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WELDABILITY PREDICTION OF HIGH STRENGTH STEEL S960QL AFTER WELD THERMAL CYCLE SIMULATION

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This paper presents weld thermal cycle simulation of high strength steel S960QL, and describes influence of cooling time $t_{8/5}$ on hardness and impact toughness of weld thermal cycle simulated specimens. Furthermore, it presents analysis of characteristic fractions done by electron scanning microscope which can contribute to determination of welding parameters for S960QL steel.

Key words: high strength steels, S960QL steel, weldability, weld thermal cycle simulation, hardness, toughness

INTRODUCTION

Lack of experience in both design and implementation, as well as in exploitation of mobile and stable pressure vessels made of high strength alloyed steel, indicated the need to carry out experiments to assess weldability of these steels, in order to improve the quality and reliability of products produced by welding of these steels. Research into weldability of real welded joints can be complex, expensive and time consuming. That led to finding out opportunities to shorten duration of experiments by performing researches in a simulator, i.e. on weld thermal cycle simulated samples. The steel S960QL was selected for this research, since it has been recently used in production of various cranes. Due to lack of sufficient data on weldability of that steel and its behavior during exploitation, and keeping in mind potential risks of failure, there is a need for more detailed research and contributions to the field of optimization of welding parameters. In order to understand problems of producing pressure vessels out of microalloyed high strength steels, one should study effects of temperature fields on the transformation of microstructure during welding, which influences mechanical properties of welded joints. That influences can be expressed through the cooling speed and cooling time within the microstructure transformation. This paper elaborates the study into influences of cooling time from 800 to 500 °C on the hardness and impact toughness of simulated samples made out of high strength steel S960QL.

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PLAN OF EXPERIMENT

Specimens of the S960QL steel 57 x 11 x 11 mm were prepared for testing on Smitweld simulator. Specimens were cut out in the direction of base material rolling. The thickness of base material was 15 mm. Testing of hardness and toughness of simulated samples was carefully planned. The experiment aimed to prove dependence of hardness and impact toughness on the cooling speed, i.e. cooling time $t_{8/5}$ for the most critical weld zone along the fuzion line. The experiment was set up as a simulation of weld thermal cycle in single pass thermal simulation. When simulating a single pass weld, the samples were heated at different temperatures (600, 700, 800, 900, 1 100 and 1 350 °C) and then cooled at a cooling time $t_{8/5}$ = 10 s. Since some samples were heated at a temperature lower than 800 °C, the cooling time 800 - 500 °C could not be measured, instead of which cooling time from 500 - 300 °C ($t_{5/3}$) was measured. Chemical composition and basic mechanical properties of tested high strength steel S960QL are presented in the Table 1 and Table 2.

Table 1 **Composition of S960QL steel [1,2]**

C	0,17
Si	0,47
Mn	1,42
P	0,008
S	0,003
Cr	0,59
Mo	0,56
Ni	0,79
Nb	0,02
V	0,05
Cu	0,03
Ti	0,01

Research objective was to determine changes in the structure that occur during weld thermal cycle and

Table 2 **Mechanical properties of S960QL steel [1,2]**

Yield Strength $R_{p0,2}$ / MPa		1 020
Tensile Strength R_m / MPa		1 080
Elongationa A_5 / %		16
Contraction Z / %		61,9
Toughness, K_V / J longitudinally	at 0 °C	158
	at -20 °C	76
	at -40 °C	58

changes of hardness. For that purpose was predicted single and double pass weld thermal cycling of specimens made from S960QL steel. For the single thermal cycling was prepared 36 specimens.

Heating rate from room temperature to maximal temperature was 200 °C/s. Holding of specimen at maximal temperature was 0,5 s. Final temperature after weld thermal cycle simulation was 150 °C. Desirable cooling time from 800 to 500 °C for specimens heated to maximal temperature 800 °C and over that temperature was $t_{8/5}$ = 10 s and obtained cooling time was lightly different and was shown in Table 3.

Table 3 **Parameters of single pass weld thermal cycle simulating**

Specimen mark	T_{max} / °C	$t_{8/5}$ or $t_{5/3}^{*}$ / s
6.1	605,6	29,5*
6.2	604,2	29,4*
6.3	605,6	28,3*
6.4	607,2	28,5*
6.5	610,5	28,3*
6.6	610,5	28,3*
7.1	712,5	29,0*
7.2	718,8	29,0*
7.3	739,5	27,6*
7.4	713,4	26,4*
7.5	717,1	28,2*
7.6	716,8	28,8*
8.1	824	10,8
8.2	811,2	11,5
8.3	829,2	11,1
8.4	816,4	11,1
8.5	811,2	11,3
8.6	813,5	11,3
9.1	926,9	10,6
9.2	919,9	10,7
9.3	913,8	10,8
9.4	913,4	10,8
9.5	927,6	10,5
9.6	913.2	10,8
11.1	1 121,1	8.9
11.2	1 111,8	9,6
11.3	1 116,5	9,6
11.4	1 131,2	9,3
11.5	1 123,3	9,9
11.6	1 110,9	9,7
13.1	1 363,1	9,5
13.2	1 359,2	9,8
13.3	1 360,8	8,0
13.4	1 358,7	8,8
13.5	1 359,0	8,3
13.6	1 354,0	8,0

Specimens heated to 800 °C or over that temperature during cooling have cooing time from 800 to 500 °C ($t_{8/5}$). Specimens with maximal temperature less than 800 °C have cooling time from 500 to 300 °C ($t_{5/3}$).

RESULTS OF SIMULATION

After preparing and polishing of samples obtained in the first experiment, photos of microstructure were taken and magnified 50, 200, 500 and 1 000 times. Microstructures of fracture at a temperature of 20 °C are shown in the Figure 1.

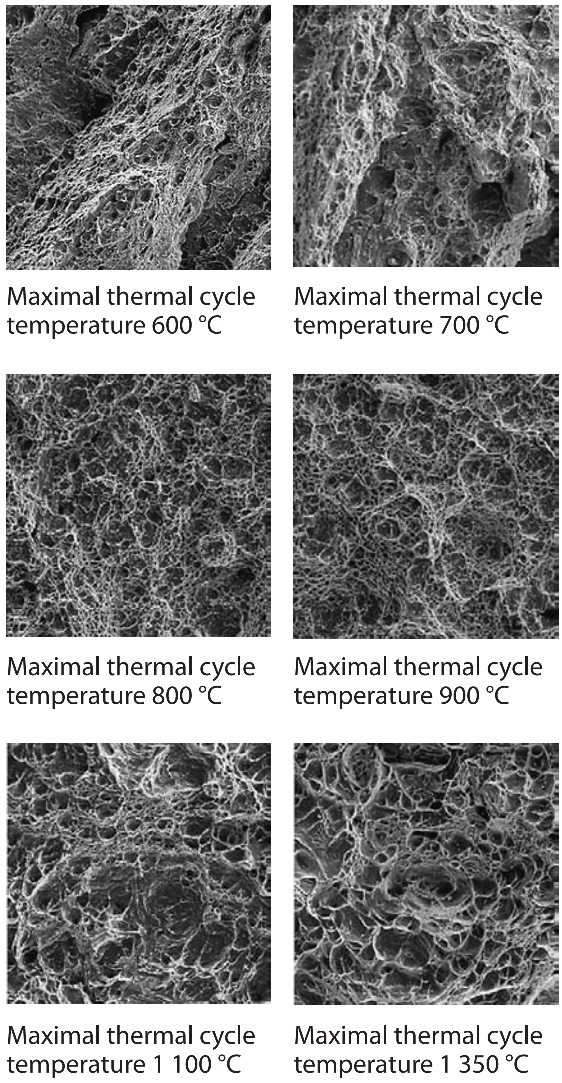

Figure 1 Structure of the steel S960QL after simulation of welding process (temperature of heating 600, 700, 800, 900, 1 100 and 1 350 °C) – magnification 500 x.

Before welding process simulation, the steel S960QL exhibited fine-grained structure of tempered martensite and bainite. The sample heated to 600 °C did not exhibit significant changes in its structure. Heating temperature to 700 °C also did not cause significant changes (temperature of tempering was 680 °C), both in hardness and in structure. The sample heated to 800 °C exhibited increase in grains and decrease of hardness. Heating to 900 °C caused even greater increase in grains

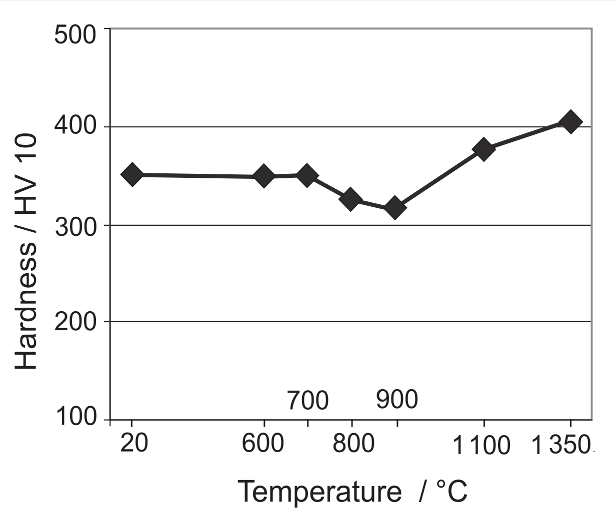

Figure 2 Dependence of medium hardness values on single-pass simulation temperature (base material at 20 °C, heating to temperatures 600, 700, 800, 900, 1 100 and 1 350 °C)

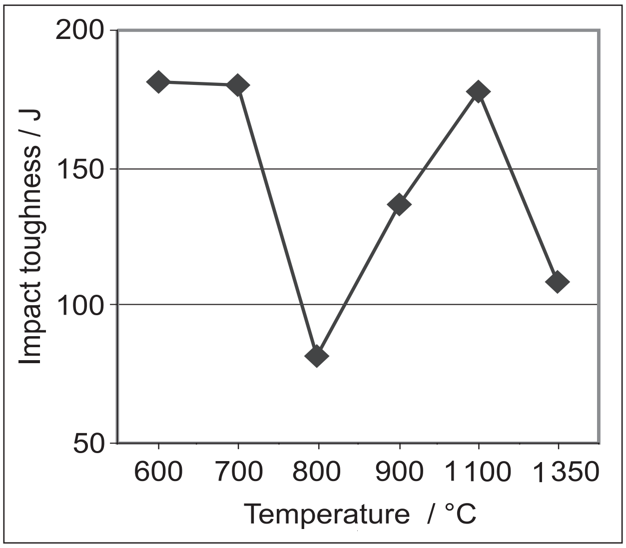

Figure 3 Dependence of impact toughness on T_{max} of simulated cycle (600, 700, 800, 900, 1 100 and 1 350 °C); testing of impact toughness done at a temperature of 20 °C

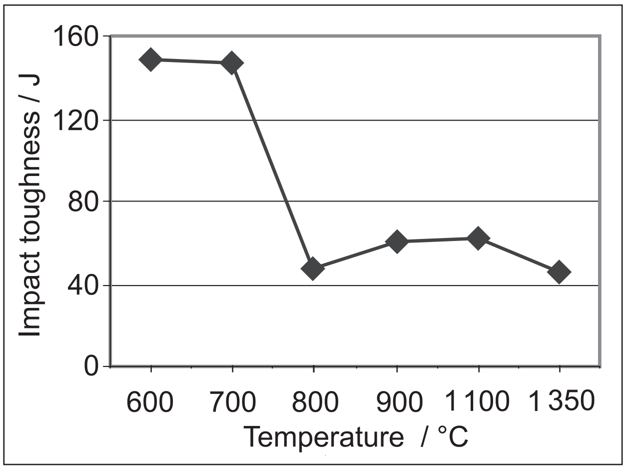

Figure 4 Dependence of impact toughness on T_{max} of simulated cycle (600, 700, 800, 900, 1 100 and 1 350 °C), testing of impact toughness done at a temperature of – 30 °C

and further decrease of hardness. There was separation of precipitates observed in the samples heated to higher temperatures (1 100 and 1 350 °C). The heat affected an increase in hardness and structural transformations into martensitic-bainitic structure. Such structure presupposes even greater increase in hardness. The Figure 2 shows that medium hardness values measured in the middle of sample were dependent on the temperature.

Impact toughness on simulated specimens in this experiment was measured at + 20 °C and – 30 °C. Diagrams of dependence of impact toughness at a temperature of + 20 and – 30 °C in single-pass weld thermal cycle simulation on maximum temperature of weld thermal cycle are shown in Figures 3 and 4.

As shown in the diagram, maximum values of impact toughness were obtained within simulation at T_{max} 1 100 °C.

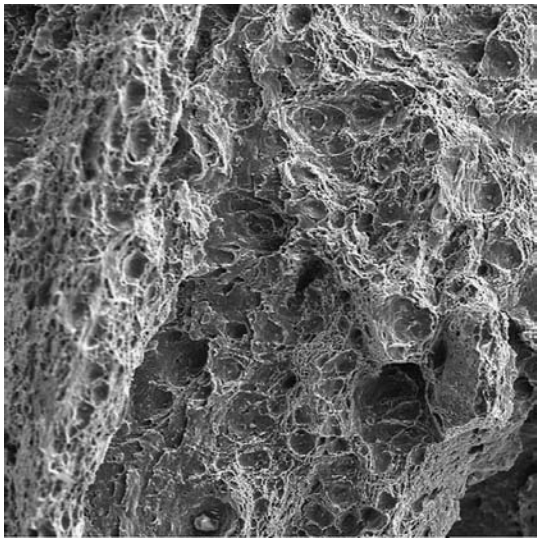

Figure 5 Testing of toughness and fracture of specimen at $t_{8/5}$ = 10 s, at temperature 20 °C; fractographic appearance of tough fracture, magnification 500 x

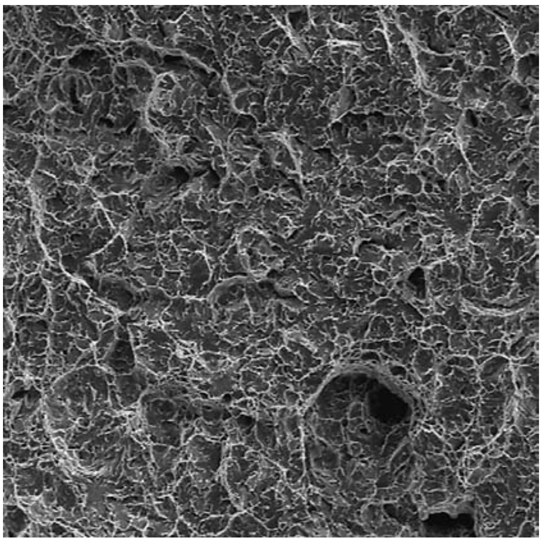

Figure 6 Testing of toughness and fracture of specimen at $t_{8/5}$ = 10 s, temperature - 30 °C; fractographic appearance of significantly fragile fracture, magnification 500 x

As presented in the diagram, minimal values of impact toughness were obtained at T_{max} of simulation of 800 °C. Temperature higher than that caused an increase of impact toughness, which correlated to decrease of hardness. The toughness was further decreased when raising the T_{max} of simulation to 1 350 °C. Figures 5 and 6 show tough fracture (testing performed at 20 °C) and fragile fracture (testing performed at – 30°C) for specimens with maximal weld thermal cycle temperature 1 350 °C.

CONCLUSION

Cooling speed, i.e. cooling time $t_{8/5}$ significantly influenced the microstructure and mechanical properties of welded joints. [3-5] Selection of optimal cooling speed can contribute to satisfactory relations between hardness and impact toughness, i.e. it can provide microstructure that is less susceptible to occurrence and development of cold cracks in production welded structures. [6-7] Hardness results after single thermal cycling showed hardness gap in Heat Affected Zone (Figure 2) with hardness values lower than base metal. That occurrence is inevitable, but its „width" and „depth" can be reduced by providing small amount of heat into the material (reducing the „width"). This procedure reduces the „depth" of gap of hardness. Simulation of one-pass HAZ enables detection of the weakest point in the weld joint and presents relatively faster and very useful way for studying relevant structural changes in the HAZ. Within one-pass welding simulation, satisfactory hardness and microstructure are obtained after thermal cycing in temperature range from 1 100 to 1 350 °C, i.e. bainitic-martensitic structure and hardness of 370 - 410 HV (Figure 2). Results of impact strenght at 20 and -30 °C after single pass weld thermal cycle simulation are shown at Figure 3 and 4. Impact toughness at -30 °C is over 27 J for all specimens heated at different maximal temperatures. The next investigation will be performed at double weld thermal cycle simulated specimens and real welded joints. Results of single cycle thermal simulation and mechanical properties investigations gave prety good standpoint for further investigations.

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