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IMPACT ENERGY ANALYSIS OF QUENCHED AND TEMPERED FINE GRAIN STRUCTURAL STEEL SPECIMENS AFTER WELD THERMAL CYCLE SIMULATION

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The paper presents impact energy results of thermal cycle simulated specimens of quenched and tempered fine grain structural steel S960QL. These results are obtained by examining notched Charpy specimens. Upon performed metallographic analysis and measured hardness, total impact energy is separated into ductile and brittle components.

Key words: quenched and tempered fine grain structural steel, welding thermal cycle, impact energy, cooling time $t_{8/5}$

INTRODUCTION

In order to understand effects of cooling rate on properties of welded joints, it is important to study effects that temperature fields have on transformation of microstructure during welding. The cooling rate and cooling time from 800 to 500 °C ($t_{8/5}$) can be used to express such effects. Available literature which describes influence of temperature fields on mechanical properties of improved micro alloyed steel S960QL welded joints does not elaborate in details the effects that cooling rate and cooling time from 800 to 500 °C ($t_{8/5}$) may have on hardness and impact toughness. Cooling time affects structure of the heat affected zone (HAZ) and weld metal (WM), as well as mechanical properties of welded joints. [1] Optimal cooling rate and cooling time from 800 to 500 °C ($t_{8/5}$) can be achieved by well-balanced relations between hardness and resistance to cold cracking in production.

Proper cooling rate and cooling time from 800 to 500 °C ($t_{8/5}$) can contribute to achievement of optimal mechanical properties in welded joints and resistance to different types of cracking during production and service. Welding parameters and heat input during welding should be kept in certain limits in order to obtain appropriate microstructure and mechanical properties of any welded joint. Under certain limits, lower values of heat input usually enable faster cooling and may result in too fragile structures. Higher values of heat input over certain limit will result in too coarse grain size and may reduce strength. Limits should be avoided and an optimal heat input shall be determined. [2]

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PLAN OF RESEARCH

The research plan involved simulation of weld thermal cycle with various cooling times from 800 to 500 °C on samples of steel S960 QL (compositions and mechanical properties are presented in Tables 1 and 2), dimensions 11 x 11 x 57 mm. The specimens were cut out alongside the direction of base material with milling process. Base material thickness was 15 mm. Determined duration of cooling from 800 to 500 °C was 8, 10, 12, 14, 16 and 20 s.

Table 1 **Composition of steel S960QL [3]**

Base material		HRN EN 10025	Laboratory findings
Elements content, / wt %	C	max. 0,20	0,17
	Si	max. 0,80	0,47
	Mn	max. 1,70	1,42
	P	max. 0,02	0,008
	S	max. 0,01	0,003
	Cr	max. 1,50	0,59
	Mo	max. 0,70	0,56
	Ni	-	0,79
	Nb	-	0,02
	V	-	0,05

Table 2 **Mechanical properties of steel S960QL [3]**

Mechanical properties	HRN EN 10025	Laboratory findings
Yield strength R_e / MPa	min. 960	1020
Tensile strength R_m / MPa	980 -1150	1080
Elongation A_5 / %	26	16
Charpy impact energy / J	0°C 50	63

The research focused on investigation of impact energy and microstructure after weld thermal cycle simulation.

WELD THERMAL CYCLE SIMULATION

Figure 1 presents the weld thermal cycle simulator TCS 1405 Smitweld, which was used to perform heating and cooling of specimens. Heating of specimens was done on electrical resistant principle.

Specimens with thermo couples before (left) and after weld thermal simulation (right) are shown in Figure 2.

Thermo couples were used for temperature monitoring during heating and cooling of specimens, as well as for regulation of cooling rate and cooling time from 800 to 500 °C. Dilatometer was fixed next to thermo couple to record expansion during heating and shrinkage during cooling of specimen. It helped to determine phase transformations "α" in "γ" during heating and "γ" in "α" during cooling. An example of thermal cycle simulation diagram for cooling time $t_{8/5}$ 8 and 20 s is shown in Figure 3.

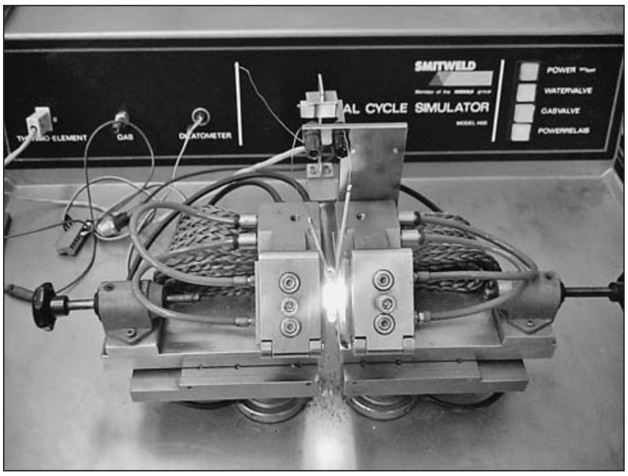

Figure 1 Smitweld TCS 1405 weld thermal cycle simulator

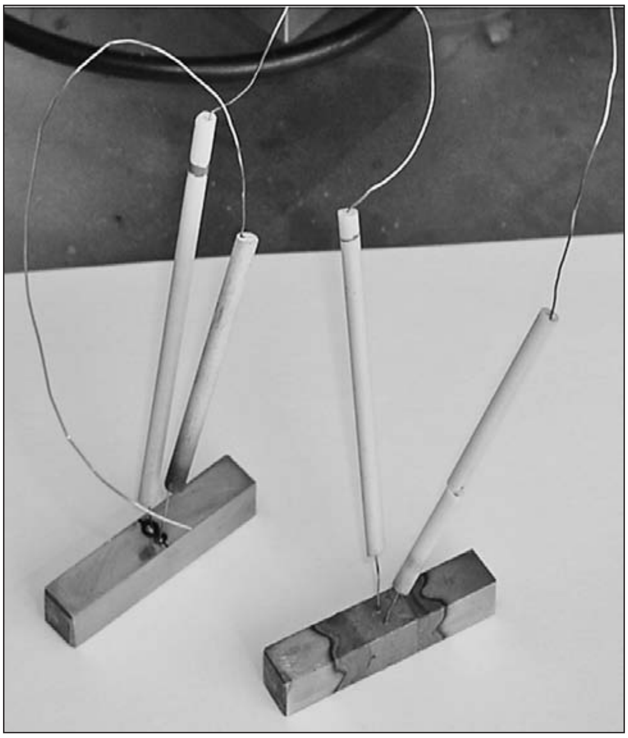

Figure 2 Specimens with thermo couple for weld thermal cycle simulation before (left) and after (right) thermal simulation

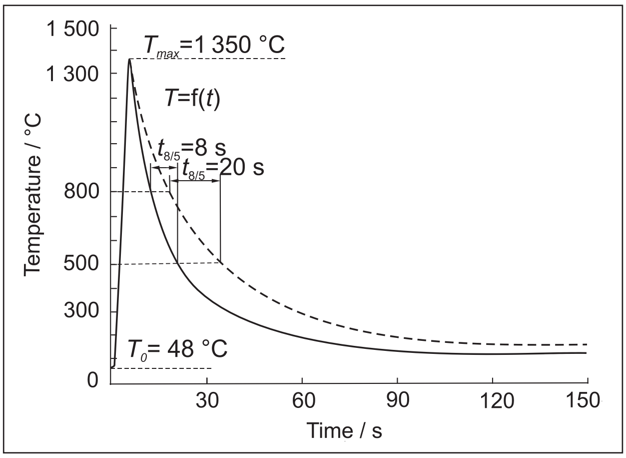

Figure 3 Example of weld thermal cycle simulation diagram for cooling time $t_{8/5}$ 8 and 20 s

Simulations of thermal cycles were carried out on samples with 0,5 seconds holding at the maximum thermal cycle temperature. Cooling speed was $v_{cooling}$ = 200 °C / s. Table 3 overviews simulation parameters (maximum cycle temperature T_{max}, cooling time between 800 and 500 °C - $t_{8/5}$ and final temperature T_{final} for all specimens).

Table 3 **Thermal cycle simulation data**

Specimen	T_{max} / °C	$\Delta t_{8/5}$ / s	$T_{final /}$ °C
1	1 355	8,3	<150
2	1 350	8,4	<150
3	1 356	8,3	<150
4	1 347	8,4	<150
5	1 372	10,6	<150
6	1 370	10,2	<150
7	1 361	10,8	<150
8	1 363	10,9	<150
9	1 354	12,1	<150
10	1 356	12,1	<150
11	1 369	12,0	<150
12	1 366	12,2	<150
13	1 369	14,0	<150
14	1 360	14,2	<150
15	1 364	14,1	<150
16	1 365	14,1	<150
17	1 380	16,1	<150
18	1 379	16,1	<150
19	1 360	16,2	<150
20	1 365	16,2	<150
21	1 364	20,2	<150
22	1 364	20,1	<150
23	1 360	20,1	<150
24	1 362	20,3	<150

Table 4 shows average hardness value and evaluation of microstructural phase.

Table 4 **Dependence of average hardness and cooling time $t_{8/5}$ and evaluation of microstructure after weld thermal cycle simulations**

Cooling time, $t_{8/5}$ / s	HV 10 average value for 3 measurements	Microstructure
8	408	Martensite
10	401	Martensite
12	397	Martensite
14	381	Martensite + Bainite
16	375	Martensite + Bainite
20	370	Martensite + Bainite

IMPACT STRENGTH ON WELD THERMAL SIMULATED SPECIMEN

Impact strength was examined on Charpy-hammer "AMSLER 150/300 J" equipped with a transient recorder. The recorded Force - Time graph allowed evaluation of impact effect on plasticity of examined steel and was required to initiate a crack and cause its further propagation in order to assess energy ratios, as shown in Figure 4.

All phases of the experiment included diagrams to track force and fracture energy during fracture of individual specimens. Due to large amount of specimens and data, this paper only elaborates selected state of experiment with actual duration of cooling $t_{8/5}$ = 8 s. Figure 5a shows a diagram of force and fracture energy during fracture at tested temperature of 20 °C. Figure 5b shows the microstructure of the fracture surfaces in actual duration of cooling $t_{8/5}$ = 8 s, on the breaking temperature of 20 °C.

Diagrams presented on Figures 5 and 6 provide for analysis of research results about impact energy and impact primary cooling time from 800 to 500 °C ($t_{8/5}$), as well as about temperature at which total impact energy and its components, energy cracks initiation and crack propagation energy were examined. Figure 7 shows relationship between total impact energy and testing tem-

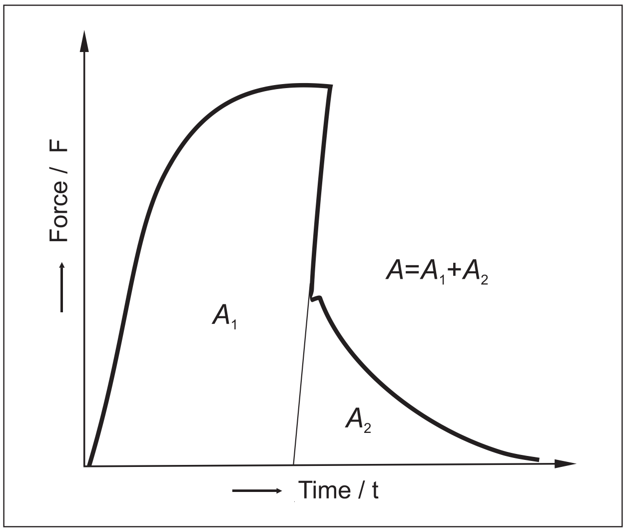

Figure 4 Total fracture energy *A* consisting of: crack initiation energy A_1 and crack propagation energy A_2

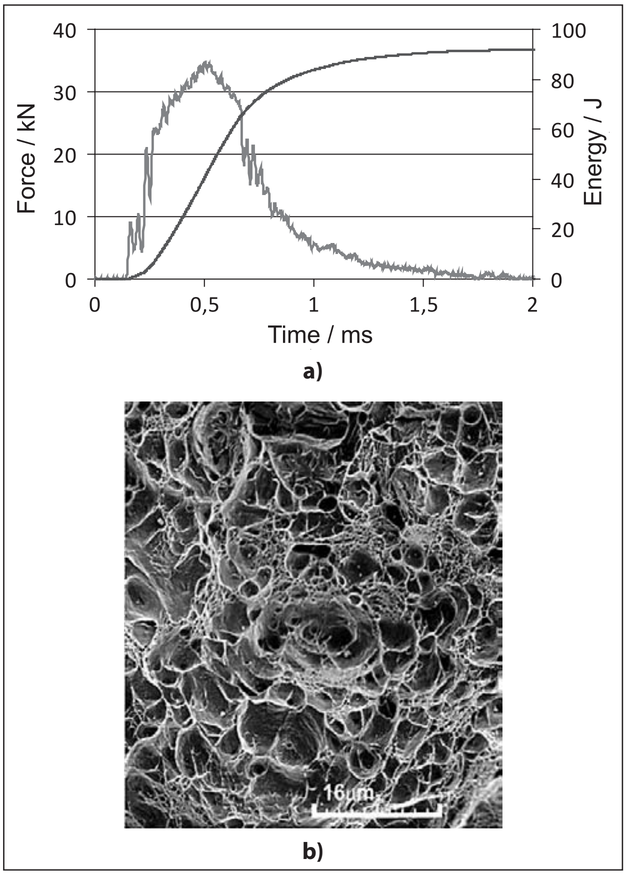

Figure 5 Testing of yield strength and fracture of a test tube at $t_{8/5}$ = 8 s and temperature of 20 °C; a) relations Force – Time and Energy – Time; b) appearance of ductile fracture

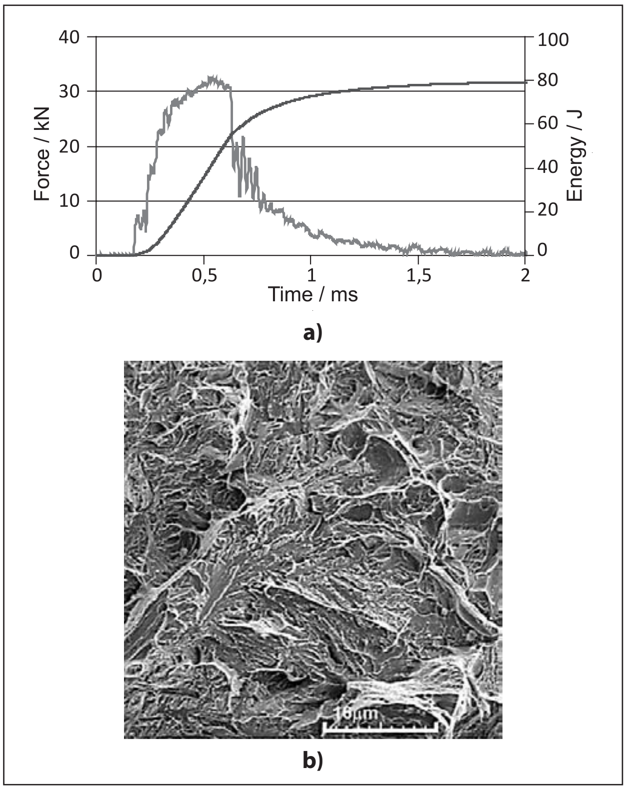

Figure 6 Testing of yield strength and fracture of a test tube at $t_{8/5}$ = 8 s and temperature of - 20 °C; a) relations Force – Time and Energy – Time; b) appearance of slightly fragile fracture

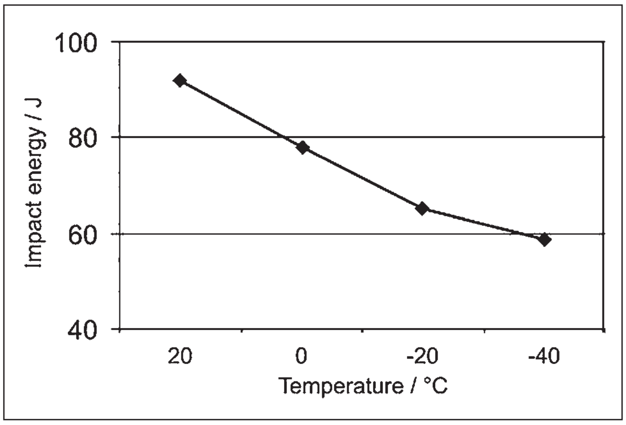

Figure 7 Relation of total impact energy K_v simulated samples at test temperature during cooling $t_{8/5}$ = 8s

perature for specimens with actual duration of cooling time of 8 s. The diagram shows arithmetic value of three tests for each test temperature.

Figure 7 shows that the fracture tendency was lower at lower temperature tests, as it was expected. In almost all test temperatures it was observed that decrease of impact strength tendency in relation to the increase of cooling time $t_{8/5}$ resulted in structural changes in simulation of thermal cycle of welding. Such occurrence was evident in figures that showed characteristic cracks for cooling time $t_{8/5}$ = 8 s (Figure 5b and 6b).

CONCLUSION

Welding technology of steel S960QL is based on controlled energy input during welding (preheating, interpass temperature, arc heat input) and strict compliance to prescribed welding parameters and activities, all with the aim to avoid cold cracks and other defects in production, and to achieve required properties of welded joints. Low heat input usually affects the increase in strength and hardness of welded joint, with residual stresses and presence of hydrogen in weld, causing cold cracks and reducing deformability and increased sensitivity to brittle fracture [4]. Simulation of thermal cycle of welding shall provide results that can be used in optimizing of welding parameters of improved micro-alloyed steel, and in real condition welding to achieve optimal mechanical properties of welded joints for the tested type of steel.

Acknowledgement

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List of symbols

- $t_{8/5}$ - Cooling time / s
- $R_{p0,2}$ - Yield strength / MPa
- R_m - Tensile strength / MPa
- K_v - Impact energy / J
- T_{max} - maximum cycle temperature / °C
- T_z - final temperature / °C
- A - Total fracture energy / J
- A_1 - Crack incitation energy / J
- A_2 - Crack propagation energy / J
- F - Force / kN
- E - Energy / J

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Note: For English language translation and editing responsible is prof. Martina Šuto, University of Osijek, Croatia