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OTPORNOST NA PRSLINE ZAVARENIH SPOJEVA NISKOLEGIRANIH ČELIKA ULTRAVISOKE JAČINE

CRACK RESISTANCE OF ULTRA-HIGH STRENGTH LOW ALLOYED STEEL WELDED JOINTS

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Rezime: Niskolegirani čelik ultravisoke jačine, sa granicom tečenja preko 1000 MPa, zavaren je elektrolučno u zaštitnoj atmosferi (GSAW) korišćenjem žičane elektrode (granica tečenja 960 MPa). Standardno ispitivanje žilavosti loma, K_{Ic} i udarne žilavosti na instrumentiranom Šarpijevom klatnu sa razdvojenim energijama nastanka i širenja prsline sprovedeno je za sve zone zavarenog spoja (osnovni metal, zona uticaja toplote i metal zavara). Rezultati su pokazali da je otpornost na prsline relativno visoka u svim zonama, pri čemu je metal zavara najslabija karika.

Ključne reči: Otpornost na prsline, Zavareni spojevi, Čelici ultravisoke jačine, žilavost loma

Abstract: Ultra High Strength Low Alloyed (UHSLA) steel, with Yield Strength more than 1000 MPa, was welded by Gas Shielded Arc Welding (GSAW) process using wire electrode (Yield Strength 960 MPa). The standard testing of fracture toughness, K_{Ic}, and impact toughness on instrumented Charpy pendulum with separated crack initiation and propagation energies was performed for all welded joint zones (base metal, heat-affected zone and weld metal). Results indicated that the crack resistance is relatively high in all zones with weld metal as the weakest link.

Key words: Crack resistance, Welded joints, Ultra-high strength steel, fracture toughness

1. INTRODUCTION

The Ultra High Strength Low Alloyed (UHSLA) steels with Yield Strength (YS) more than 960 MPa, like recently produced SIMAXX 1000, are used nowadays for mobile lifting devices, chassis for truck lightweight trailers and other load-bearing structures, [1]. While their toughness and crack resistance is still to be proved and improved, the possibility to reduce weight of large welded constructions makes them promising material for future use.

Crack resistance is a crucial issue in aforementioned UHSLA steel application, especially if considered in a heterogeneous material such as welded joints are (base metal - BM, weld metal - WM and heat-affected-zone - HAZ), and at different temperatures to evaluate the Ductile-to-Brittle Transition Temperature (DBTT), [2-8]. One should also note that under the impact load, the total impact energy is not sufficient measure for crack

resistance, since its two components, crack initiation and propagation energies, are needed to understand better material behaviour in presence of cracks, [9].

Yet another important aspect of UHSLA steel use is so-called mismatching effect, [10, 11]. Standard practice for common structural steels is to make weld metal stronger than base metal, which is considered as the safe practice since crack resistance should be an issue in this case. Nevertheless, in the case of HSLA and UHSLA steels standard practice is to produce undermatching effect, since the crack resistance issue is better handled in this way. Thus, the welding procedure specification should define filler metal with lower YS than base metal. Anyhow, as will be shown in this paper, undermatching is not guaranteed since it also depends on microstructure obtained in WM under specific welding conditions.

In this paper welding procedure for SIMAXX 1000 steel is described with an analysis of crack resistance of its welded joint, evaluated by impact and fracture toughness.

2. EXPERIMENT

2.1. Welding procedure

The Shielded Gas Arc Welding SMAW procedure was used with electrode wire Union X96, Φ1 mm, to produce 2 plates with "K" shaped welded joint, thickness 15 mm, Fig. 1, whereas the welding sequence is shown in Fig. 1b. The mixture 82 CO_2-18 Ar was used as shielding gas. Nominal mechanical properties and chemical composition of the base metal are shown in Tables 1 and 2, and in Tables 3 and 4 for the filler material. Kemppi FastMig MXF 65 was used, welding direction toward left.

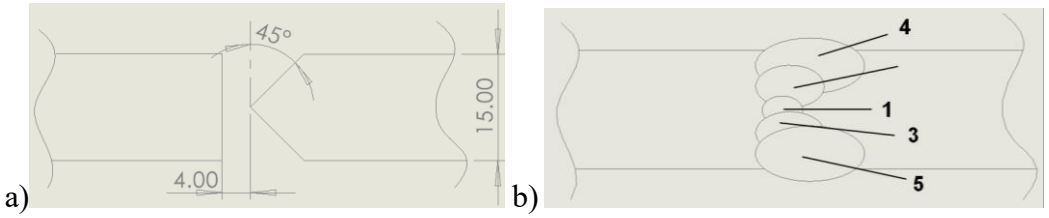


Figure 1. a) Groove geometry and b) welding sequence

Table 1. Chemical composition of the tested batch of steel SIMAX 1000

C	Si	Mn	P	S	Cu	Al	Cr	Mo	Ni	N	Al	V	Nb	Ti
0.175	0.28	1.02	0.008	<0,004	0.206	0.045	0.54	0.445	0.267	0.004	0.045	0.008	0.026	0.021

Table 2. Results of tensile properties of BM specimens tested at low temperatures

Test temperature, °C	Yield strength $R_{p0,2}$, MPa	Tensile strength R_m, MPa	Elongation A, %
20	988-1006	1033	14.2
-40	1028	1066	14.0

Table 2. Chemical composition of filler metal Union X96

1. % wt.						
C	Si	Mn	Ni	Cr	Ni	Mo
0.12	0.82	1.90	1.1	0.45	2.35	0.55

Table 3. Mechanical properties of filler metal Union X96

Yield strength $R_{p0,2}$, MPa, min.	Tensile strength R_m, MPa, min.	Elongation A, %, min.	Impact energy, KV, J, at 20 °C, min.
930	980	14	80

Special attention was paid to the $t_{8/5}$ parameter to control the final microstructure of WM and HAZ having in mind their high sensitivity on welding speed. Although the general recommendation for $t_{8/5}$ parameter is 10-25 s, [12], the producer recommended shorter time, 5-15 s, [1], which was used here, as one can see in Tables 5 and 6, indicating all welding parameters.

Table 5. Welding parameters for plate 1

Run No.	$T_{p/mp}$ °C	I A	U V	t_{min} mm	t sec	v_z mm/sec	Q KJ/mm	$t_{8/5}$ sec
1	150	125	18.1	3.58	238	2.1	0.86	6.3
2	145	199	24.7	2.12	132	3.8	1.03	8.7
3	145	185	24.5	2.39	159	3.1	1.17	11.3
4	145	183	23.8	2.48	168	3.0	1.16	11.1
5	145	183	23.8	2.44	164	3.0	1.16	11.1

Table 6. Welding parameters for plate 2

Run No.	$T_{p/mp}$ °C	I A	U V	t_{min} mm	t sec	v_z mm/sec	Q KJ/mm	$t_{8/5}$ sec
1	145	125	18.1	3.17	197	2.5	0.72	4.3
2	150	198	24.7	2.08	128	3.9	1.00	8.5
3	145	185	24.5	2.22	142	3.5	1.04	8.9
4	150	183	23.8	2.32	152	3.3	1.05	9.3
5	145	175	23.8	2.36	156	3.2	1.04	8.9

2.2. Tensile testing

Tensile testing was done using standard procedure with round specimens for BM and rectangular specimens for welded joint. Results are shown in Tables 7 and Fig. 2 for BM as well as in Table 8 and in Fig. 3 for welded joint, indicating failure in the BM, as shown in Fig. 4 as well.

Table 7. Tensile properties for BM

Specimen Designation	Yield Stress, $R_{p0.2}$, MPa	Tensile Strength, R_m, MPa	Elongation, A, %
BM - 1	1017	1064	19.6
BM - 2	1009	1060	18.1
BM - 3	1020	1065	17.9

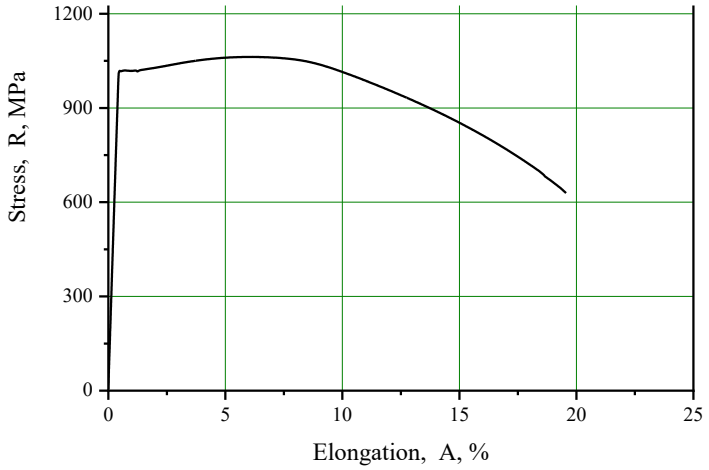


Figure 2. Diagram stress-strain for BM

Table 7. Tensile properties for welded joint

Specimen Designation	Tensile Strength, R_m, MPa	Fracture position
WJ – 1.1	1074	BM
WJ – 1.2	1060	BM
WJ – 1.3	1055	BM

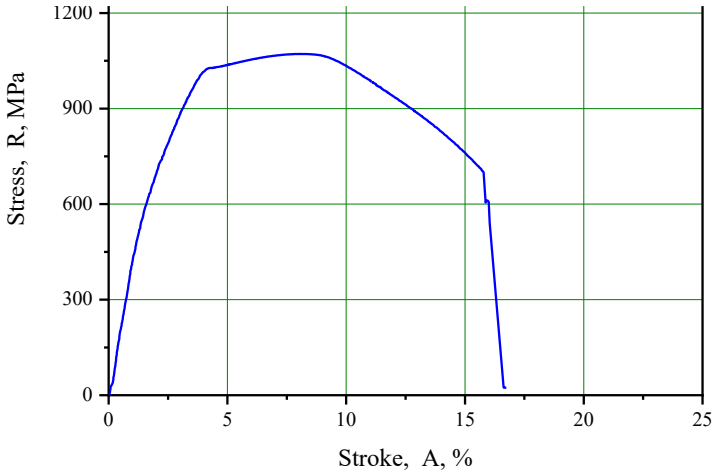


Figure 3. Diagram stress-strain for welded joint



Figure 4. Specimen WJ 1-1 after failure

2.3. Impact toughness

Impact toughness was evaluated using the instrumented Charpy pendulum, to enable separation of crack initiation and propagation energies, as described in details in [9]. Typical diagrams for BM, WM and HAZ at all 4 testing temperatures are shown in Figs. 5-7. One can see that total energy is decreasing significantly with temperature decrease, whereas differences in different zones of welded joint are not significant. As shown in Fig. 8, the DBTT for BM is -67 ºC, for WM -58 ºC and for HAZ -65 ºC.

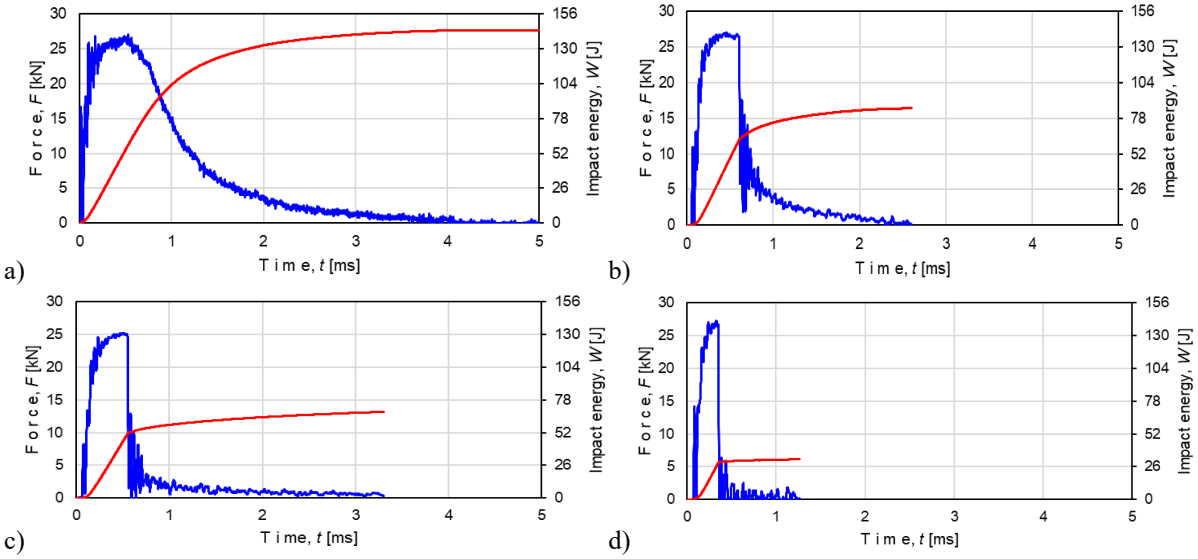


Figure 5. Force and impact energy vs. time for BM at a) +20°C, b) -20°C, c) -40°C, d) -60°C

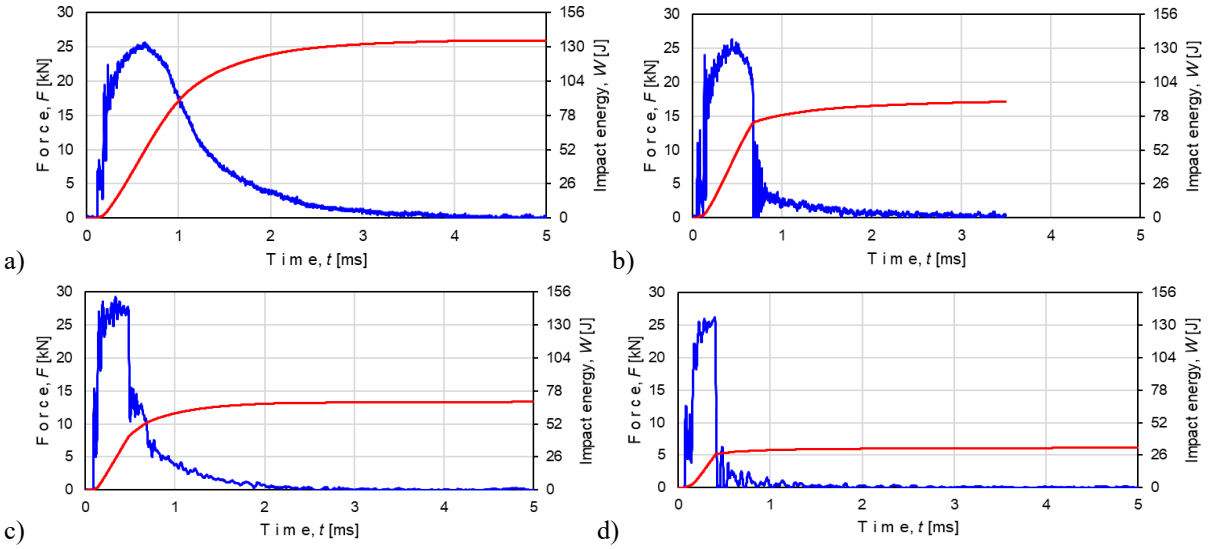


Figure 6. Force and impact energy vs. time for HAZ at a) +20°C, b) -20°C, c) -40°C, d) -60°C

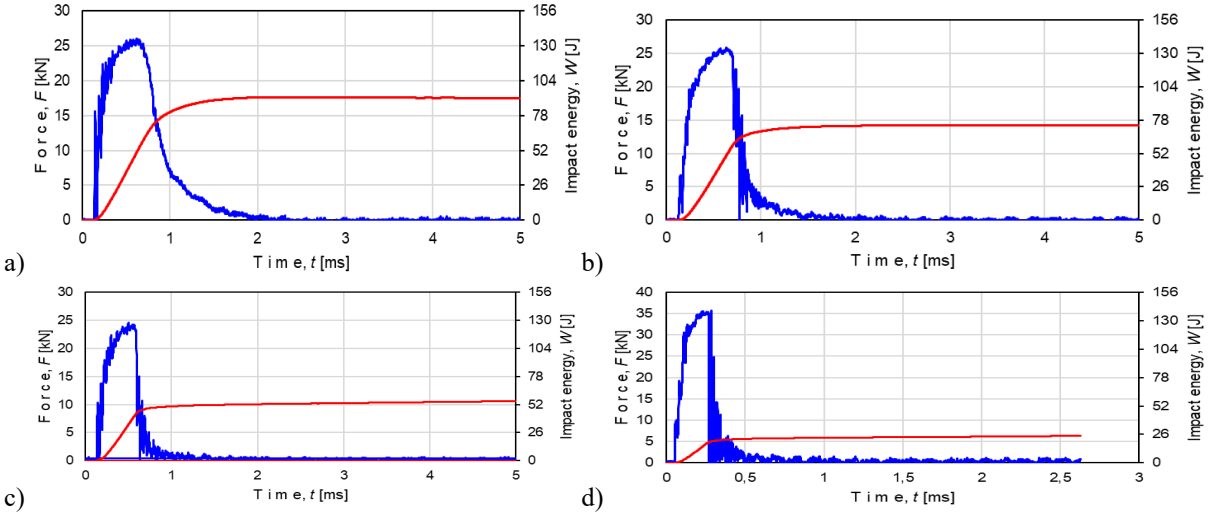


Figure 7. Force and impact energy vs. time for WM at a) +20°C, b) -20°C, c) -40°C, d) -60°C

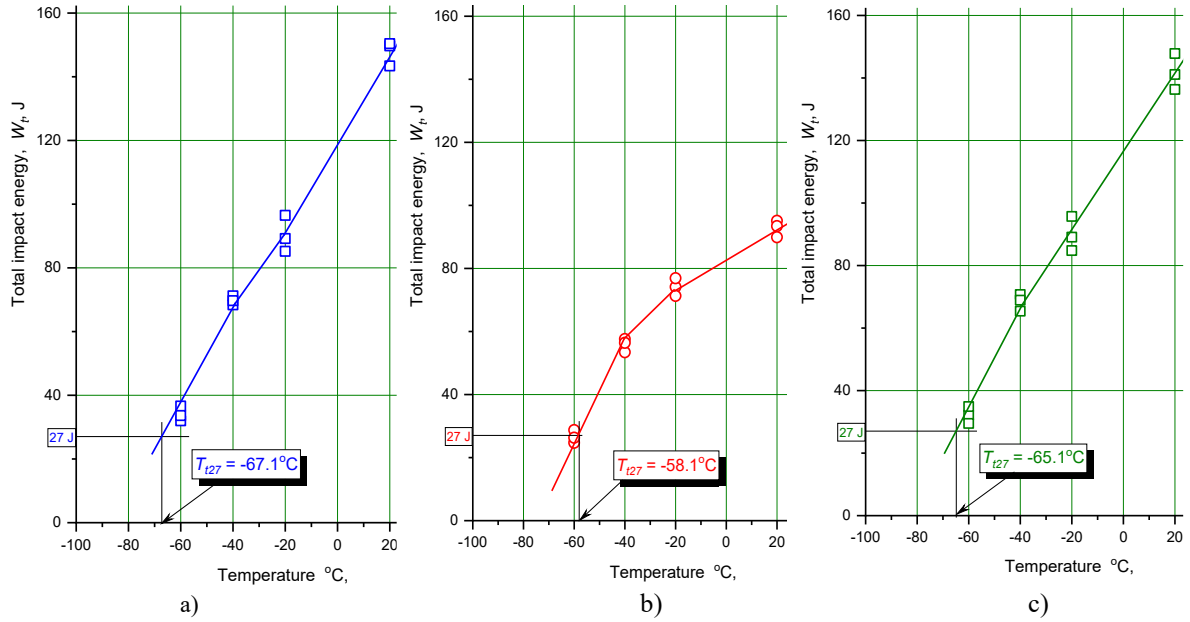


Figure 8. Dependence of total impact energy W_t on temperature a) BM, b) WM, c) HAZ, [14]

2.4. Fracture toughness

Fracture toughness was evaluated using three point bending specimens, Fig. 9, in accordance with the standard ASTM E1820-20 "Standard Test Method for Measurement of Fracture Toughness" [13]. Three groups of specimens were made, depending on the fatigue crack tip position in the welded joint, BM, WM and HAZ.

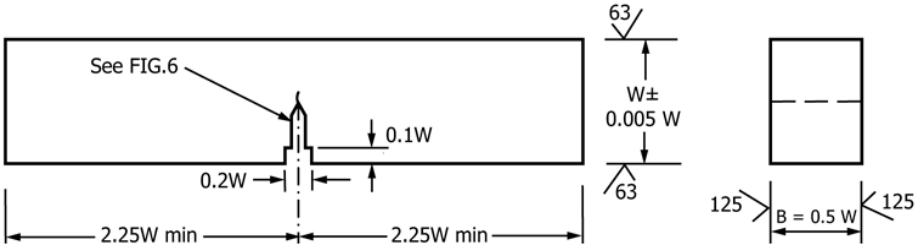


Figure 9. Standard specimen

Standard procedure included data acquisition from a servo-hydraulic system (load cell, displacement and COD extensometer), to construct the J-Δa curve and to evaluate J_{Ic}. Values of fracture toughness K_{Ic} can be calculated as follows:

$$K_{Ic} = \sqrt{\frac{J_{Ic} \cdot E}{1-\nu^2}} .$$

Results are shown in Table 8 as the minimum values of J_{Ic} and K_{Ic} obtained by testing of 3 specimens in each welded joint zone.

Table 8. Results for K_{Ic} via J_{Ic}

	BM	HAZ	WM
J_{Ic}, kJ/m^2	104.5	91.7	60.8
K_{Ic}, MPa√m	155.3	145.5	118.4

DISCUSSION

Welded joint heterogeneity effect was very low in the case of DBTT, i.e. total impact energy, as well as on the energies for crack initiation and propagation energies, as shown in Fig. 5-8, indicating the highest crack resistance of BM, as expected, but similar behaviour of WM and HAZ. Except for relatively low energy for crack initiation at -60 ºC, all other energies under impact loading are sufficient and relatively high.

Slightly stronger effect of crack tip position was obtained for fracture toughness values, as shown in Table 8, indicating 23% reduction of BM value in WM. Anyhow, once again, all fracture toughness values are relatively high and certainly satisfying for more extensive use of this steel for welded constructions which would benefit of reduced weight.

CONCLUSIONS

Based on the obtained results, it can be concluded that SIMAXX 1000 steel and its welded joints can be safely used under impact loading since its DBTT is close to -60 °C, but only if there is no pre-existing crack. On the other hand, even in the presence of cracks, SIMAXX 1000 is not sensitive to unstable crack growth under static loading.

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