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INFLUENCE OF COOLING TIME $\Delta t_{8/5}$ ON WELDED JOINT PROPERTIES OF THE THERMAL CYCLE SIMULATED TStE 420 SPECIMENS

Marko Dunđer, Ivan Samardžić, Štefanija Klarić

Preliminary notes

In this paper the influence of cooling time in temperature interval from 800 to 500 °C ($\Delta t_{8/5}$) on hardness and impact strength of thermal cycle simulated specimens from high strength fine grained steel TStE 420 is explained. Also a research on scanning electron microscope and fractography analysis of characteristic fractures on simulated specimens is performed.

Keywords: *cooling time $\Delta t_{8/5}$, hardness, impact strength*

Utjecaj trajanja hlađenja $\Delta t_{8/5}$ na svojstva zavarenog spoja kod toplinskih simuliranih uzoraka od čelika TStE 420

Prethodno priopćenje

U radu se obrazlaže utjecaj trajanja hlađenja u intervalu od 800 do 500 °C ($\Delta t_{8/5}$) na tvrdoću i udarnu radnju loma kod toplinski simuliranih uzoraka od mikrolegiranog čelika povišene čvrstoće TStE 420. Napravljeno je i ispitivanje na elektronskom scanning mikroskopu, te fraktografska analiza karakterističnih prijeloma simuliranih uzoraka.

Ključne riječi: *vrijeme hlađenja $\Delta t_{8/5}$, tvrdoća, udarna radnja loma*

1 Introduction
Uvod

Continuous demands for expanding the knowledge of production, application, but also exploitation of pressure vessels made from fine grained high strength steel, have indicated the necessity for additional research in the area of weldability of the mentioned steel type in order to improve quality and reliability of the welded products made from this micro-alloyed steel.

For this research, the fine grained high strength steel type TStE 420 is selected, due to the fact that the tank wagons used for storage and transportation of liquefied oil gas for Croatian oil industry are made of this steel. Because there are insufficient data on weldability of this steel, and its behaviour during exploitation, and also having in mind potentially possible failure risks, the need for further research and contribution of the welding parameters has arisen.

For understanding of the numerous problems during the production of pressure vessels from fine grained high strength steels, the research of the temperature fields effect on the welding microstructure transformation (and on mechanical properties of the welded joint) is important. The mentioned effect can be expressed through cooling rate (cooling time) at structure transformation.

2 Definition of the Research Problem
Definiranje problema istraživanja

The influence of the temperature fields on microstructure transformation can be expressed through cooling rate (cooling time) during structure transformation. Cooling rate has effect on heat affected zone structure, and also on mechanical properties, i.e. impact strength and hardness. By selection of the optimal cooling rate the satisfactory relation between hardness and impact strength (the microstructure that is less submissive to development of cold cracks that are specific for this group of steels) can be achieved. Based on previous experience in application of micro alloyed high strength steels, there is a risk of Stress Corrosion Cracking – SCC appearing on pressure vessels that are currently in exploitation. The value of the cooling time $\Delta t_{8/5}$ needs to be determined experimentally and for the critical part of the welded joint. Usually that is a point in heat affected zone that reaches the highest heating temperature – austenitation at approximately 1350 °C. That is the area of over heated structure with large, rapidly cooled grain.

To determine optimal value of $\Delta t_{8/5}$, anisothermic TTT diagrams with austenitation temperature of 1350 °C can be used. The most important is the value of optimal $\Delta t_{8/5}$, but for the fine grained high strength steels it is necessary to know also the low and the high limit $\Delta t_{8/5}$ value. The values that are bellow lower limit value of $\Delta t_{8/5}$ cause too fast cooling and can be a reason for the brittle structure [1]. The values that are over the high limit value of $\Delta t_{8/5}$ cause coarse grain, the decrease of strength and lower ductile-brittle transition temperature. Due to the fact that the recommended value of $\Delta t_{8/5}$ for the steel type TStE 420 is from 8 to 16 s [2], it is necessary to determine the heat input for the mean value $\Delta t_{8/5}$= 12 s as the optimal value and for the low limit ($\Delta t_{8/5}$= 8 s) and the high limit value ($\Delta t_{8/5}$= 16 s). Limit values should be avoided, and welding should be performed with optimal heat input.

2.1 Base metal
Osnovni materijal

For experimental research the micro alloyed high strength steel TStE 420 is selected (this type of steel is used for the production of pressure vessels - tank wagons for the storage and transportation of liquefied oil gas).

Data on chemical composition for this type of steel is given in Table 1, while mechanical properties are shown in Table 2. Below the values of chemical composition and mechanical properties gained from the literature source, in Tables 1 and 2, the values obtained by tests performed as a part of the investigation of the authors of this paper are also shown. In Table 3 the results of impact strength tests at different test temperatures for the mentioned steel type are shown.

Table 1. Chemical composition of the researched steel type
Tablica 1. Kemijski sastav ispitivanog čelika

BASE METAL		CHEMICAL COMPOSITION, %									
		C	Si	Mn	Pmax	Smax	Ni	N	Al	V	Cu
TStE 420	LITERATURE DATA [3]	≤ 0,20	≤ 0,60	1,00-1,70	0,030	0,025	≤ 0,80	0,025	≤ 0,020	≤0,20	≤ 0,07
	MEASURED VALUES	0,18	0,30	1,47	0,017	0,005	0,22	0,016	0,023	0,13	0,02

Table 2. The review of mechanical properties
Tablica 2. Pregled mehaničkih svojstava

BASE METAL		YIELD STRENGTH $R_{p0,2}$, N/mm²	TENSILE STRENGTH R_m, N/mm²	ELONGATION A_5, %	CONTRACTION Z, %	BENDING α = 180°	
						Transverse	Axial
TStE 420	LITERATURE DATA [3]	min. 420	530-680	min. 19	min. 55	2,5a	3,5a
Normalized state	MEASURED VALUES	422	577	30	61,9	+	+

Table 3. Minimum impact strength KV
Tablica 3. Minimalna udarna radnja loma KV

BASE METAL		ROLLING DIRECTION	IMPACT STRENGTH *KV*, J					
			TEMPERATURE, °C					
			20	0	-20	-40	-50	-60
TStE 420	LITERATURE DATA [3]	transverse	63	55	47	34	27	-
		axial	40	34	27	20	16	-
	MEASURED VALUES [6]	Laboratory result - transverse	261	257	245	182	55	-

2.2 Hardness tests on simulated specimens
Ispitivanje tvrdoće na simuliranim uzorcima

Often, welded joint hardness data are not given as complete information that welding expert could use with sufficient reliability for further weldability analysis and estimation of welded joint behaviour in exploitation. Hardness of welded joint and hardness of the base metal could be observed from the statistical theory of samples point of view, which means that final measurement hardness result can have any value from the given basic set of hardness value. Dissipation of hardness measured values is larger at welded joint than in base metal, due to the fact that welded joint consists of weld metal and heat affected zone, and these zones consist of individual areas.

On real samples of welded joint it is not always possible to measure hardness in all the areas and on sufficient number of samples, so that measuring of hardness is often performed on simulated specimens.

In Figure 1 the schematic review of the hardness measurement method on simulated samples is shown.

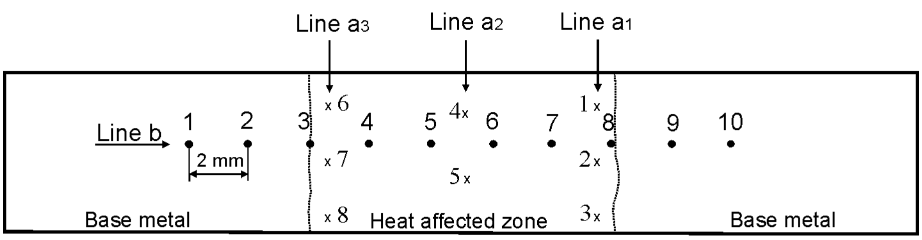

Fig. 1. Hardness test on contour (line a_1, a_2, a_3) and cross section (line b) of the thermal cycle simulated specimen
Slika 1. Mjerenje tvrdoće po konturi (niz a_1, a_2, a_3) i presjeku (niz b) toplinski simuliranog uzorka

2.3 Impact strength tests on simulated specimens
Ispitivanje udarne radnje loma na simuliranim uzorcima

The determination of the impact strength in welded joint heat affected zone is one of the disputable mechanical tests that are performed on welded constructions. Problems related to determination of impact strength in heat affected zone are mostly related to the fact that welded joint with base metal represents a heterogeneous unit, in which every part has its own mechanical properties. There are many different methods with various loading conditions and also various methods of the fracture assessment for the investigation of the impact strength. Anyhow, these methods differ mostly according to the shape and dimensions of the test specimens, but the difference in the shape and dimensions of the notch itself is also important. Beside the expended energy for the fracture of the test specimens, there is also another criterion, and that is the appearance of the fracture surface.

It is observed that the expended energy for the fracture of the test specimen is lower with reduction of the temperature. Further investigations have shown that this is connected with the material property to transit to brittle state at temperatures lower than certain temperature. That temperature is called ductile-brittle transition temperature. As the criteria of transition to brittle state, the value of the energy or the appearance of the fracture surface (specific amount of grained fracture appearance as an indicator of the brittle fracture) is considered.

The adopted criterion for the brittle state transition according to the literature source [4] is energy of 27,5 J.

2.3.1 Charpy – V impact tests
Ispitivanje udarne radnje loma Charpy-V metodom

This test is used for assessment of material toughness, i.e. the property of material to break with higher or lower plastic deformation.

Usually, during welding there is no problem to achieve the required value of the weld strength, but the achievement of uniform toughness in the heat affected zone is a much harder task.

For steel types with good weldability the toughness of the heat affected zone can be the same as the guaranteed toughness of the base metal. The lower toughness values can be a problem during welding of steel with higher carbon content and on high strength steel types. Limiting the heat input, application of preheating or by post-welding heat treatment, can solve this problem.

The reduction of the toughness in the heat affected zone is usually the consequence of the "transformation hardening". It appears, first of all, due to microstructure transformations during heating and cooling of the welded joint. The nature of these transformations depends on chemical composition of the steel, maximal temperature of the observed welded joint critical point and the cooling rate expressed through cooling time between temperatures of 800 to 500 °C ($\Delta t_{8/5}$).

The notch placement has a crucial influence on the toughness test results in the heat affected zone, so it is necessary to carefully consider the structure of the heat affected zone regarding the type of the welded steel, and precisely determine the placement of the notch during toughness measurement of the heat affected zone. The precondition for obtaining the fracture energy in heat affected zone is covering of the clearly defined structure area.

3 Plan of Experiment
Plan pokusa

For the simulator tests the specimens (probes) are prepared from the base metal (with thickness 15 mm) by cutting on dimensions 57x11x11 mm.

There were a large number of specimens during experimental research, so the following marking scheme is used:

S – Specimens simulated on simulator of thermal cycle type Smitweld.

The first number on the specimen mark represents the temperature of the toughness test.

1 – room temperature (20 °C)
2 - temperature of 0 °C
3 - temperature of -20 °C
4 - temperature of -40 °C
5 - temperature of -60 °C

The second number represents cooling time from 800 to 500 °C ($\Delta t_{8/5}$).

0 - cooling time $\Delta t_{8/5}$ = 5 s
1 - cooling time $\Delta t_{8/5}$ = 10 s
2 - cooling time $\Delta t_{8/5}$ = 25 s
3 - cooling time $\Delta t_{8/5}$ = 50 s

The last number stands for the number of the specimen.

3.1 Simulation of the Welding Thermal Cycle
Simuliranje toplinskog ciklusa zavarivanja

In Figures 2 and 3 the thermal cycle simulator TCS 1405 Smitweld is presented in which the heating and cooling of test probes is performed. The simulation of the thermal cycle is conducted in the shielding gas atmosphere (argon).

This test is often used for examination of the base metal weldability, because the costs of examination are lower than other methods of weldability examination, and the influence of a greater number of variables can be reviewed.

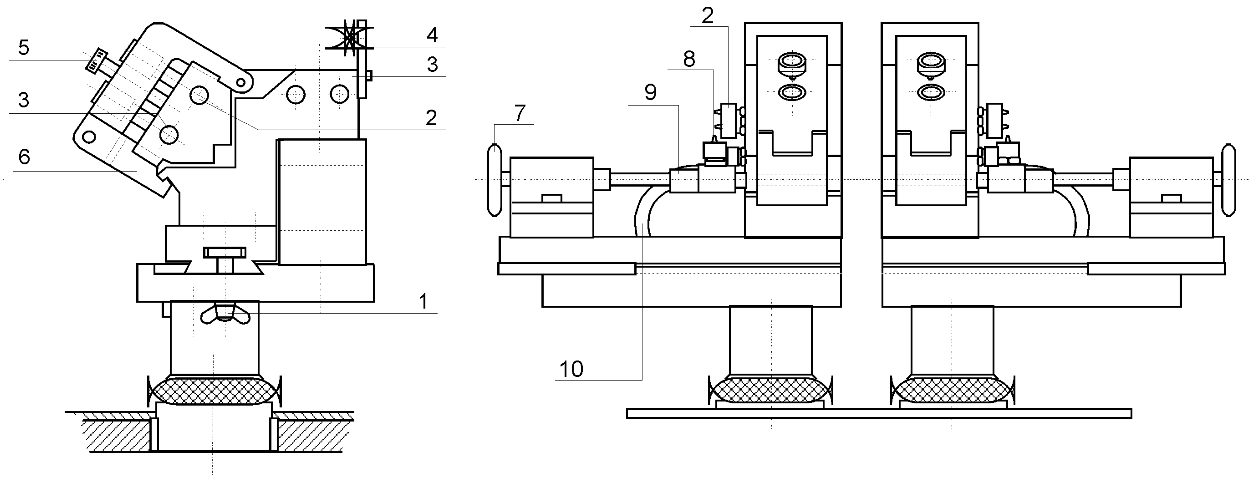

Fig. 2. Execution unit of simulator of thermal cycle type Smitweld TCS 1405 [5]
(Where: 1 - Base screw with bolt, 2 - Pipe connectors for indirect cooling, 3 - Water flow canals for indirect cooling, 4 - Dilatometer porter and temperature sensor, 5 - Base screw for jaws, 6 - Jaw block for fixation, 7 - Contraction screw for direct cooling application, 8 - Pipe connectors for direct cooling, 9 - Direct cooling block and 10 - Current cable)
Slika 2. Izvršna jedinica simulatora toplinskog kruga tipa Smitweld TCS 1405 [5]
(Gdje je: 1 – temeljni vijak s maticom, 2 – priključci za cijevi za indirektno hlađenje, 3 – kanali za protok vode za indirektno hlađenje, 4 – nosač dilatometra i mjerača temperature, 5 – temeljni vijak za čeljusti, 6 – blok čeljusti za učvršćenje, 7 - vijak za stezanje kod primjene direktnog hlađenja, 8 - priključci za cijevi za direktno hlađenje, 9 - blok za direktno hlađenje i 10 – kabel za struju)

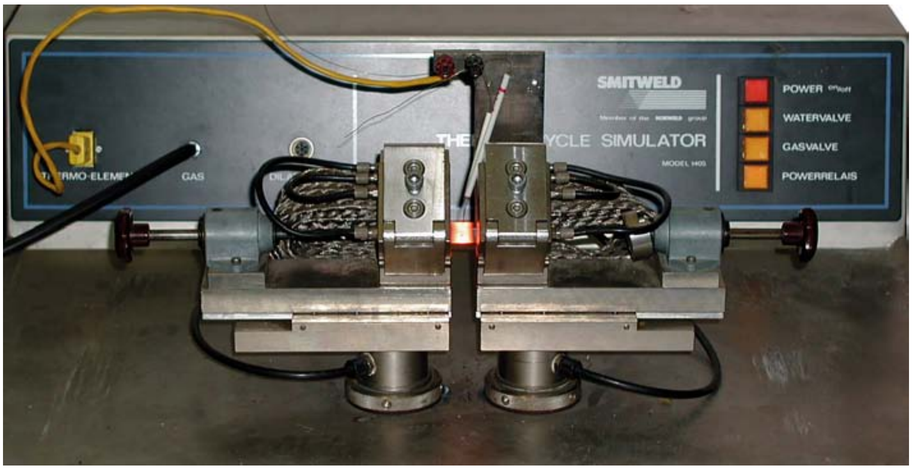

Fig. 3. Detail of simulation of test probe on simulator of thermal cycle type Smitweld TCS 1405
Slika 3. Simulacija toplinskog ciklusa na uređaju TCS 1405 Smitweld

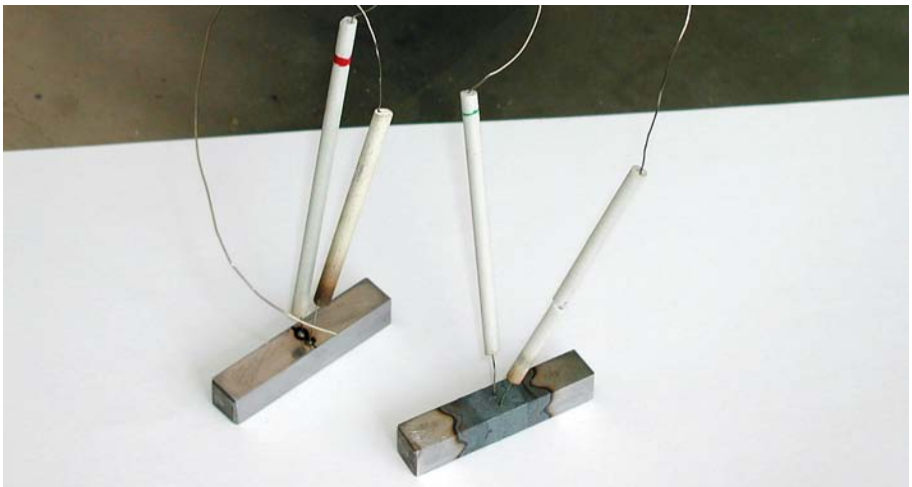

Fig 4. Test probe before examination and after welding thermal cycle simulating
Slika 4. Epruveta za ispitivanje prije i nakon simuliranja toplinskog ciklusa zavarivanja

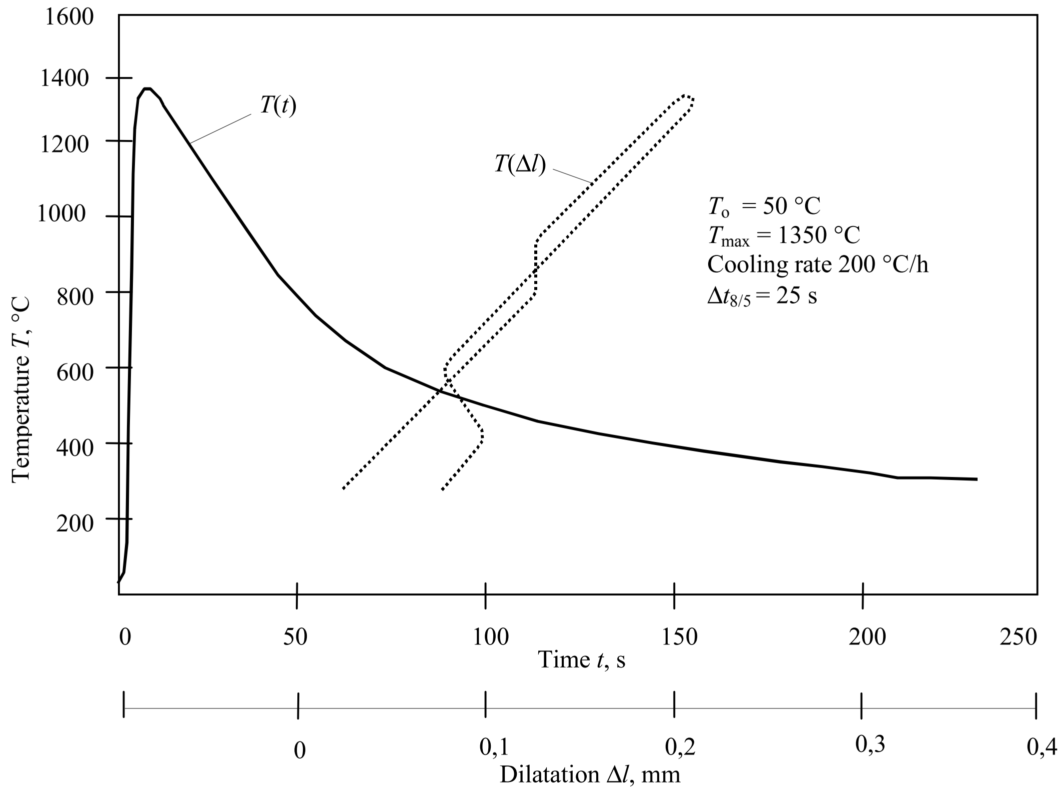

Fig 5. Single pass welding thermal cycle simulation diagram – transition of the temperature and dilatation during simulation cycle
Slika 5. Dijagram jednoprolazne simulacije toplinskog ciklusa zavarivanja – promjena temperature i dilatacije tijekom trajanja ciklusa simulacije

Table 4. Welding thermal cycle simulating parameters (without keeping at austenitation temperature)
Tablica 4. Parametri simuliranja zavarivačkog toplinskog ciklusa bez držanja uzorka na temperaturi austenitizacije

NUMBER	TEST MARK	T_{max}, °C	$\Delta t_{8/5}$, s	T_z, °C	NUMBER	TEST MARK	T_{max}, °C	$\Delta t_{8/5}$, s	T_z, °C
1	S 101	1341	5	< 130	41	S 121	1354	25,6	< 150
2	S 102	1344	5,2	< 130	42	S 122	1355	25,4	< 150
3	S 103	1351	5	< 130	43	S 123	1355	25	< 150
4	S 104	1344	4,8	< 130	44	S 124	1354	25,4	< 150
5	S 201	1343	5,2	< 135	45	S 221	1358	25,6	< 145
6	S 202	1340	5	< 135	46	S 222	1358	25,5	< 145
7	S 203	1351	5	< 135	47	S 223	1368	25,6	< 145
8	S 204	1339	5	< 135	48	S 224	1355	25,6	< 145
9	S 301	1344	5	< 135	49	S 321	1363	25,6	< 145
10	S 302	1349	5	< 135	50	S 322	1374	25,6	< 145
11	S 303	1349	5,1	< 135	51	S 323	1369	25,1	< 145
12	S 304	1367	5	< 135	52	S 324	1357	25,6	< 145
13	S 401	1341	4,9	< 137	53	S 421	1357	25,6	< 145
14	S 402	1352	5	< 137	54	S 422	1353	25,6	< 145
15	S 403	1348	5	< 137	55	S 423	1358	25,6	< 145
16	S 404	1342	5	< 137	56	S 424	1356	25,3	< 145
17	S 501	1349	5,1	< 137	57	S 521	1360	25,6	< 125
18	S 502	1348	4,9	< 137	58	S 522	1380	25,6	< 143
19	S 503	1349	5	< 137	59	S 523	1381	25,8	< 131
20	S 504	1351	5	< 137	60	S 524	1379	25,7	< 143
21	S 111	1363	10	< 137	61	S 131	1350	51,2	< 160
22	S 112	1360	9,9	< 137	62	S 132	1355	50,8	< 160
23	S 113	1358	10	< 137	63	S 133	1351	50,8	< 160
24	S 114	1363	10,1	< 137	64	S 134	1350	50,7	< 160
25	S 211	1363	10,1	< 137	65	S 231	1357	51	< 160
26	S 212	1359	9,6	< 137	66	S 232	1355	51,4	< 160
27	S 213	1370	10,2	< 137	67	S 233	1352	50,8	< 160
28	S 214	1365	10,1	< 137	68	S 234	1351	50,6	< 160
29	S 311	1371	9,6	< 135	69	S 331	1356	51	< 160
30	S 312	1378	9,6	< 135	70	S 332	1352	51	< 160
31	S 313	1361	9,7	< 135	71	S 333	1352	51	< 160

Table 4. Welding thermal cycle simulating parameters (without keeping at austenitation temperature)(continuation)
Tablica 4. Parametri simuliranja zavarivačkog toplinskog ciklusa bez držanja uzorka na temperaturi austenitizacije (nastavak)

NUMBER	TEST MARK	T_{max}, °C	$\Delta t_{8/5}$, s	T_z, °C	NUMBER	TEST MARK	T_{max}, °C	$\Delta t_{8/5}$, s	T_z, °C
32	S 314	1360	9,8	< 135	72	S 334	1351	51	< 160
33	S 411	1371	10,2	< 135	73	S 431	1352	51	< 160
34	S 412	1371	10,2	< 135	74	S 432	1351	51,2	< 160
35	S 413	1357	10	< 135	75	S 433	1360	50,8	< 160
36	S 414	1355	10,1	< 137	76	S 434	1355	50,7	< 160
37	S 511	1355	10,2	< 135	77	S 531	1351	51	< 156
38	S 512	1355	10,2	< 135	78	S 532	1351	51	< 156
39	S 513	1359	9,9	< 136	79	S 533	1352	50,9	< 156
40	S 514	1359	9,9	< 136	80	S 534	1352	50,9	< 156

Table 5. Results of hardness tests on specimens (one pass simulation T_{max} ≈1350 °C – according to figure 1 (line a)-contour method
Tablica 5. Izmjerene tvrdoće uzoraka (jednostruko simuliranje T_{max} ≈1350 °C - prema slici 1 (niz a) – konturna metoda

TEST MARK	Hardness HV 10								
	Measurement								
	1	2	3	4	5	6	7	8	Middle value of hardness
S 101 ($\Delta t_{8/5}$ = 5 s)	380	381	367	393	**401**	369	361	359	376
S 102 ($\Delta t_{8/5}$ =5,2 s)	373	361	363	388	**391**	365	355	354	369
S 103 ($\Delta t_{8/5}$ = 5 s)	375	377	369	388	394	366	353	356	372
S 111 ($\Delta t_{8/5}$ = 10 s)	348	346	343	389	391	343	341	339	357
S 112 ($\Delta t_{8/5}$ = 9,9 s)	340	339	334	380	378	334	333	331	346
S 113 ($\Delta t_{8/5}$ = 10 s)	328	329	340	382	388	353	343	342	351
S 121 ($\Delta t_{8/5}$ = 25,6 s)	279	283	281	300	302	287	280	284	287
S 122 ($\Delta t_{8/5}$ = 25,4 s)	281	285	285	299	**306**	283	281	281	288
S 123 ($\Delta t_{8/5}$ = 25 s)	279	280	283	300	303	280	281	279	286
S 131 ($\Delta t_{8/5}$ = 51,2 s)	245	247	253	**270**	269	243	249	241	252
S 132 ($\Delta t_{8/5}$ = 50,8 s)	249	244	250	256	258	245	244	248	249
S 133 ($\Delta t_{8/5}$ = 50,8 s)	243	247	250	259	261	244	247	249	250

4 Test Results
Rezultati ispitivanja

4.1 Results of hardness tests on simulated specimens
Rezultati ispitivanja tvrdoće simuliranih uzoraka

The measurement of hardness is conducted by contour method according to Figure 1 (line a_1, a_2, a_3), and also, hardness is measured through cross section of the specimen as it is shown in Figure 1 (line b).

Results of hardness measurements are shown in Tables 5 and 6 and diagrams in Figures 6 and 7.

The values in Table 5 show that increase of cooling time $\Delta t_{8/5}$ results in decrease of hardness.

Maximal values of hardness in heat affected zone are 401 HV at cooling time $\Delta t_{8/5}$= 5 s, 391 HV at cooling time $\Delta t_{8/5}$= 10 s, 306 HV at cooling time $\Delta t_{8/5}$= 25 s and 270 HV at $\Delta t_{8/5}$= 50 s.

Dependence of measured hardness *HV* 10 middle values of (values shown in Table 5) on cooling time $\Delta t_{8/5}$ is shown in Figure 6.

Maximal values of hardness are expected in the area of maximal temperature of thermal cycle simulated specimen (these are locations of the thermoelement placement for temperature recording during heating cycle and cooling of specimens). These are locations of measurement marked with numbers 5 and 6 in Table 6. Middle values of hardness values on locations 5 and 6 for individual samples and cooling time $\Delta t_{8/5}$ are shown in Figure 7.

The values of hardness shown in Table 6 indicate that by increase of cooling time $\Delta t_{8/5}$ the hardness decreases. Maximal values of hardness are 417 HV at cooling time $\Delta t_{8/5}$= 5 s, 394 HV at cooling time $\Delta t_{8/5}$= 10 s, 313 HV at cooling time $\Delta t_{8/5}$= 25 s and around 263 HV at cooling time $\Delta t_{8/5}$= 50 s.

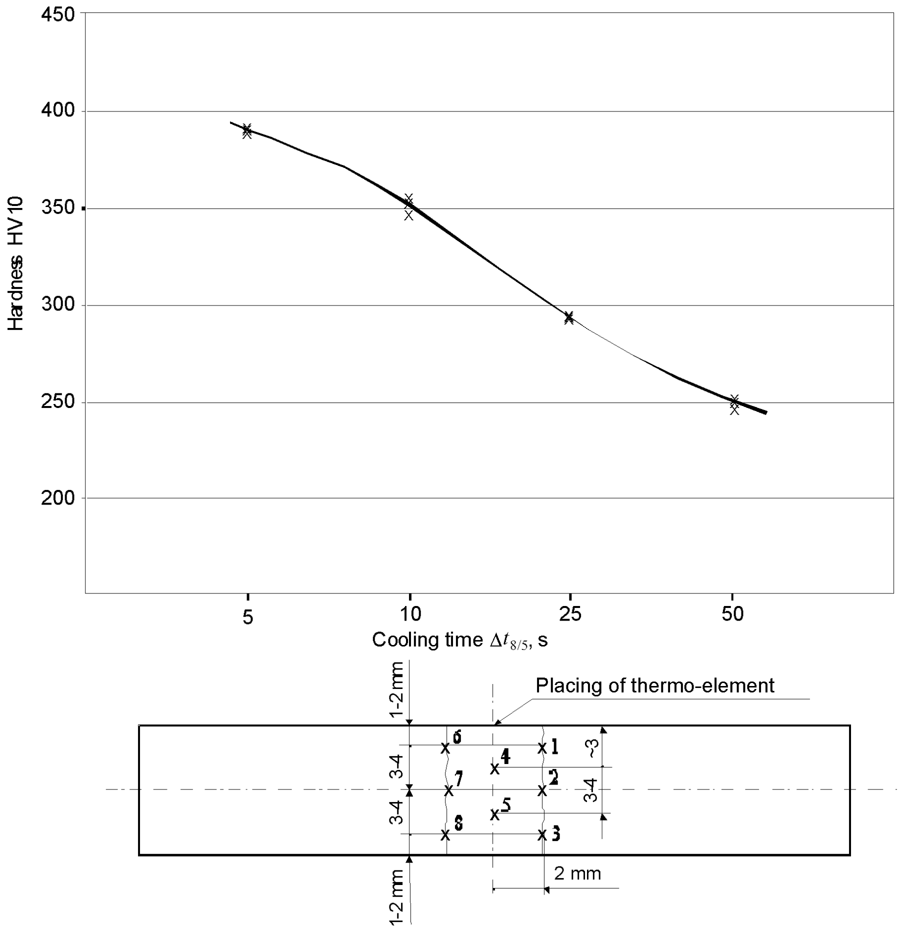

Fig. 6. Relation between middle values of hardness and cooling time 800 to 500 °C ($\Delta t_{8/5}$) – measurement of hardness by contour method
Slika 6. Ovisnost tvrdoće o trajanju hlađenja 800 do 500 °C ($\Delta t_{8/5}$) – mjerenje tvrdoće konturnom metodom

Table 6. Results of hardness tests on specimens (one pass simulation T_{max} ≈1350°C – according to Figure 1 (line b)-cross section method of hardness measurement)
Tablica 6. Izmjerene tvrdoće uzoraka (jednostruko simuliranje T_{max} ≈1350 °C - prema slici 1 – (niz b) – tvrdoće mjerene po presjeku)

OZNAKA PROBE	Hardness HV 10									
	MEASUREMENT									
Measurement location	1	2	3	4	**5**	**6**	7	8	9	10
Distance, mm	2	4	6	8	**10**	**12**	14	16	18	20
S 501 ($\Delta t_{8/5}$ = 5,1 s)	183	179	312	367	**390**	**397**	345	297	179	179
S 502 ($\Delta t_{8/5}$= 4,9 s)	181	182	303	355	**393**	**401**	358	305	181	183
S 503 ($\Delta t_{8/5}$ = 5 s)	180	178	308	351	**398**	**417**	349	310	180	178
S 511 ($\Delta t_{8/5}$ = 10,2 s)	177	177	253	343	**383**	**376**	341	279	183	181
S 512 ($\Delta t_{8/5}$ = 10,2 s)	181	183	249	331	**380**	**394**	342	266	179	183
S 513 ($\Delta t_{8/5}$ = 9,9 s)	180	179	260	339	**388**	**391**	335	259	183	180
S 521 ($\Delta t_{8/5}$ = 25,6 s)	179	179	221	264	**312**	**306**	254	230	179	179
S 522 ($\Delta t_{8/5}$ = 25,6 s)	180	178	229	271	**308**	**313**	259	233	183	180
S 523 ($\Delta t_{8/5}$ = 25,8 s)	178	177	231	279	**302**	**300**	263	227	177	180
S 531 ($\Delta t_{8/5}$ = 51 s)	179	183	221	244	**251**	**255**	236	221	177	177
S 532 ($\Delta t_{8/5}$ = 51 s)	183	180	225	247	**259**	**261**	243	223	181	183
S 533 ($\Delta t_{8/5}$ = 50,9 s)	177	180	219	241	**261**	**263**	239	220	180	179

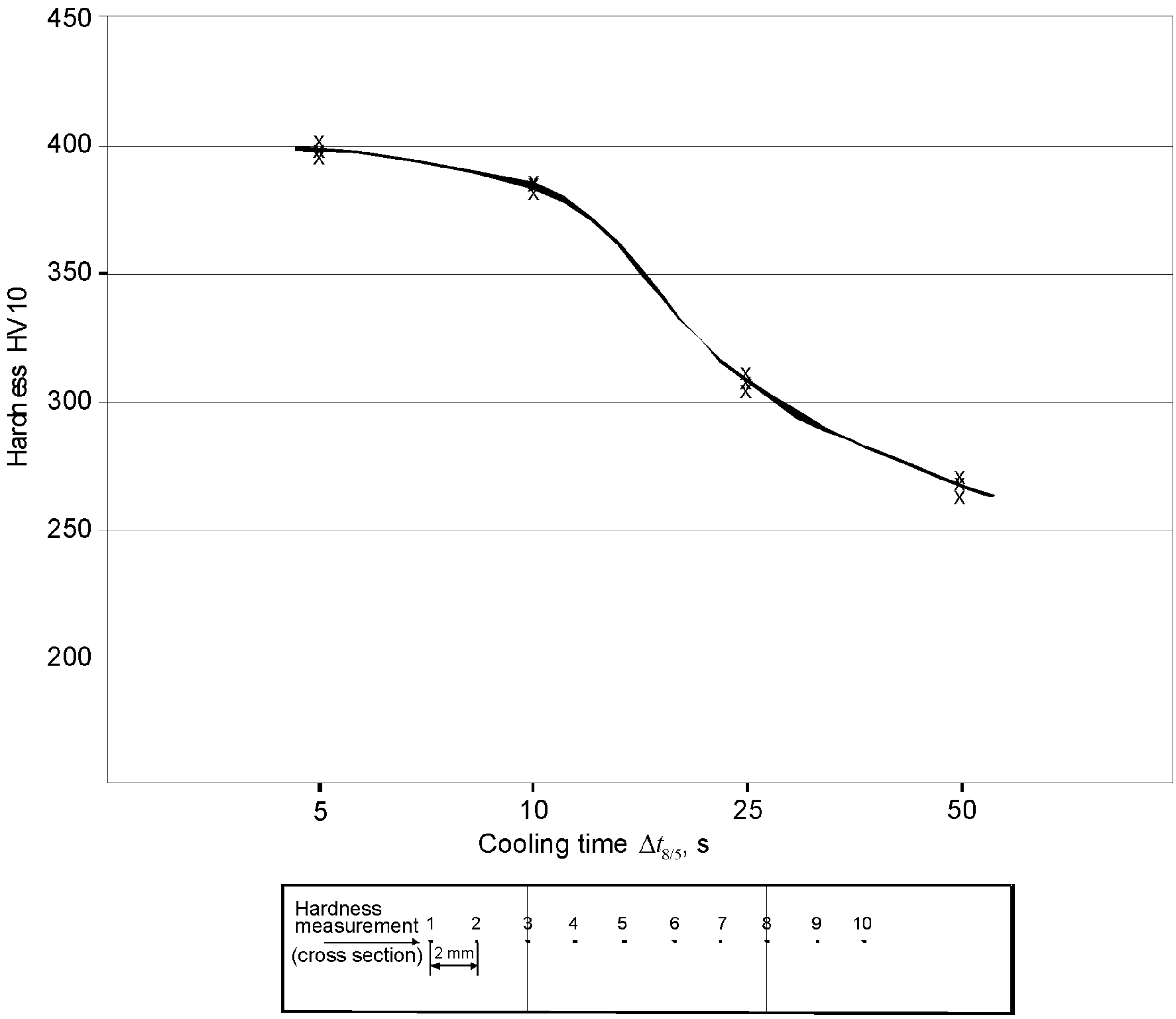

Fig. 7. Relation of maximal hardness arithmetic values and cooling time from 800 to 500 °C ($\Delta t_{8/5}$) – measurements of hardness on cross section (arithmetic value of maximal hardness is calculated from individual values from measurement locations 5 and 6 for every sample and individual cooling time)

Slika 7. Ovisnost aritmetičkih vrijednosti maksimalnih tvrdoća o trajanju hlađenja 800 do 500 °C ($\Delta t_{8/5}$) – mjerenje tvrdoće po presjeku (aritmetička vrijednost maksimalne tvrdoće izračunavala se od pojedinačnih vrijednosti na lokaciji mjerenja 5 i 6 za svaki uzorak i pojedino trajanje hlađenja)

4.2 Results of impact strength tests on simulated specimens

Rezultati ispitivanja udarne radnje loma simuliranih uzoraka

Impact strength on simulated specimens was tested by the Charpy method, at temperatures 20 °C; 0 °C; -20 °C; -40 °C and -60 °C. The results of impact strength tests for simulated samples are shown in Table 7.

Relation between impact strength and cooling time $\Delta t_{8/5}$ at thermal cycle simulated specimens is shown in Figure 8. Temperatures of impact strength measurement are also pointed out in the same figure.

It can be noticed from the figure that impact strengths are lower at lower test temperatures, what is in compliance with expectations. At all test temperatures the decrease of impact strength with increase of cooling time $\Delta t_{8/5}$, is noticed as a result of structural transformations during welding thermal cycle simulation. During the specimens' simulation at high temperatures and by keeping the specimens at these temperatures, in heat affected zone, there is a grain growth and coagulation of the precipitant. This phenomenon causes a decrease of toughness, especially at lower temperatures, which explains the decrease of toughness shown by curves (temperature 20, 0, -20 and –40 °C – Figure 8) [6].

Table 7. Values of the impact strength obtained by testing the simulated specimens at different temperatures
Tablica 7. Vrijednosti udarne radnje loma dobivene pri ispitivanju simuliranih uzoraka na različitim temperaturama

Number	Test mark	$\Delta t_{8/5}$, s	K_V, J	Test temperature, °C
1	S 101	5	59	20
2	S 102	5	58	20
3	S 103	5	61	20
4	S 104	5	56	20
5	S 201	5	49	0
6	S 202	5	47	0
7	S 203	5	45	0
8	S 204	5	52	0
9	S 301	5	38	-20
10	S 302	5	37	-20
11	S 303	5	41	-20
12	S 304	5	49	-20
13	S 401	5	36	-40
14	S 402	5	33,5	-40
15	S 403	5	32	-40
16	S 404	5	35	-40
17	S 501	5	14	-60
18	S 502	5	18	-60
19	S 503	5	15	-60
20	S 504	5	13	-60
21	S 111	10	57	20
22	S 112	10	48	20
23	S 113	10	52	20
24	S 114	10	55	20
25	S 211	10	47	0
26	S 212	10	45	0
27	S 213	10	49	0
28	S 214	10	46,5	0
29	S 311	10	36	-20
30	S 312	10	40	-20
31	S 313	10	44	-20
32	S 314	10	39	-20
33	S 411	10	32	-40
34	S 412	10	34	-40
35	S 413	10	30	-40
36	S 414	10	32	-40
37	S 511	10	16	-60
38	S 512	10	13	-60
39	S 513	10	15	-60
40	S 514	10	12	-60
41	S 121	25	42	20
42	S 122	25	46	20
43	S 123	25	45	20
44	S 124	25	43,5	20
45	S 221	25	35	0
46	S 222	25	32	0
47	S 223	25	30	0
48	S 224	25	29,5	0
49	S 321	25	24	-20
50	S 322	25	22	-20
51	S 323	25	25	-20
52	S 324	25	23	-20
53	S 421	25	18	-40
54	S 422	25	20	-40
55	S 423	25	19	-40
56	S 424	25	21	-40
57	S 521	25	10	-60
58	S 522	25	11	-60
59	S 523	25	9	-60
60	S 524	25	12,5	-60
61	S 131	50	35	20
62	S 132	50	32	20
63	S 133	50	37	20
64	S 134	50	36	20
65	S 231	50	26	0
66	S 232	50	28	0
67	S 233	50	25	0
68	S 234	50	27,5	0
69	S 331	50	17	-20
70	S 332	50	19	-20
71	S 333	50	21	-20
72	S 334	50	20	-20
73	S 431	50	10	-40
74	S 432	50	8	-40
75	S 433	50	8	-40
76	S 434	50	9	-40
77	S 531	50	6	-60
78	S 532	50	5	-60
79	S 533	50	4,5	-60
80	S 534	50	6	-60

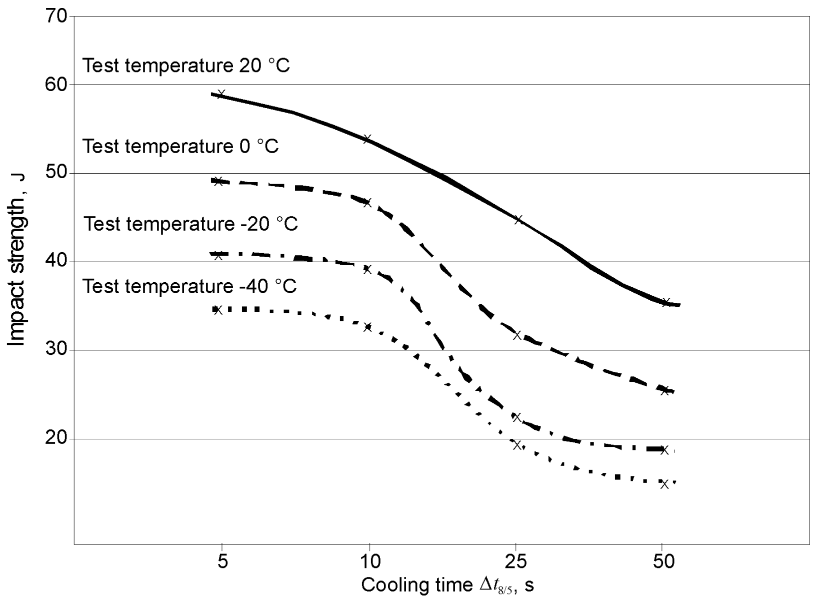

Fig. 8. Relation of impact strength and cooling time $\Delta t_{8/5}$ on simulated specimens
Slika 8. Ovisnost udarne radnje loma od trajanju hlađenja $\Delta t_{8/5}$ simuliranih uzoraka

4.3 Results of research on scanning electron microscope
Rezultati ispitivanja na elektronskom mikroskopu

Due to the fact that research of impact strength has shown that increase of cooling time results in decrease of impact toughness, the overview and analysis of characteristic specimens on scanning electron microscope was performed. Altogether, six specimens were scanned on electron microscope type "Quanta 200" ("FEI", SAD) with magnification of 50 000 times. During these tests there was a vacuum in the test chamber of 5 x 10^{-3} Pa.

Characteristics of specimens analysed on scanning electron microscope are shown in Table 8.

Two characteristic fracture surfaces of specimens selected from Table 8 are shown in Figure 9.

Table 8. Characteristics of simulated specimens scanned on electron microscope
Tablica 8. Prikaz karakteristika skeniranih simuliranih uzoraka na elektronskom mikroskopu

Test mark	S101	S301	S111	S311	S121	S321
KV, J	59,0	38,0	57,0	36,0	42,0	24,0
$\Delta t_{8/5}$, s	5	5	10	9,6	25,6	25,6
Test temperature	20 °C	- 20 °C	20 °C	-20 °C	20 °C	-20 °C
Fracture type	ductile	brittle	ductile	brittle	2/3 ductile	brittle

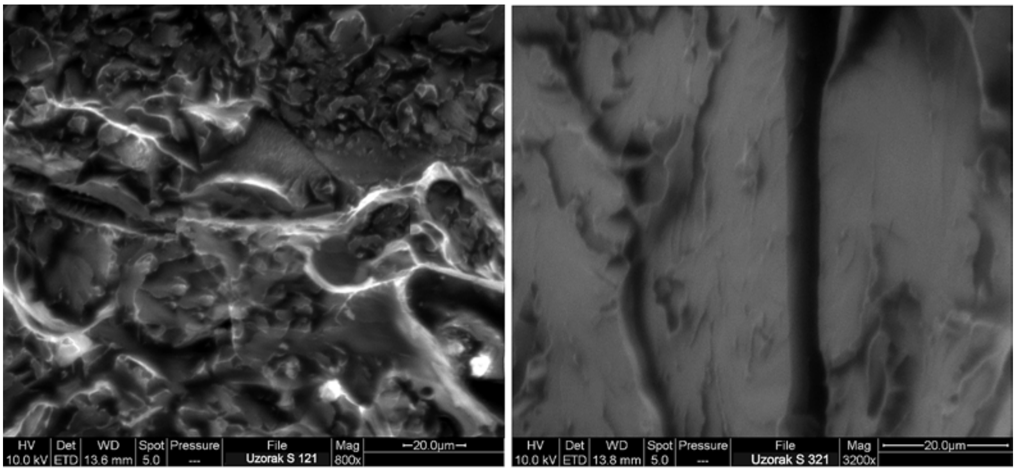

Fig. 9. Fracture surfaces of specimens S121 and S321
Slika 9. Prijelomne površine uzorka S121 i S321

5 Conclusion
Zaključak

Experimental research of hardness and impact strength on thermal cycle simulated specimens (steel type TstE 420) has shown clear relationship of hardness and impact strength and cooling time in temperature interval from 800 to 500 °C. Due to the fact that there is one pass thermal cycle simulation (test probes were subjected to one thermal cycle of heating and cooling), the comparison of these samples and real one pass welded joints is possible. Similar approach could be applied at multi pass welding, where hardness and impact strength values could be compared for multi pass thermal cycle simulated samples.

This research was limited to investigation of hardness and impact strength distribution of one pass thermal cycle simulated specimens which in indirect manner reproduce the image of structure and properties of individual areas in heat affected zone. The analysis of characteristic fracture surface was performed by scanning electron microscope. The next step in these researches will be the analysis of real one pass and multi pass welding, and comparison of properties and structures of real welded joint with structures of one pass and multi pass thermal cycle simulated specimens. Relevant weldablity data for this type of steel can be gained this way, and also, there is a need for acceleration and reduction of extensive and expensive weldability research on real welded joints.

6 Literature
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Author's Address (Adresa autora):

Dr. sc. Marko Dunđer
HOLDINA d.o.o. Sarajevo, BiH

Prof. dr. sc. Ivan Samardžić
University of Osijek
Mechanical Engineering Faculty
Trg I. B. Mazuranic 2
35000 Slavonski Brod, Croatia
E-mail: isamar@sfsb.hr

Mr. sc. Štefanija Klarić
University of Osijek
Mechanical Engineering Faculty
Trg I. B. Mazuranic 2
35000 Slavonski Brod, Croatia
E-mail: Stefanija.Klaric@sfsb.hr