CODEN STJSAO
ZX470/1434

ISSN 0562-1887
UDK 621.791.4:539.42:669.14.018.292

Weldability Investigation of TStE 420 After Weld Thermal Cycle Simulation

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Keywords

Hardness
HSLA steel
Weldability
Weld thermal cycle simulation

Ključne riječi

HSLA čelik
Simulacija toplinskog ciklusa zavarenog spoja
Tvrdoća
Zavarljivost

Received (primljeno): 2009-09-01
Accepted (prihvaćeno): 2010-02-19

Original scientific paper

The paper presents a short description and overview of the weld thermal cycle simulation methods. An experimental investigation on the weld cycle simulated specimens is predicted by a plan of experiment using single cycle simulation. The obtained hardness results are compared with double cycle simulated specimens results of individual points in the heat-affected zone. Beside that, the characteristic microstructures of points in the heat-affected zone after a single weld thermal cycle simulation are given. A thermal simulation method is suitable for different weldability examinations. In this paper, the authors would like to investigate the maximal hardness of individual points in the weld joint what is important when considering cold cracking sensitivity.

Ispitivanje zavarljivosti čelika TStE 420 nakon simulacije toplinskog ciklusa zavarivanja

Izvornoznanstveni članak

U radu se daje kratak opis i pregled metoda simulacije toplinskog ciklusa zavarivanja. Planom eksperimenta je predviđeno eksperimentalno istraživanje na toplinski cikliranim uzorcima. Mjerenjem dobiveni rezultati tvrdoće nakon jednostruke simulacije toplinskog ciklusa u zoni utjecaja topline su uspoređeni s rezultatima nakon dvostruke simulacije toplinskog ciklusa. Pored toga, u radu su prikazane karakteristične mikrostrukture pojedinih točaka u zoni utjecaja topline nakon jednostruke simulacije toplinskog ciklusa zavarivanja. Simulacija toplinskog ciklusa je prikladna za različita ispitivanja zavarljivosti, a u ovom su radu autori željeli istražiti maksimalno očekivane tvrdoće pojedinih točaka u zoni utjecaja topline što je važno kod razmatranja osjetljivosti prema hladnim pukotinama.

1. Introduction

The investigations on the weld thermal cycle simulators can enable the complex determination and prediction of weld joint sensitivity to cold cracks in the heat-affected zone (HAZ). At individual laboratory methods which require real welding of different weld groves and different geometry, the influence of the factors on weldability of the base material is evident. These methods give information about particular crack sensitivity and for complex weldability investigation it is necessary to use more experimental methods. The inadequacy of these investigations is deviation and scattering of the weld cycle simulation parameters compared to the real welding parameters. At the thermal weld cycle simulation, the peak temperature of the weld cycle is lower than the maximal temperature in the HAZ. It is practically very close to the fusion line. Beside the mentioned inadequacy, the previous long time experience has shown the possibility of reliable prediction of mechanical properties in the HAZ of the weldments.

2. Weld thermal cycle simulation

In the last several years, the weld thermal cycle simulation has been used for the weldability investigations regarding the existence of different microstructure types

Symbols/Oznake

HV	– hardness – tvrdoća	T	– time, s – vrijeme
T	– temperature, °C – temperatura	$t_{8/5}$	– cooling time from 800 to 500 °C – vrijeme hlađenja od 800 do 500 °C

and detailed investigations of the HAZ which is very complex from the microstructure standpoint, as well as the heterogeneous structure. At investigations in the HAZ of the real weldments, it is not easy and sometimes it is not possible to obtain the appropriate specimens for very narrow locations inside the HAZ. At the weld thermal cycle simulations, it is possible to produce every individual point in the HAZ. In this way, it is possible to consider different problems and questions regarding the behaviour of the base metal during the heating and cooling at welding. By the thermal simulation, it is possible to realise sufficient wide range of homogenous and repeatable microstructures. Therefore, in that way, it is possible to apply the easy examination procedures, which are commonly used..

However, due to relatively small specimen dimensions at thermal simulation investigations, it is not possible to include the residual stresses which follow the real welding. Beside that, the absence of hydrogen monitoring during simulations can significantly change the estimation of weldability in the HAZ.

Some modern simulation equipment gives the possibility of thermal cycling with hydrogen and metal interaction monitoring.

2.1. Types of weld thermal cycle simulators

The investigators who studied the problems of weld thermal cycle simulations, have developed several simulator models appropriate for the simulation of welding thermal cycle. They are different in shape and specimen dimensions, in heating and cooling mode, in mode of hydrogen and metal interaction monitoring and some other parameters.[2]

The simulations are performed on the equipment which is suitable for the commonly used methods for mechanical and other properties examinations. The power sources are made on electro resistant and electro induction principles that facilitate enough and controlled heat input during heating. The available heat power source is sufficient for very fast heating which is equal to

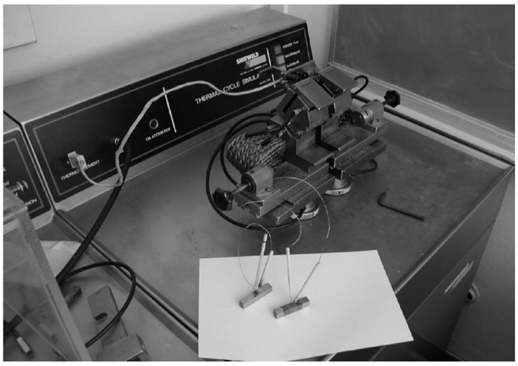


Figure 1. Gleeble (a) [3] and Smitweld (b) weld thermal cycle simulators

Slika 1. Gleeble (a) [3] i Smitweld (b) simulatori toplinskog ciklusa zavarivanja

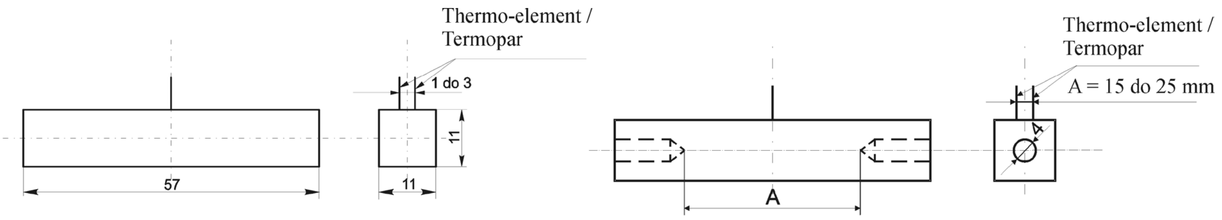


Figure 2. The dimensions of thermal cycle specimens according to Smitweld TCS 1405 method, in the case of indirect cooling (a) and in the case of indirect and additional direct cooling of specimen by water (b) [4]

Slika 2. Dimenzije uzoraka za simulaciju toplinskog ciklusa po metodi Smitweld TCS 1405, u slučaju indirektnog hlađenja (a), te indirektnog i dodatnog direktnog hlađenja uzorka vodom (b) [4] that at the real arc welding processes. By thermal cycling methods, it is possible to produce TTT (Temperature – Time – Transformation) diagrams which are useful to use at heat treatment procedures, as well as for the prediction of arc welding parameters. Most commonly used thermal cycling methods are Gleeble, Thermorestor and Smitweld (Figure 1).

2.2. Specimens for weld thermal cycle simulations

Figures 2. to 4. show the dimensions of specimens for thermal cycle simulation according to three most popular thermal cycle simulation methods.

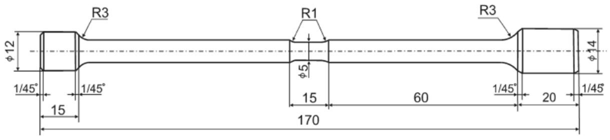


Figure 3. The dimensions of thermal cycle specimens according to Thermorestor-W method [4]

Slika 3. Dimenzije uzorka za simulaciju toplinskog ciklusa po metodi Thermorestor-W [4]

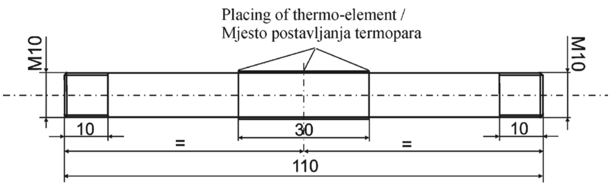


Figure 4. The specimen for weld thermal cycle simulation by Gleeble method [5]

Slika 4. Uzorak za simulaciju toplinskog ciklusa zavarivanja po Gleeble metodi [5]

2.3. Single and double weld thermal cycle simulations

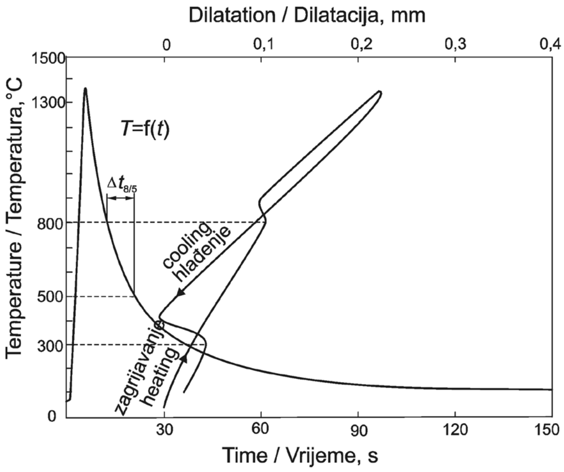
Usually, at single weld thermal cycle simulations, the thermal cycles with peak temperature between 1200 and 1350 °C are acceptable and desirable. It is possible to use single (Figure 5a) and double (Figure 5b) or multipass welding cycling and in this way to produce individual points in the HAZ of the weldment. After that, it is possible to perform mechanical (hardness and toughness testing, tensile testing, etc.) or metallurgical examinations.

At double thermal cycling, it is determined that high thermal cycle with low peak temperature (< 500 °C) had no influence on the microstructure of the following cycle. Therefore, it can be neglected.

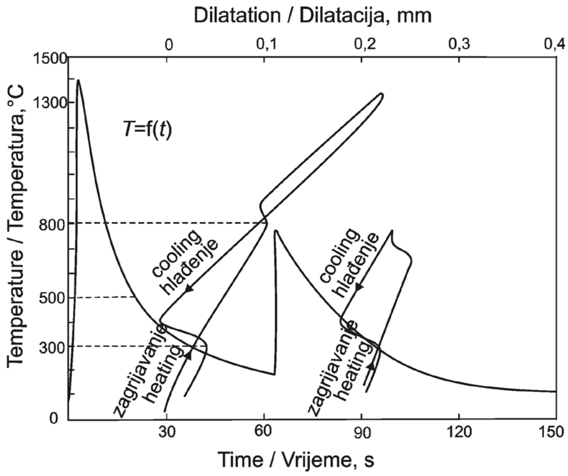
3. Plan of experiment

The comparison of single and double weld thermal cycle simulation of specimens is performed by the experimental investigation. In Table 1 and Figure 6, the plan of experiment of the single weld thermal cycle simulation is given. The heating rate to peak thermal cycle temperature was 200 °C/s. After 3 s at peak temperature, the cooling follows, see diagrams $T = \mathrm{f}(t)$. Single cycle peak temperatures were 600, 700, 780, 960, 1100 and 1300 °C.

Double thermal cycle simulation is performed on the specimens after the first simulation with peak temperature 1360 °C. The heating rate to peak temperature was 200 °C/s, stopping at peak temperature was for 3 sec., and then the second cycle with peak temperatures 600, 700, 780, 960, 1100 and 1350 °C follows. The following activities are hardness measurement, examination of microstructure and other mechanical properties of simulated specimens.



a)



b)

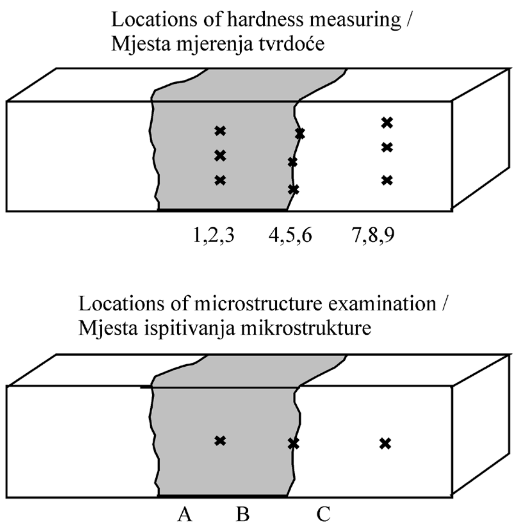
Figure 5. Single (a) and double (b) weld thermal cycle simulation; temperature-time and temperature-dilatation relationships.

Slika 5. Jednostruka (a) i dvostruka (b) simulacija toplinskog ciklusa zavarivanja: temperatura-vrijeme i temperatura-dilatacija međuovisnosti.

Table 1. Plan of experiment – single weld thermal cycle simulation

Tablica 1. Plan eksperimenta – jednostruka simulacija toplinskog ciklus azavarivanja

Specimen / Uzorak	Thermal cycle peak temperature, °C / Maksimalna temperatura toplinskog ciklusa
1.1	1300
1.2	1300
1.3	1300
2.1	1100
2.2	1100
2.3	1100
3.1	960
3.2	960
3.3	960
4.1	780
4.2	780
4.3	780
5.1	700
5.2	700
5.3	700
6.1	600
6.2	600
6.3	600



3.1. Results of experimental investigation

An example of thermal cycle simulation of specimen on Smitweld simulator is given in Figure 7. The single and double thermal cycle simulated specimens are shown in Figure 8. $T = (t)$ diagrams for each single cycled specimen is given in Figure 9.

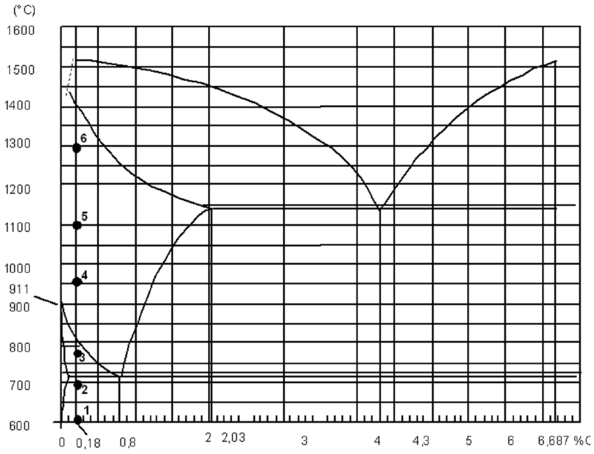


Figure 6. Fe_3-C diagram with points in the HAZ (Heat-affected zone) which will be obtained by thermal simulation

Slika 6. Fe_3-C dijagram s točkama u ZUT (Zona utjecaja topline) koje će se dobiti toplinskom simulacijom

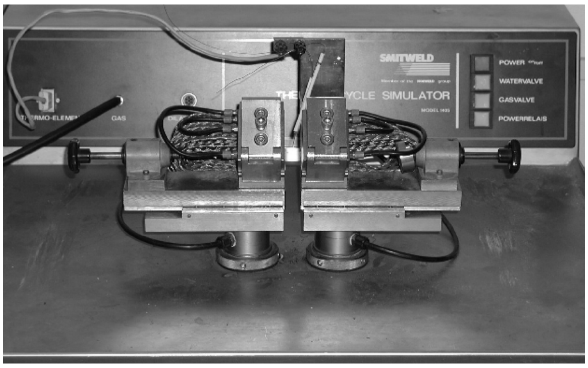


Figure 7. Smitweld thermal cycle simulator in application

Slika 7. Smitweld simulator toplinskog ciklusa u primjeni

a) b)

Figure 8. Single thermal cycled (a) and double cycled (b) specimens at different peak temperatures in the HAZ

Slika 8. Jednostruko ciklirani (a) i dvostruko ciklirani (b) uzorci sa različitim maksimalnim temperaturama u ZUT

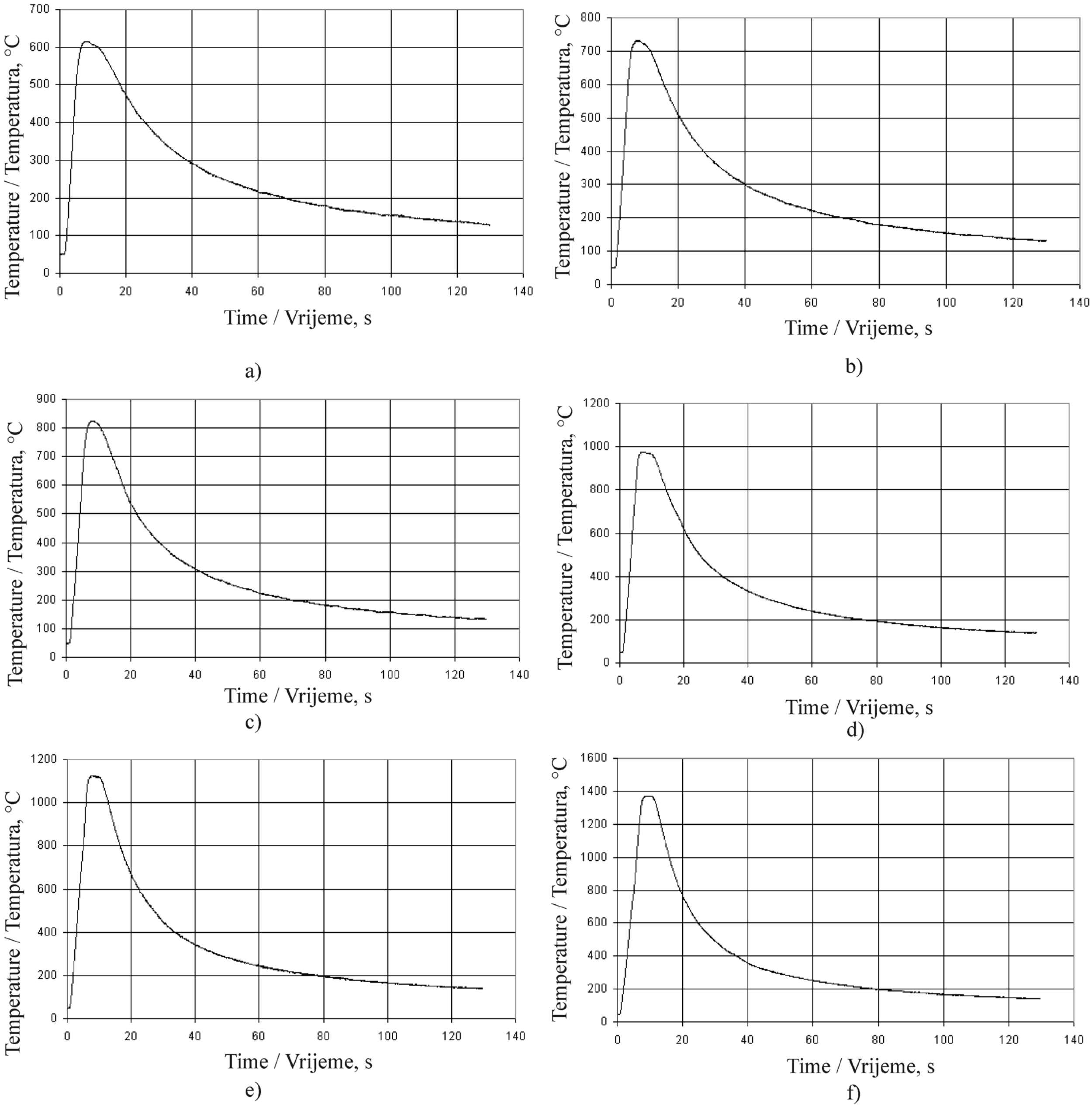


Figure 9. Diagrams T=f(t) for single cycle thermal simulated specimens with peak temperature: 600 °C (a), 700 °C (b), 780 °C (c), 960 °C (d), 1100 °C (e) and 1300 °C (f).

Slika 9. Dijagrami T=f(t) za jednostruko ciklirane uzorke s maksimalnim temperaturama: 600 °C (a), 700 °C (b), 780 °C (c), 960 °C (d), 1100 °C (e) i 1300 °C (f).

3.2. Hardness measurements

After the preparation of specimens for the microstructure analysis and taking pictures with a digital camera, the measurements of hardness were performed. On each specimen, hardness was measured in the middle of the specimen. The results of the provided measurements are shown in Table 2.

It is clear from the table that with peak temperature increase, after cooling the hardness also increases. It can be explained with the structure change due to heating and cooling. The hardness results after double thermal cycle simulation are given in Figure 10.

Table 2. Hardness values after single weld thermal cycle simulations (locations of measurements available on sketch in Table 1)

Tablica 2. Vrijednosti tvrdoće nakon jednostruke simuacije toplinskog ciklus azavarivanja (lokacije mjerenja dostupne na skici u tablici 1)

Measuring location and hardness Hv1 / Mjerena lokacija i tvrdoća										
Specimen / Uzorak	Thermal cycle peak temperature / Maksimalna temperatura toplinskog ciklusa, °C	1	2	3	4	5	6	7	8	9
1	1300	330	373	363	413	353	363	185	195	197
2	1300	330	330	358	217	263	251	263	266	283
3	1300	348	378	363	272	330	358	193	263	212
4	1100	330	330	334	330	248	254	199	201	219
5	1100	330	339	330	339	330	251	185	185	224
6	1100	330	330	330	234	276	286	201	210	214
7	960	297	293	297	254	260	269	210	208	201
8	960	263	254	248	217	195	219	182	185	178
9	960	234	272	269	217	214	221	197	193	191
10	780	212	229	219	234	237	239	239	257	254
11	780	203	217	214	195	185	205	195	195	193
12	780	203	205	199	210	221	205	185	185	175
13	700	191	185	185	185	212	171	185	185	175
14	700	210	195	193	195	201	201	201	189	199
15	700	195	193	199	313	269	263	205	203	214
16	600	199	201	205	229	212	205	195	199	199
17	600	212	212	214	199	208	205	201	201	203
18	600	212	217	219	210	208	217	201	219	210

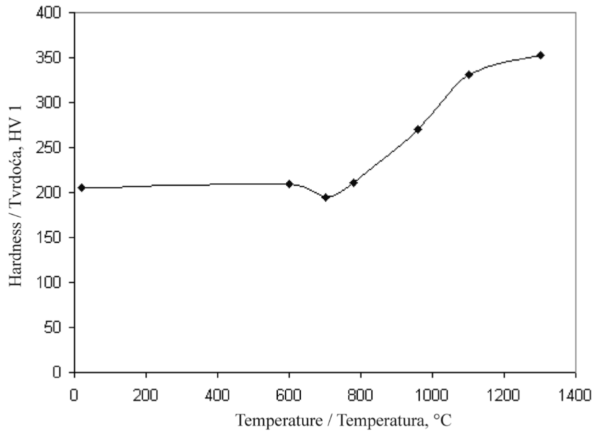


Figure 10. Hardness distribution HV 1 (mean values, n=9) in relationship to peak thermal cycle temperature after single thermal cycle simulation

Slika 10. Distribucija tvrdoće HV 1 (srednje vrijednosti, n=9) ovisno o maksimalnoj temperaturi toplinskog ciklusa nakon jednostruke toplinske simulacije

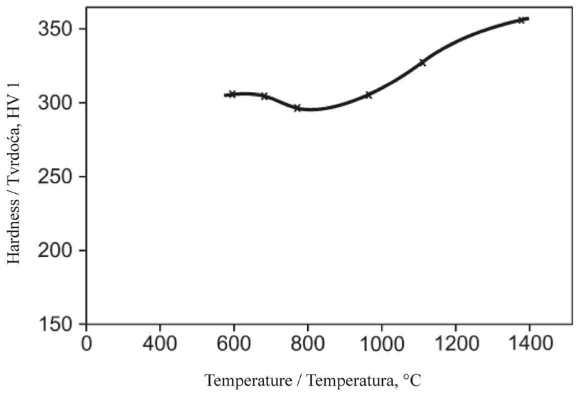
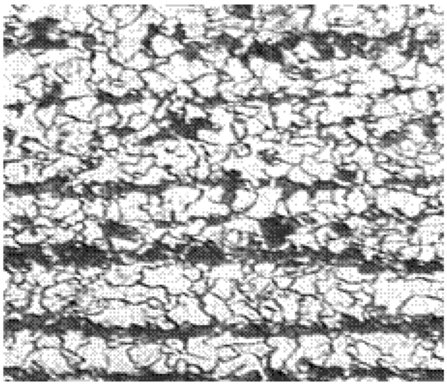


Figure 11. Hardness distribution HV 10 (mean values, n=5) in relationship to peak thermal cycle temperature after second thermal cycle simulation. (Peak temperature of the first cycle was 1350 °C, stopping at peak temperature was for 3 s).

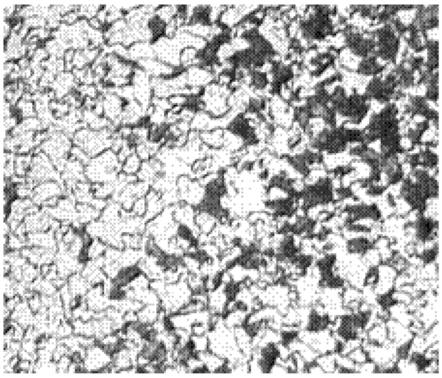
Slika 11. Vrijednosti tvrdoće HV10 (srednje vrijednosti, n=5) ovisno o maksimalnoj temperaturi nakon druge simulacije toplinskog ciklusa. (Vršna temperatura kod prvog toplinskog ciklusa je bila 1350 °C, uz zadržavanje od 3 s)

3.3. Microstructure in the HAZ after single cycle simulation

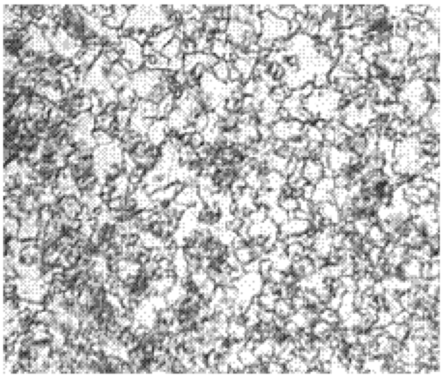
The microstructures of single weld thermal cycle simulation show the influence of the peak temperature and the location of individual points in Fe3C diagram. It is reflected on hardness, as well as on other mechanical properties. Higher peak temperature means higher hardness and sensitivity to cold cracks. That effect is more visible in the microstructure of the specimen with the highest peak temperature (1300 °C).



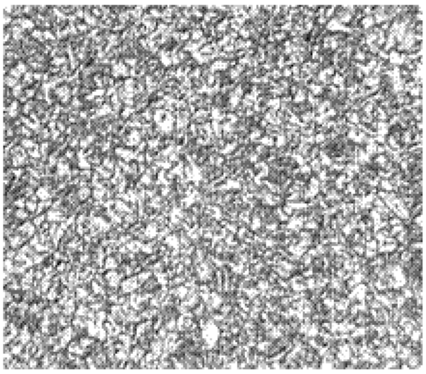
Max. thermal cycle temperature / Maksimalna temperatura toplinskog ciklusa, 600 °C



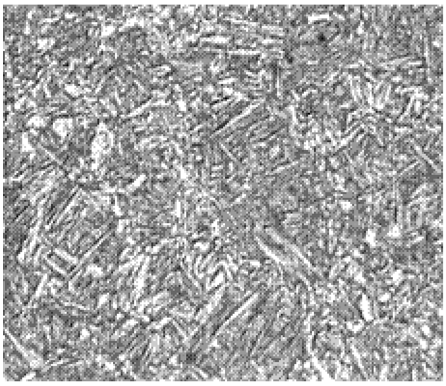
Max. thermal cycle temperature / Maksimalna temperatura toplinskog ciklusa, 700 °C



Max. thermal cycle temperature / Maksimalna temperatura toplinskog ciklusa, 780 °C



Max. thermal cycle temperature / Maksimalna temperatura toplinskog ciklusa, 960 °C



Max. thermal cycle temperature / Maksimalna temperatura toplinskog ciklusa, 1100 °C

Max. thermal cycle temperature / Maksimalna temperatura toplinskog ciklusa, 1350 °C

Figure 12. Microstructures of peak thermal simulated specimens points: 600 °C (a), 700 °C (b), 780 °C (c), 960 °C (d), 1100 °C (e) and 1300 °C (f)

Slika 12. Mikrostruktura točaka s maksimalnim temperaturama toplinskog ciklusa: 600 °C (a), 700 °C (b), 780 °C (c), 960 °C (d), 1100 °C (e) i 1300 °C (f)

3.4. Impact toughness measurements

Impact toughness according to Charpy – V method is measured on the test specimens on which the simulation of double weld thermal cycle for different max. cycle temperature is performed. The obtained results of impact toughness are given in Table 3.

Table 3. Impact toughness results on the test probes after double thermal cycle at different peak cycle temperatures of the second cycle. (Peak temperature of the first cycle was 1350 °C, stopping at peak temperature was for 3 s).

Table 3. Udarne žilavosti na dvostruko cikliranim uzorcima, na različitim maksimalnim temepraturama drugog ciklus. (Vršna temperatura kod prvog toplinskog ciklusa je bila 1350 °C, uz zadržavanje od 3 s).

Temperature / Temperatura, ° C	Test probe number / Ispitni uzorak	Impact toughness values / Udarna žilavost, J
600	1	47
	2	48
	3	40
700	1	39
	2	62
	3	43
780	1	93
	2	136
	3	119
960	1	53
	2	51
	3	50
1110	1	35
	2	35
	3	32
1350	1	22
	2	22
	3	20

4. Conclusions

The obtained hardness and microstructures of the single and double thermal cycled specimens showed the influence of heating and cooling parameters on the individual points in the HAZ. By the thermal cycling, it is possible to produce the critical points in the HAZ and to find the appropriate cooling rate in order to obtain the optimal mechanical and other properties of critical points in the HAZ. By the additional real welding, it is possible to confirm these results easier and faster than without the thermal cycling. The performed investigations on high strength steel TStE 420 show that it is weldable if the cooling rate and the cooling time are properly selected ($t_{8/5}$ = 10 s). Maximal hardness values at single and double thermal cycling are relatively close for the cooling time $t_{8/5}$ = 10 s. The higher hardness values mean higher sensitivity to cold cracks during welding and this investigation shows that we can expect maximal hardness values in the HAZ less than 400 HV for the selected cooling time $t_{8/5}$ = 10 s. But the problem, which we did not expect, is toughness weakening in the points closer to the fusion line (higher temperatures than 1110 5 °C). Therefore, it is necessary to investigate that problem in the future investigations.

Acknowledgments

The presented results derive from a scientific research project (Advanced joining technology in light mechanical constructions No. 152-1521473-1476) supported by the Croatian Ministry of Science, Education and Sports.

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