M. DUNĐER, S. ARAČIĆ, I. SAMARDŽIĆ

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IMPACT ENERGY ANALYSIS OF HSLA SPECIMENS AFTER SIMULATED WELDING THERMAL CYCLE

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This paper presents impact energy results of specimens made from high strength fine grained steel TStE 420 after thermal cycle simulation. These results are obtained by examining Charpy specimens. Metallographic analysis is performed, hardness is measured and total impact energy is divided into ductile and brittle components.

Key words: HSLA, Welding thermal cycle, Impact energy, Cooling time $\Delta t8/5$

Analize udarne radnje loma toplinski simuliranih uzoraka HSLA. U radu su prikazani rezultati udarne radnje loma toplinski simuliranih uzoraka mikrolegiranog čelika povišene čvrstoće TStE 420 dobiveni eksperimentalnim ispitivanjem Charpy epruveta. Izvršena je metalografska analiza, mjerene su tvrdoće i ukupna energija udara razdvojena je na duktilnu i krhku komponentu.

Ključne riječi: mikrolegirani čelici povišene čvrstoće, toplinski ciklus zavarivanja, udarni rad loma, vrijeme hlađenja $\Delta t_{8/5}$

INTRODUCTION

In the technically advanced world there has always been a tendency to create lighter bearing constructions in order to achieve different advantages like lower production costs, energetic efficiency in exploitation of light mobile constructions (i.e. components of rail & road vehicles, cranes, marine vessels etc.), better anti-corrosive properties, reduction of environment pollution, better quality, safety and reliability of product, etc. The development and production of HSLA (High Strength Low Alloy Steel) have, together with achievements concerning their properties, opened up new ways of their application. In particular, oil industry demands and the global increase of oil consumption have influenced the development of pressure vessels, rail wagons and tanks. With broader use of HSLA, the first problems appeared. One of the most serious problems was stress corrosion damage [1]. HSLA TStE 420 was intentionally selected for this examination, since it is the material recently chosen for the construction of rail tanks that are used for transportation and storage of liquidized oil gas needed for Croatian oil processing industry.

DEFINITION OF THE RESEARCH PROBLEM

Studies dealing with the influence of thermic fields on mechanical properties of HSLA welds, as well as preliminary tests carried out on the thermal cycle simulator at the Welding Laboratory at the Mechanical Engineering Faculty in Maribor, have shown that insufficient insight exists as to the effect of cooling speed or cooling time from 800^{o} to 500^{o} C ($\Delta t_{8/5}$) on hardness and toughness of HSLA type TStE 420. Special emphasis is put on the effect of cooling speed on hardness and toughness of one-pass welds performed on this material. The cooling time $\Delta t_{8/5}$ needs to be established experimentally for the weakest zone of the welded joint – the part of the Heat Affected Zone (HAZ) closest to the melting border. An optimal $\Delta t_{8/5}$ value is crucial, but for HSLA steel the minimum and maximum limit value also need to be known. Any value below minimal usually implies too fast cooling and can cause brittle structure [2,3]. Values above maximal will cause too big grain size and strength decrease. Since for TStE 420 $\Delta t_{8/5}$= 8 to 12 s [4] is recommended, the optimal heat immission for $\Delta t_{8/5}$= 10s must be determined, while 8s will serve as minimum and 12s as maximum value. Marginal values should be avoided and an optimal heat immision at welding should be used.

Impact energy testing has been carried out on Charpy testing machine, type Rpk 300, „Amsler“, at the Faculty of Mechanical Engineering in Maribor. For the simulator testing, the specimens (55x11x11mm) have been prepared (1mm has been added because of corrosion during thermal cycle simulation on the specimens without Ar-gas protection). The specimens have been cut in the direction of base material rolling. Each plate used to make specimens was pre-checked for fibre alignment. Base material thickness was 15 mm.

M. Dunđer, Holdina d.o.o. Sarajevo, Bosnia and Herzegovina, S. Aračić, I. Samardžić, University of Osijek, Faculty of Mechanical Engineering Slavonski Brod, Croatia.

Table 1. **Chemical composition and mechanical properties of HSLA TStE 420.**

Steel	Chemical composition in mass %;									
	C	*Si*	*Mn*	*P*	*S*	*Ni*	*N*	*Al*	*V*	*Cu*
TStE 420	0,18	0,3	1,47	0,017	0,005	0,22	0,016	0,023	0,13	0,02
	Mechanical properties at standard room temperature									
	Yield Strength $R_{p0,2}$, MPa		Tensile Strength R_m, MPa		Elongation A_5, %		Contraction Z, %		Bending α=180 °	
									Longit.	Trans.
	422		577		30		61,9		+	+
	Impact energy, K_V in J at 20°C, -20°C and -40°C, longitudinally									
	40J, 27J and 20J according to data [5], testing results: 261J, 245J and 182J									

Simulation of the welding thermal cycle

For heating and cooling of specimens, the Thermal Cycle Simulator TCS 1405 Smitweld was used (figure 1,2,3). The specimens were heated by electrical resistance. At $\Delta t_{8/5}$= 5, 10, 25 and 50 s, induced heat was conveyed indirectly, by means of water-cooled jaws. At shortest cooling time, $\Delta t_{8/5}$= 5 s, the accumulated heat had to be conveyed even faster, so the test tubes were longitudinally drilled in advance for direct water circulation cooling. Ni–CrNi thermocouple has been attached in the middle of each test specimen.

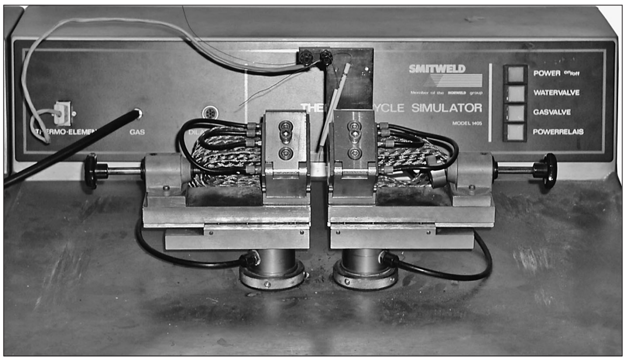

Figure 1. Smitweld TCS 1405 thermal cycle simulator during the welding thermal cycle simulation.

The thermal cycle simulation on the specimens has been performed without maintaining maximal temperature in order to prevent austenitisation. The cooling regime was determined by required cooling speed. Table 2 shows all simulation data (maximal cycle temperature T_{max}, cooling time $\Delta t_{8/5}$ between 800 and 500°C and final temperature T_z).

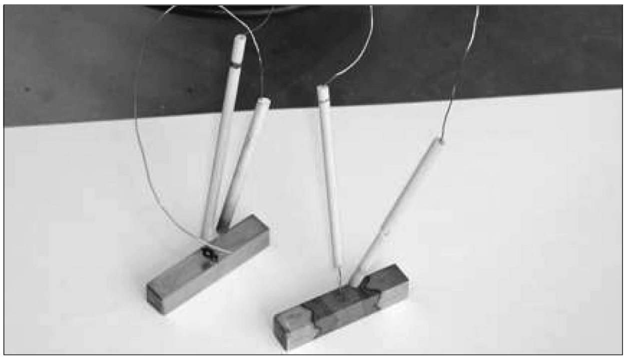

Figure 2. Specimen for welding thermal cycle simulation with thermo couple, before (left) and after (right) welding thermal cycle simulation.

Table 3 shows mechanical properties of the simulated microstructures – hardness and resulting single microstructural phase.

RESULT DATA OF THE IMPACT ENERGY ANALYSIS ON SIMULATED SPECIMENS

The examination of impact energy was performed on Charpy testing machine, type "AMSLER 150/300 J" with a transient recorder. The recorded force - time

Table 2. **Thermal cycle simulation data**

Serial no.	T_{max}, °C	$\Delta t_{8/5}$, s	T_Z, °C		Serial no.	T_{max}, °C	$\Delta t_{8/5}$, s	T_z, °C
1	1341	5	< 130		13	1354	25,6	< 150
2	1344	5,2	< 130		14	1355	25,4	< 150
3	1343	5,2	< 135		15	1358	25,4	< 145
4	1343	5,2	< 135		16	1358	25,6	< 145
5	1339	5	< 135		17	1355	25,6	< 145
6	1344	5	< 135		18	1363	25,2	< 145
7	1363	10	< 137		19	1350	51,2	< 160
8	1360	9,9	< 137		20	1355	50,8	< 160
9	1363	10,1	< 137		21	1357	50,7	< 160
10	1359	9,6	< 137		22	1355	50,8	< 160
11	1371	10,2	< 135		23	1356	51	< 160
12	1365	10,1	< 137		24	1351	50,6	< 160

Table 3. Cooling time $\Delta t_{8/5}$ dependence on hardness and resulting microstructural components.

Cooling time, $\Delta t_{8/5}$, s	HV 10 average value for 10 runs	Microstructure
5	397	Martensite + Bainite
10	388	Martensite + Bainite
25	312	Bainite
50	261	Bainite + Ferrite along the grain boundary

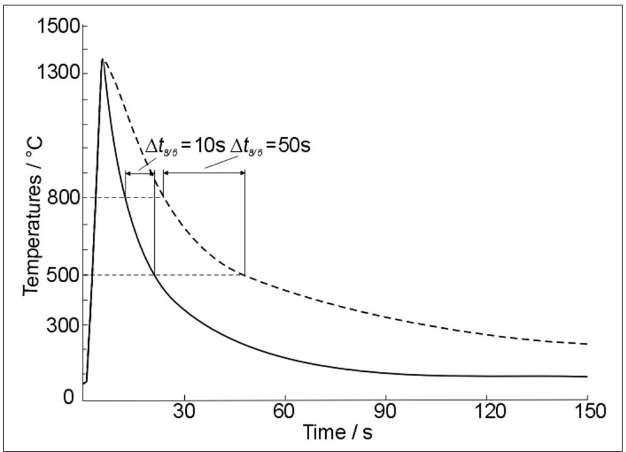

Figure 3. An example of thermal cycle simulation diagrams for cooling time $\Delta t_{8/5}$ 10 and 50 s.

graph enabled the evaluation of impact effect on the plasticity of examined steel and the assessment of en-

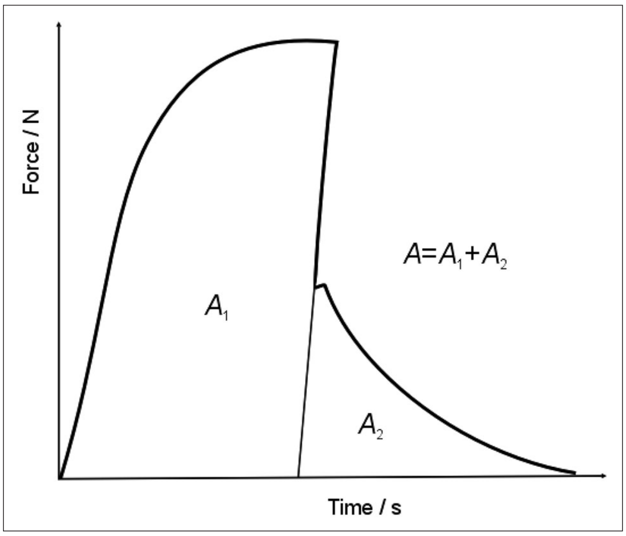

Figure 4. Total fracture energy A consisting of: crack initiation energy A_1 and crack propagation energy A_2.

ergy ratios required to initiate a crack and to cause its further propagation, as shown in Figure 4.

The impact energy on specimens welded in a simulated welding cycle has been tested according to Charpy, at temperatures of 20°C; -20°C and -40°C. Received data are presented in table 4 and represent the average value of two measurements.

Based on received data, two relations are presented: force (F) – time (τ) and energy (E) – time (τ); (Figures

Table 4. **Results of impact energy on specimens performed in one welding thermal cycle simulation.**

Serial no	T_{max}, °C	$t_{8/5}$, s	Total impact energy A, J	Crack initiation energy A_1, J	Crack propagation energy A_2, J
1	20	5	59	44	15
2		5,2			
3	-20	5,2	40	29	11
4		5,2			
5	-40	5	34	26	8
6		5			
7	20	10	55	42	13
8		9,9			
9	-20	10,1	35	26	9
10		9,6			
11	-40	10,2	32	24	8
12		10,1			
13	20	25,6	44	33	11
14		25,4			
15	-20	25,4	24	17	7
16		25,6			
17	-40	25,6	16	11	5
18		25,2			
19	20	51,2	35	25	10
20		50,8			
21	-20	50,7	19	15	4
22		50,8			
23	-40	51	8	6	2
24		50,6			

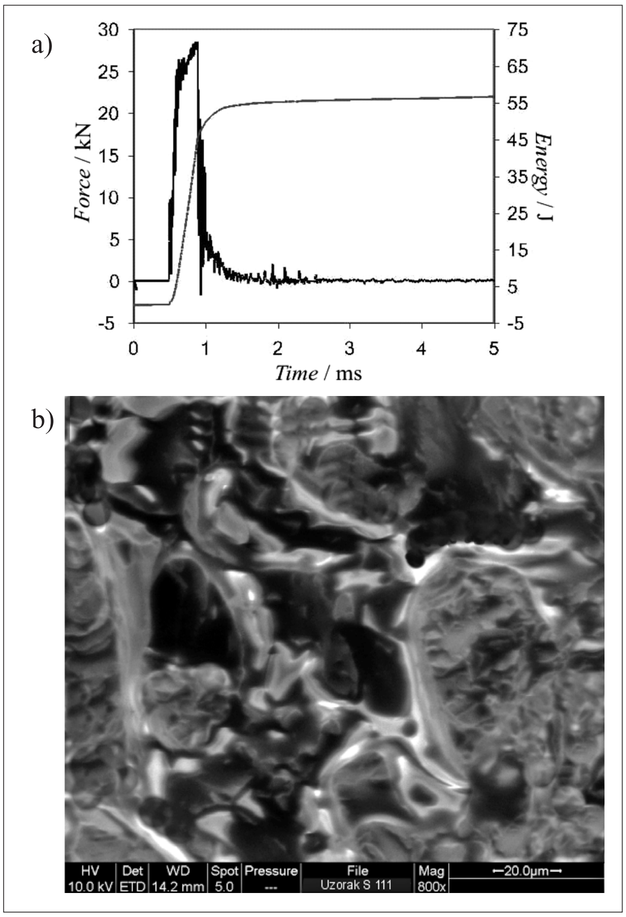

Figure 5. Testing of toughness and fracture of a specimen at $\Delta t_{8/5}$ = 5 s and a temperature of 20°C; a) relations force – time and energy – time; b) fractographic appearance of a rather ductile fracture.

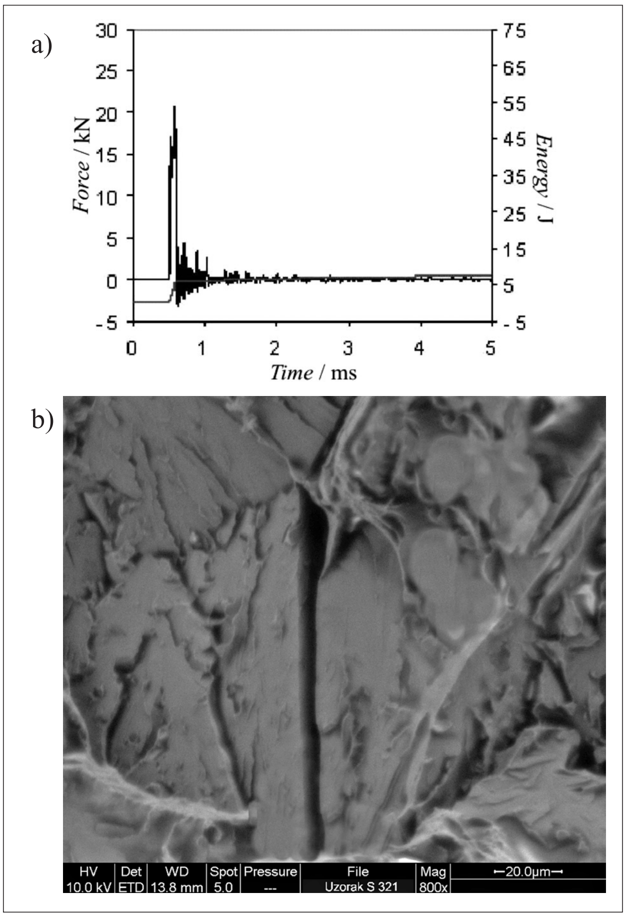

Figure 6. Testing of toughness and fracture of a specimen at $\Delta t_{8/5}$ = 25 s and a temperature of -40°C; a) relations force – time and energy – time; b) fractographic appearance of an almost totally brittle fracture.

5a and 6a). Due to the large quantity of resulting diagrams, figure 5 only shows an example of ductile material behaviour whereas Figure 6 illustrates brittle material behaviour. In addition to diagrams showing the relations force – time and energy – time, characteristic fractographic appearance of pretty ductile and almost totally brittle fractures are also shown.

The resulting diagrams as shown in Figures 5a and 6a enable the analysis of test results of impact energy, primarily the influence of cooling time from 800 to 500°C ($\Delta t_{8/5}$), the thermal influence under testing conditions on the total impact energy and its components, as well as the crack initiation energy and the crack propagation energy.

Figure 7 shows the relation of total impact energy and cooling time $\Delta t_{8/5}$. Test temperatures are marked.

As could be expected, Figure 7 indicates that impact energy is lower at lower testing temperatures. At all testing temperatures a decrease of impact energy at increased cooling time $\Delta t_{8/5}$ was observed as the consequence of structural changes which occurred during the simulated welding thermal cycle [5]. This can be observed from the results shown in table 4 and from figures showing characteristic fractures at two cooling times $\Delta t_{8/5}$ (Figures 5b and 6b).

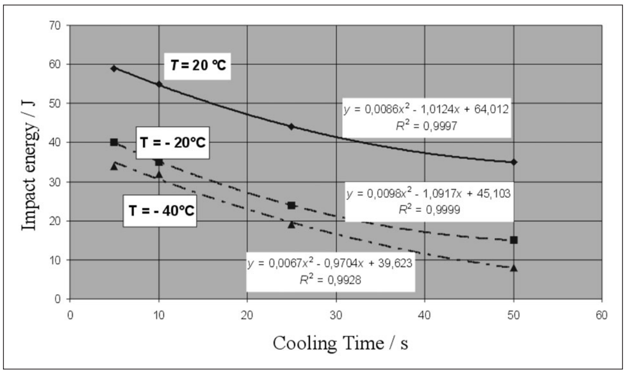

Figure 7. Relation of total impact energy K_V and cooling time $\Delta t_{8/5}$ at marked test temperatures.

CONCLUSION

During simulation at high temperatures for a long period of time, HAZ exhibits grain growth and precipitation coagulation. This causes decreased toughness, particularly at lower temperatures (20°C, -20°C, -40°C), as shown in the diagram (Figure 7). It can be also concluded that satisfactory total impact energy (above 27,5 J [6]) is recorded with the specimen, whose HAZ resulted from cooling time of $\Delta t_{8/5}$ = 5 and 10 s. Since not only the total impact energy but also the hardness of simulated specimens were examined (ranging from 380 – 394 HV for $\Delta t_{8/5}$ = 10s) we can conclude with certainty that cooling time of $\Delta t_{8/5}$ = 10s completely meets the required criteria of total fracture energy and values of maximal hardness:

– Received impact energy research data demonstrate a connection between the simulated HAZ and cooling time $\Delta t_{8/5}$. At increased cooling time, impact energy is decreasing, which is even more obvious at cooling times longer than $\Delta t_{8/5}$ = 10s. Impact energy also drops with lower test temperatures, as can be observed with lowest impact energy values at -40 °C,
– HSLA TStE 420 should be welded only at so chosen parameters to achieve a cooling time from 800 to 500°C within 8 to 10 seconds. At such regime, HAZ hardness along the melting line remains below maximal, while impact energy values exceed the marginal values for the transition into the brittle state,
– The results of thermal simulation of one-pass HAZ indicate the trend of parameter settings for real welding of TStE 420. In addition, thermally simulated samples could be examined further for their proneness to stress corrosion, by using accelerated testing methods. Such further research would contribute to the selection of optimal welding regimes that would result in maximal quality and reliability of welded joints of pressure vessels.

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Note: Responsible translator: Željka Rosandić, Faculty of Mechanical Engineering, Slavonski Brod, Croatia