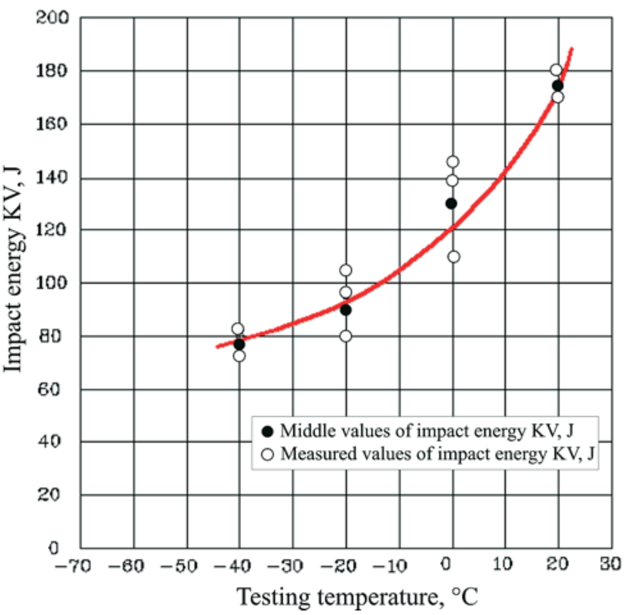

Figure 9 *Graphical presentation of the dependence of the impact toughness on the testing temperature*
Slika 9 *Grafički prikaz ovisnosti udarne radnje loma o temperaturi ispitivanja*

Table 11 *Results of testing the impact toughness*
Tablica 11. *Rezultati ispitivanja udarne radnje loma*

Specimen	KV/J	Charpy Absorbed Energy/ J	Test temperature/ °C
Base material S960 QL steel			
1	185	196	+20
2	210		
3	195		
HAZ - S960 QL steel			
1	173	178	+20
2	180		
3	180		
1	140	131	0
2	110		
3	144		
1	79	93	–20
2	105		
3	95		
1	70	76	–40
2	83		
3	75		

The reduction in test temperatures reduces also the impact energy, Fig. 9. At a low temperature –40 °C also, the heat affected zone showed a high value of impact toughness of 76 J. In order to estimate the macro-structure of the weld and the value of hardness, the test P3-12 macro cross section was made, Fig.10.

Figure 10 *Macro cross section of specimen P 3- 12*
Slika 10. *Makropresjek epruveta P 3-12*

It can be noted that the test P3 was welded with two different welding consumables. The structure is homogeneous without any visible defects. On specimen P3-12 the hardness at three levels according to Fig. 6 has been measured. The hardness was measured in the base material, HAZ and the weld. The measured hardness values are presented in Tab. 12.

The measured hardness values in HAZ are relatively equal to the measured hardness values of the base material. Almost the same hardness values of HAZ and the base material were measured at levels 2 and 3 of the cross section

(Fig. 6), and somewhat greater hardness values were measured at level 1 of the same cross section. The reason lies in the influence of multi-run welding so that the subsequent weld thermally processes the previous weld, as well as the heat affected zone which is formed due to the action of the previous weld. The lowest hardness values have been measured in the weld at all three levels of the cross section. For the better overview of the relation between the measured hardness a graphical presentation of the measured hardness was made based on Tab. 12. The graphical presentation (Fig. 11) clearly shows the arrangement of hardness measured along the specimen cross section. Also the decline in hardness in the weld measured at level 3 (marked black) is emphasised.

Table 12 *Measured hardness values on specimen P3 -12*
Tablica 12. *Izmjerene vrijednosti tvrdoća na epruveti P3 -12*

P 3-12	Meas. point	Hardness HV10		
		1	2	3
B.M.	1	345	356	345
	2	345	345	345
HAZ Fusion line	3	360	364	356
	4	364	356	356
Weld	5	300	290	260
	6	320	290	245
Fusion line HAZ	7	370	356	356
	8	360	345	356
B.M.	9	348	345	345
	10	356	334	345

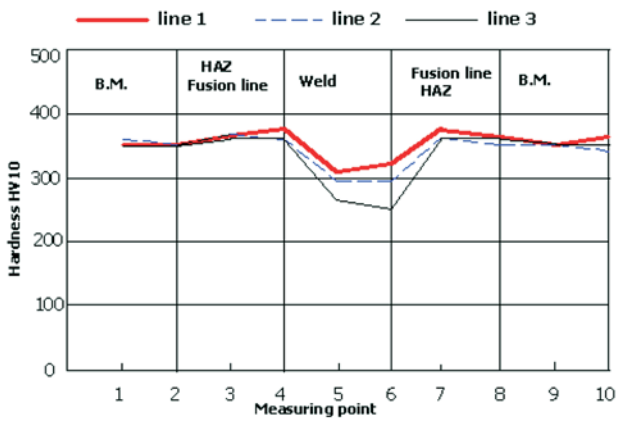

Figure 11 *Graphical presentation of the measured hardness on specimen P3- 12, Table 12*
Slika 11. *Grafički prikaz izmjerenih tvrdoća na epruveti P3-12, Tablica 12*

This is also understandable since the first run was made with a wire which has lower hardness in relation to the wire used to make the final welds. The obtained results of impact toughness and hardness in multi-layer welding have shown the advantages of this technique in relation to the technique of single-layer i.e. single-run welding.

4.2.3 Analysis of results
Analiza rezultata

The estimate of the weldability of micro alloyed high-strength steel of type S960 QL was performed with the application of the mathematical model and experimentally. By inserting concrete data into the mathematical model value P_w= 0,31 was obtained and it was concluded that S960 QL steel is susceptible to the occurrence of cold cracks. The performed RD-test and the welding of additional samples with varying number of runs and welding parameters have shown that with the proper choice of the welding parameters the welds of satisfactory quality can be made, without any defects such as cracks, porosity, etc. This is best proven by the macro cross section of the RD test, Fig. 5. That the welding parameters of RD test have been well determined and controlled during welding, is shown also in the measured hardness values on the specimen of RD - test (Tab. 6). The measured hardness values in HAZ do not differ a lot from the measured hardness of the base material, which shows that there is no occurrence of hard phases in HAZ, which cause the occurrence of cracks. The analysis of the influence of the number of runs on hardness has shown that the measured hardness values in HAZ in a single-run welding (Tab. 8) reach the values of up to 400 HV10. This indicates that in the HAZ microstructure there are hard phases that improve the hardness and consequently also the risk of the occurrence of cold cracks.

In double-run welding the measured hardness values in HAZ (Tab. 9) are lower than in single-run welding. Especially low hardness values of HAZ have been measured along specimen cross section S2 (Fig. 8) at the level of measuring lines 2 (Fig. 7B). These hardness values are almost equal to the hardness values measured on the base material which confirms the positive influence of the subsequent weld on the structure of the weld metal and the heat affected zone formed by the action of the previous weld. This can be seen in the multi-layer welding where the hardness in HAZ was measured along the cross-section of specimen P3-12 (Fig. 10) and does not differ much from the measured hardness of the base material, Tab. 12.

The relatively high values of the impact toughness in HAZ (Tab. 11) have been obtained also at low temperatures of –40 °C where the measured value amounts to 76 J.

5 Conclusion
Zaključak

Based on the performed mathematical and experimental analysis of S960 QL steel weldability from the aspect of cold crack susceptibility and obtaining of satisfactory mechanical properties the following can be concluded:

- The implementation of mathematical models facilitates the selection of welding parameters and reduces the costs of making trial welds and necessary testing. Mathematical methods have been used to prove the proneness of S960 QL steel to the occurrence of cold cracks and the Itto-Bessyo mathematical model was used to calculate adequate temperatures of pre-heating and inter-passes.
- RD test on steel S960 QL proved that it is possible to avoid the occurrence of cold cracks if welding and pre-heating parameters obtained on the basis of the mathematical model are applied.
- The hardness measurement results have shown that the application of multi-run welding with regular heat input acts positively on the HAZ microstructure and metal weld of HAZ and weld metal.
- The measurement of impact toughness has shown that even at low measurement temperatures of –40 ºC with optimal heat input, pre-heating and maintenance of inter-layer temperature obtained by mathematical models high values can be achieved.

The paper has shown that proper selection of welding parameters, as well as their strict compliance may produce steel S960 QL weld joints of satisfactory quality. Good results obtained by measurements of impact toughness and hardness indicate that the welding parameters T_0, T_m, $t_{8/5}$ and E_{ef} defined by the mathematical models assure satisfactory mechanical properties. It should be noted here that in welding S960 QL steel the defined parameters have to be strictly observed since even the smallest deviation may have negative influence on the weld quality.

Based on the factor test plans, in further research an attempt will be made to develop a mathematical model that will use the weld parameters to determine, i.e. forecast the mechanical properties of the weld and the possibility of cold cracks' occurrence. The development of this model would significantly contribute to the understanding of the action of influencing factors on the mechanical properties of the weld and the susceptibility to the occurrence of cold cracks. The model would also significantly facilitate the welding of high-strength steels in practice.

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