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DEPENDENCE OF HARDNESS AND IMPACT ENERGY ON COOLING TIME $\Delta t_{8/5}$ AND TEMPERATURE FOR S960QL

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Preliminary Note – Prethodno priopćenje

The paper deals with research into dependence of hardness and impact energy of thermal cycle simulated specimens of fine-grained structural steel S960QL on cooling time from 800 to 500 °C and on tested temperature. Results were obtained by measuring hardness of HV 10 and by experimental testing of Charpy notched tubes on instrumented Charpy hammer. Total impact energy, initiation energy and fracture propagation energy needed for occurrence of fracture is also elaborated.

Key words: structural steel, quenched, hardness, impact energy, cooling time $\Delta t_{8/5}$

INTRODUCTION

Developments of modern fine-grained structural steel has induced many benefits, manifested mostly through reduction of mass in construction of mobile welded structures and structure products. Welding of modern fine-grained steel is a great challenge for welding engineers because of possible difficulties during welding, and requirements on high quality and reliability of welded structures and products. Modern machines, bridges, ships or vehicles require welded joints and base materials to be of great static and dynamic strength, which service will result in reduction of weight and provide for additional savings through reduced energy consumption during service. These materials provide for better performance of lightweight constructions due to favorable ratio of weight and strength, because of which engineers are increasingly using fine-grained structural steels. This paper elaborates weldability of fine-grained structural steel S960QL [1] with relatively high hardness and strength. These are important properties of fine-grained structural steels. [2]

RESEARCH METHOD

Available literature dealing with effects of temperature fields on mechanical properties of S960QL steel welds, and preliminary researches performed by the authors on weld thermal cycle simulator indicate that there is no enough information how cooling time from 800 to 500 °C ($t_{8/5}$), i.e. cooling speed affects hardness and toughness of welded joints of the mentioned steel. It is important to differ effect of cooling speed on hardness and toughness of single-pass and double-pass welding because of different effects of weld thermal cycle in single pass welding and in double-pass welding. Duration of cooling from 800 to 500 °C affects structure of HAZ and consequently mechanical properties, i.e. impact energy and hardness. By selecting optimum cooling time, satisfactory relation between hardness and impact energy can be achieved, leading to microstructure that is less susceptible to cold cracks, which are typical for this group of steel. Cooling time $t_{8/5}$ shall be determined experimentally for the weakest weld zone, for a part of heat affected zone (HAZ) along the fusion line. Such determination is usually made on a zone that reaches the highest temperature through heating - austenitization of approximately 1 350 °C. This is the area of overheating structure with coarse rapidly cooled grains. Welds of S960Q steel are often expected to have dynamic strength, which further complicates the welding technology. Figure 1 shows the Wöhler diagram of changes in strength as depending on number of loading cycles under alternating loading conditions.

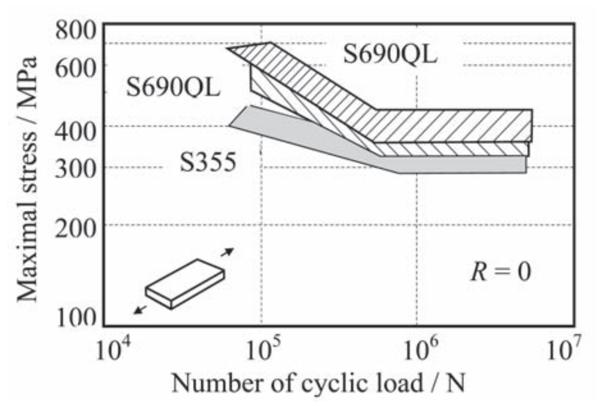

Figure 1 Dependence of maximal strain on loading S960QL [3]

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Chemical composition of tested steel is overviewed in the Table 1, and mechanical properties are stated in the Table 2.

Table 1 **Chemical composition of the steel S960QL [4]**

Base materials		EN 10025-6	Batch 653409
Elements content, cwt / %	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 S960QL**

Yield strength R_e / MPa	Tensile strength R_m / MPa	Elongation A_5 / %	Charpy impact energy / J
1 020	1 080	16	158

THERMAL CYCLE SIMULATION

The Smitweld TCS 1405 weld thermal cycle simulator was used for heating and cooling of specimens. Specimens used for testing by thermal cycle simulation were of 55 x 11 x 11 mm. Thermal cycle simulation was performed by holding specimens for 0,5 s at the highest temperature of the first thermal cycle (I) T_{max} = 1 350 °C and at different temperatures within the second thermal cycle (II). The maximal temperatures of the second (II) thermal cycle were: 1 350, 1 100, 900 and 800 °C. Cooling from 800 to 500 °C was performed in different duration (8, 10, 12, 14, 16 and 20 s), aiming to obtain different properties in heat affected zone along the fusion line (coarse-grained zone). Obtained parameters of thermal cycling for maximal temperature I and II, thermal cycle T_{max} = 1 350 °C, and duration of cooling between 800 and 500 °C ($t_{8/5}$) are presented in the Table 3. Final temperature after thermal cycling was 150 °C.

RESEARCH RESULTS

Results of hardness testing

After weld thermal cycle simulation, hardness was measured on all samples at locations as presented on Figure 2.

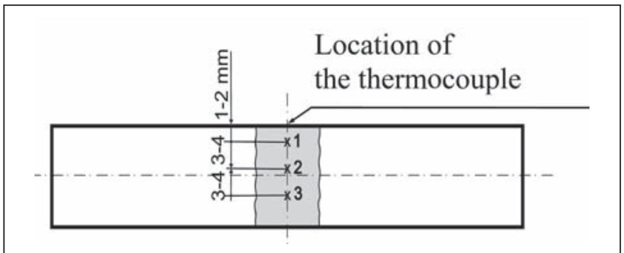

Figure 2 Locations for measuring of hardness on thermal simulation samples

Table 3 **Thermal cycle simulation data**

Mark sample	T_{max}, I and II cycle / °C	$t_{8/5}$, I and II cycle / s
811	I 1 355,1 II 1 350,0	8,3 8,1
812	I 1 356,0 II 1 356,1	8,4 8,3
813	I 1 356,1 II 1 350,0	8,3 8,7
814	I 1 347,5 II 1 350,2	8,4 8,5
1011	I 1 357,7 II 1 366,8	10,2 10,6
1 012	I 1 365,5 II 1 369,7	10,8 10,2
1 013	I 1 372,6 II 1 380,2	10,9 10,8
1 014	I 1 356,0 II 1 376,8	10,9 9,2
1 211	I 1 353,6 II 1 355,8	12,0 12,1
1 212	I 1 366 II 1 368,8	12,2 12,1
1 213	I 1 365,6 II 1 357,4	12,2 12,0
1 214	I 1 361,0 II 1 360,2	12,2 12,5
1 411	I 1 369,0 II 1 359,8	14,1 14,0
1 412	I 1 365,0 II 1 359,8	14,2 14,1
1 413	I 1 365,3 II 1 363,6	14,6 14,3
1 414	I 1 357,0 II 1 365,3	14,4 14,1
1 611	I 1 379,8 II 1 379,1	16,2 16,1
1 612	I 1 365,0 II 1 359,8	16,2 16,4
1 613	I 1 362,5 II 1 360,0	16,3 16,4
1 614	I 1 364,0 II 1 364,8	16,0 16,1
2 011	I 1 360,0 II 1 359,3	20,1 20,2
2 012	I 1 362,0 II 1 365,3	20,3 19,8
2 013	I 1 358,2 II 1 350,0	21,2 20,1
2 014	I 1 361,0 II 1 356,3	20,4 21,0

The Figure 3 shows a diagram of mean values for hardness after double simulation (three measurements for each experiment phase) as being dependent on cooling time from 800 to 500 °C ($t_{8/5}$) and maximal temperature of the second thermal cycle (1 350, 1 100, 900 and 800 °C).

As seen above, there is no significant increase in hardness at maximal temperature of the second thermal cycle at 800 °C. Slight change in hardness occurred at maximal temperature of the second thermal cycle at 900 °C. By increasing maximal temperature of the second thermal cycle simulation above 900 °C, hardness also increased to reach the maximal at a temperature of 1 350 °C.

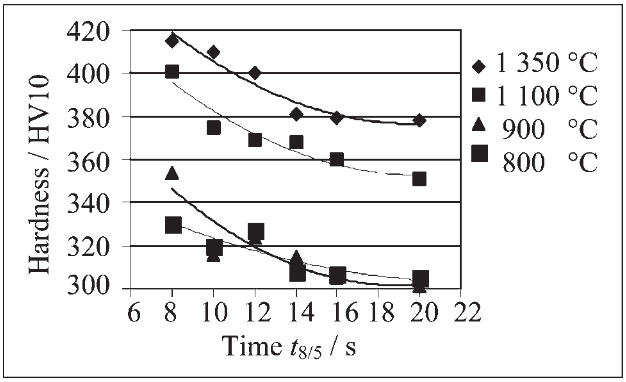

Figure 3 Diagram of hardness values in dependence on simulation temperature and cooling time $t_{8/5}$ (8, 10, 12, 14, 16 and 20s)

Results of impact energy testing

Testing of impact energy was performed at temperatures of 20, 0, -20 and -40 °C. The Figure 4 presents the force–time curve, and of Figure 5 shows energy-time curve for testing at a room temperature. Figures 6 and 7 present results of testing at a temperature of -40 °C.

The Figure 8 presents total impact energy (E_u), initiation energy (E_i) and propagation energy (E_p) of fracture by double thermal cycling (I cycle 1 350 °C, II cycle 800, 900, 1 100 and 1 350 °C). Cooling time from 800 to 500 °C was $t_{8/5}$= 12 s. Testing was performed at a room temperature.

Results of tests on hardness are shown in Figure 8 ($t_{8/5}$= 12 s, temperature of 20 °C). Figure 9 presents por-

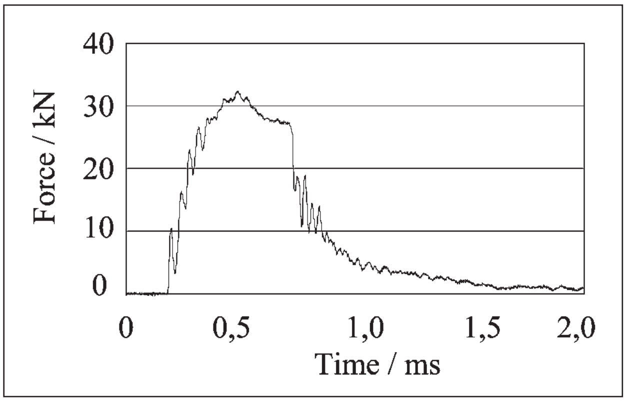

Figure 4 The force – time curve for testing of hardness at a room temperature

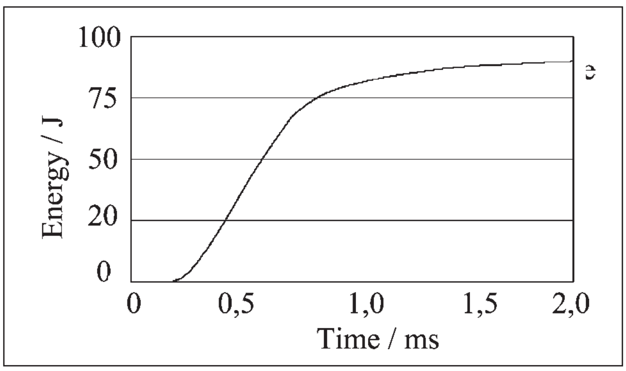

Figure 5 The energy–time curve for testing of hardness at a room temperature

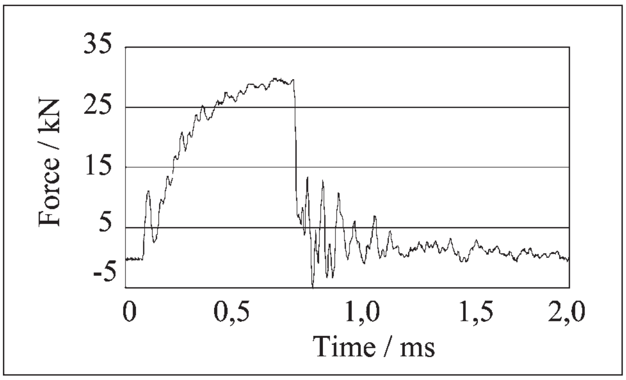

Figure 6 The force–time curve for testing of hardness at -40 °C

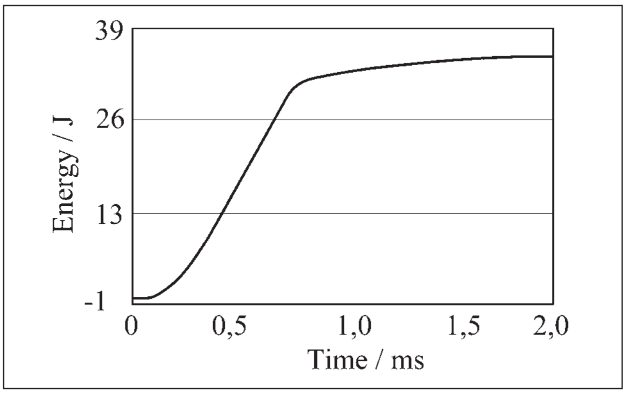

Figure 7 The energy–time curve for testing of hardness at -40 °C

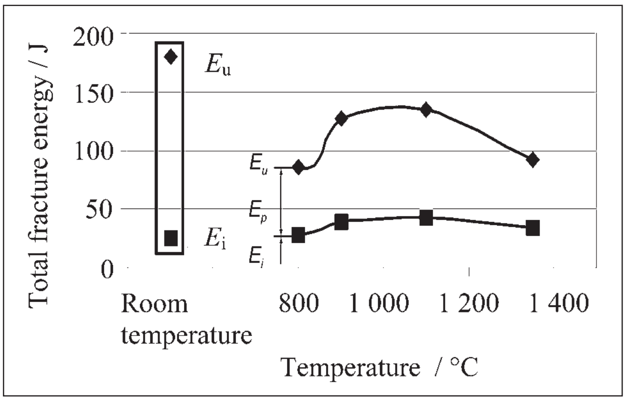

Figure 8 Total impact energy E_u at 20°C and differences between total impact energy, initiation energy E_i and propagation energy E_p of fracture (testing at room temperature)

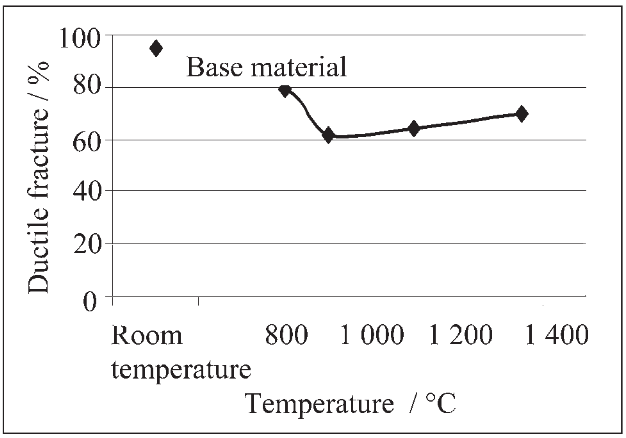

Figure 9 Dependence of ductile fracture on maximal temperature of the second thermal cycle for results in previous figure

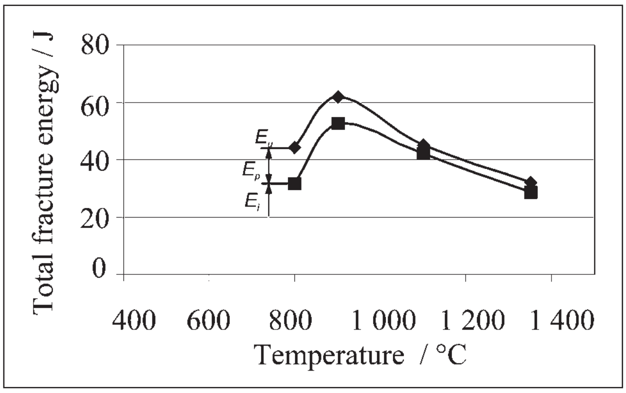

Figure 10 Total impact energy E_u for testing at -40°C and differences between total impact energy, initiation energy E_i and propagation energy E_p of fracture

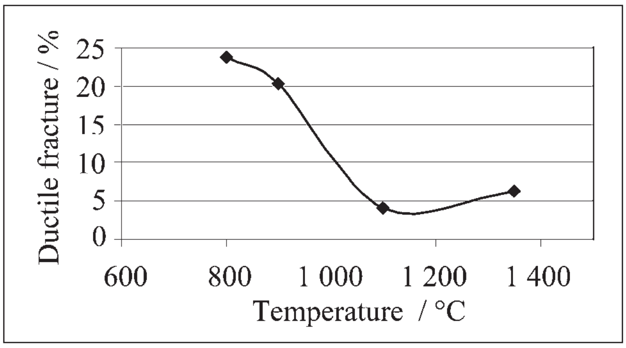

Figure 11 Dependence of ductile fracture on maximal temperature of the second thermal cycle for results in previous Figure

tions of ductile fracture as depending on maximal temperature of the second thermal cycle.

Figures 10 and 11 show results of testing impact energy at -40 °C.

At a maximal temperature of the second thermal cycle 1 350 °C, the structure was fragile - coarse grained martensite, and the values of impact energy were lower. The structure changed to fine-grained martensitic bainite after reducing maximal temperature of the second thermal cycle simulation, which caused an increase in toughness. Structure of base material is tempered martensitic bainite and values for impact energy are quite high (above 150 J). Testing of impact energy at -40 °C indicated relatively low hardness which values do not lower under 35 J in weld thermal cycle simulation at a temperature of 1 350 °C. At lower temperatures of weld thermal cycle simulation there was occurrence of increased impact energy which values were above 40 J.

CONCLUSION

Weld thermal cycle simulation enables gaining of results useful in optimization of welding parameters of improved fine-grained structural steels. The highest values of hardness were obtained by cooling time from 800 to 500 °C, for 8 and 10 s, at a maximal temperature of second thermal cycle simulation of 1 350°C. The lowest values of impact energy were obtained at a temperature of - 40 °C, while maximal temperature of second thermal cycle simulation was 1 350 °C. The lowest values of hardness are correlated with coarse martensitic grain, which is conditioned by hardness above 400 HV (Figure 3). The highest values of impact energy are characterized by subcritical HAZ (maximal temperature of the second thermal cycle simulation 1 100 °C), with hardness values above 130 J (Figure 8).

Acknowledgement

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