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INVESTIGATION OF ELASTIC-PLASTIC FRACTURE MECHANICS PARAMETERS OF QUENCHED AND TEMPERED HIGH-STRENGTH STEEL WELDS

ISTRAŽIVANJE PARAMETARA ELASTOPLASTIČNE MEHANIKE LOMA ZAVARA POBOLJŠANOG ČELIKA VISOKE ČVRSTOĆE

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- elastic-plastic fracture mechanics parameters
- welded joints
- S690QL, S890QL

Ključne reči
- poboljšani čelici povišene čvrstoće
- parametri elasto-plastične mehanike loma
- zavareni spojevi
- S690QL, S890QL

Abstract

The high-strength quenched and tempered steels in high stressed structures allow significant reduction of the plate thickness, and thus lighter structures. Such steels easily meet customer high strength requirements with satisfactory toughness, even at temperatures down to –60°C. Due to lack of supported complete design codes, and modest experience, these steels require further investigation. This paper outlines the results of standard tests of elastic-plastic fracture mechanics parameters, e.g. crack growth resistance curves, J-Δa, CTOD-Δa, as well as evaluation of critical material properties, J_{Ic}, $CTOD_{Ic}$, and elastic fracture mechanics parameter K_{Ic}, for both, base and weld metal.

Izvod

Upotreba poboljšanih visokočvrstih čelika u visoko opterećenim konstrukcijama omogućava značajno smanjenje debljine, te time i lakše konstrukcije. Pored visoke čvrstoće, ovi čelici poseduju i zadovoljavajuću žilavost na temperaturama do –60°C. S obzirom da nisu potpuno zastupljeni u projektnim kodovima, uz skromno eksploatacijsko iskustvo, ovi čelici zahtevaju dalje istraživanje. U ovom članku dati su rezultati standardnih ispitivanja parametara elasto-plastične mehanike loma, t.j. krivih otpornosti na rast prsline, J-Δa, CTOD-Δa, kao i procena kritičnih parametara, J_{Ic}, $CTOD_{Ic}$, i parametra elastične mehanike loma, K_{Ic}, za osnovni metal i metal šava.

INTRODUCTION

Development trends of high-strength (HS) steels are defined by high mechanical, technological and design demands that provide corresponding safe, optimum and reliable use in structures as mobile cranes, bridges, road and train vehicles, mining equipment, pressure vessels, pipelines, ships and offshore structures. Those trends are generally characterised by use of relatively novel chemical and production concepts, as microalloying (MA), low-alloying (LA), thermo-mechanical (TM) rolling, accelerated cooling (ACC), quenching and tempering (QT).

The strongest class of HS steels are those produced by QT treatment (HSQT), with the yield strength in specified range from 460 MPa up to 960 MPa.

Thus, use of HSQT steels provide almost "doubled" benefits contained in reduced structure weight, and in particular reduced fabrication costs, especially for welding, due to less filler material, welding time, and therefore less expenses for testing the welds. For optimum application of HSQT steels in high-loaded structures good weldability and high-resistance against brittle fracture are required, which is provided by relatively low carbon equivalent (CE) and satisfactory toughness at sub-zero temperatures.

However, use of HSQT steels is often restricted, due to limitation of yield to tensile strength (Y/T) ratio in several design codes. Also, there is lack of known customer or steel behaviour experience, and in particular lack of reliable and appropriate knowledge on HSQT fracture mechanics toughness, e.g. resistance to brittle fracture or ductile tearing and transition temperature. Nevertheless, there is an advance in fracture mechanics, particularly assessment procedures developed (as Eurocode 3, SINTAP or novel FITNET), where material impact toughness and fracture mechanics properties may be employed to provide more reliable and safe assessment or design. More over, there is a research, based on known fracture mechanics toughness properties, which shows that the Y/T-ratio is not a proper value for assessment of HSQT steel structural safety in case of multiaxial loading, /1/.

Of special concern considering the most used application of HSQT steels in welded structures is weld heterogeneity or mismatching. Particularly, welds are well known as defect-containing structural joints, where application of fracture mechanics (FM) comes to its distinctive usage, /2-4/.

Therefore, to gain more confidence in HSQT steels by means of employing material fracture parameters, conventional tensile and impact tests must be followed by testing of FM parameters, /5/, as defined in relevant testing standards, e.g. ASTM E1820 for base metal, or BS 7448 for base and weld metals. Due to the general high toughness of modern HSQT steels, the application of LEFM concepts, K_{Ic}, does not lead to proper results, and therefore EPFM parameters as CTOD or J-integral become important, /6/.

The paper will outline known standardised or required HSQT steel properties, as well as results of experimental investigation of tensile, impact and EPFM properties of two welds made in S690QL and S890QL steels.

KNOWN PROPERITES AND WELDABILITY ISSUES

In accordance to EN 10025-6, HSQT steels are provided in strength classes from S460Q to S960Q, where three-digit number after letter "S" (for structural), represents minimum required yield strength, R_{eH}, and the letter "Q" is quenching and tempering (QT) delivery condition. There are three toughness classes specified for transition temperatures, T_{27J},: –20°C, –40°C ("L") and –60°C ("L1"), /7/.

Considered steels, S690QL and S890QL, must have maximum carbon equivalent (CE), 0,65 and 0,72, in respect (for thicknesses lesser than 50 mm).

Table 1 presents chemical composition of product analysis for all grades, and Table 2 presents required tensile properties and impact energy of two subject grades, /7/.

Steels specified in /7/ do not have unlimited suitability for various welding processes, since the behaviour of a steel during and after welding depends not only on the material but also on component dimensions and shape, and on the manufacturing and service conditions.

General requirements for arc welding of HSQT steels are specified in EN 1011-2. The main weldability problem of HSQT steels is the sensitivity to cold cracking that increases as increasing product thickness and strength level. Due to typical fine-grained microstructure, HSQT steels may suffer significant grain coarsening, and toughness degradation, if excessive heat input is applied during welding.

For optimal welding and avoidance of cold cracking, on one side, and toughness degradation, on the other, EN 1011-2 approach is based on "Cooling concept", $\Delta t_{8/5}$.

By considering provided calculations in EN 1011-2 for required preheat temperature, T_p, and heat input, E, due to required range of $\Delta t_{8/5}$, it is possible to define the optimum welding condition. Figure 1 shows an example of such optimum welding condition, for $\Delta t_{8/5}$ in range of 5-20 s (up to 15 s, for S890 grade), which is a most proposed range from steel manufacturers, /1, 8/.

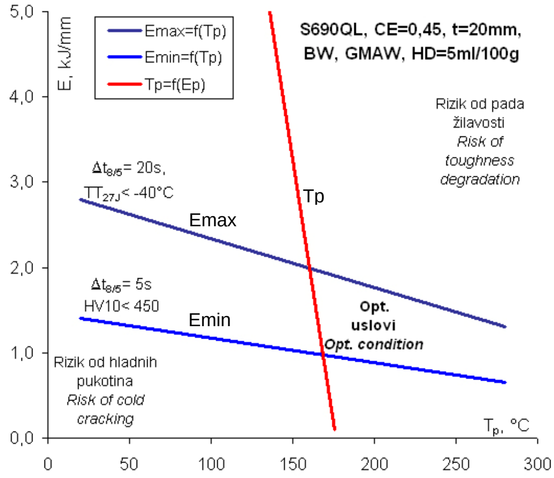


Figure 1. Optimum welding condition for commercial steel grade, S690, metal 20 mm thick, with CE = 0.45, and selected GMAW welding process; E = 1.0–2.0 kJ/mm, T_p = 160–170°C.
Slika 1. Optimalni uslovi zavarivanja za komercijalni kvalitet čelika S690QL, debljine 20 mm, sa CE = 0,45, i izabrani MAG postupak zavarivanja; E = 1,0–2,0 kJ/mm, T_p = 160–170°C

Table 1. Required chemical product analysis, EN 10025-6 (all grades).
Tabela 1. Zahtevani hemijski sastav čelika, EN 10025-6 (svi kvaliteti)

Grade	C max	Si max	Mn max	P max	S max	N max	B max	Cr max	Cu max	Mo max	Nb max	Ni max	Ti max	V max	Zr max
Q QL QL1	0.22	0.86	1.80	0.030 0.025 0.025	0.017 0.012 0.012	0.016	0.006	1.60	0.55	0.74	0.07	2.1	0.07	0.14	0.17

Table 2. Required mechanical properties of two subject steel grades, EN 10025-6.
Tabela 2. Zahtevane mehaničke osobine ispitivanih čelika, EN 10025-6

Grade	Material number	Required tensile properties			Required toughness - impact energy, J at testing temperature			
		Yield strength min. R_{eH}, MPa	Tensile strength R_m, MPa	Elongation A, %	0°C	–20°C	–40°C	–60°C
S690QL	1.8928	690	770–940	14	50J	40J	30J	–
S890QL	1.8983	890	940–1100	11	(35J)	(30J)	(27J)	

Except impact toughness requirements, there are no other required fracture properties for HSQT steels, as LEFM or EPFM parameters in standards or design codes. It is up to design engineers to consider such material properties, or calculate it as a requirement, in designing or assessing different type of steel structures. For such selection and calculations, it is of importance to consider all loads and type of steel structure. For example, to select reliable material, American pipeline regulations (ASME B31.8) require minimum shear value (percentage of ductile fracture) of Charpy specimens on design temperatures, as well as impact energy, CVN (or KV), for brittle fracture control or for ductile crack arrest, /9/. Similarly, European regulations, such as Eurocode 3 (App. C and EN 1993-1-10), define minimum service temperature according to known T_{27J} transition temperature, or maximum permissible BM thickness, which depends on reference temperature, known stress level and presumed flaws, /8, 10/.

When considering FM parameters, more exact are national materials' specifications, as Norsok M-120, /11/, which define required $CTOD_{Ic}$ = 0.25 mm, for base material with thickness above 40 mm (weldable offshore S690). Norsok M-101, /12/, standard for fabrication of steel structures, states that for welding procedure qualification (WPQR or PQR, for BM thickness above 50 mm) required critical value, $CTOD_{Ic}$ (WM), must be specified by design engineer.

Available reports on FM testing of HSQT steels show lesser value of FM parameters in comparison to HSACC steels, and mostly for S690 grade (BM only) in range of: $CTOD_{Ic}$ = 0.140–0.235 mm, K_{JIc} = 167–246 $MPam^{0.5}$, /1, 13/.

Generally, it is obvious that there is a deficiency of known or required FM parameters for HSQT steels.

This lack of knowledge and due to limited experience, FM evaluation of HSQT structural steels requires detailed examination. This is important, if novel procedures and techniques (Eurocode, FITNET), are about to be employed for design or assessment of HSQT steel structures.

EXPERIMENT SETUP AND TESTING

Pairs of HSQT steel plates of grades S690QL and S890QL are machined for X-joint and butt-welded using GMAW process. Essential parameters for welding procedure are given in Table 3. Table 4 shows results of limited chemical analysis performed on both, weld fusion zone (WM) and base metal (BM). Typical welds macrograph, as well as hardness, HV10, and its mismatch distribution, MM (HV_{BM}/HV_{WM}), along root line are shown in Fig. 2.

Tensile tests are performed in accordance to EN 10002 and EN 895, for base metal (BM) and welded joint, respectively. Lateral specimens (LS) perpendicular to welded joint, with weld metal at the centre, and complete weld metal (WM) specimens are sampled and prepared for welded joint tensile testing (Table 5).

Impact toughness (EN 10045-1) of BM, WM and HAZ is tested on instrumented Charpy pendulum, using standard specimens 10×10 mm and V2-notch, to determine total impact energy, KV, separated in energy for crack initiation, KV_i, and crack propagation, KV_p (Fig. 3). For investigation of transition temperature, T_{27J}, corresponding to 27 J total impact energy, impact testing is performed at various temperatures, from +20°C to –60°C (–100°C), including –40°C, for which BM impact energy is specified to min. 27 J (Fig. 4).

Elastic-plastic fracture mechanics (EPFM) parameters for BM and WM are determined in accordance to ASTM E1820 and BS 7448-2, using three-point bend (single-edge notched – SEB) specimens. Full-thickness WM specimens are perpendicular to welded joint (Table 6). Typical fracture surface appearance is presented in Table 7.

Typical results of EPFM resistance curves are presented in Fig. 5 for S690QL and in Fig. 6 for S890QL steel. All specimens exhibited testing in plane stress condition, ductile fracture and load maximum in load-displacement curves, followed by stable crack propagation.

Table 3. Welding procedure details.
Tabela 3. Detalji postupka zavarivanja

Steel	Joint	Process	Position	Welding parameters		Thickness	Consumable Boehler	Preheat temperature	Heat input	Calculated $\Delta t_{8/5}$
				Current	Voltage					
S690QL	X	GMAW (135)	Flat (PA)	140–250A	21–28V	30 mm	X70-IG	200°C	1–1.2 kJ/mm	6–10 s
S890QL						20 mm	X90-IG	150°C		

Table 4. Chemical composition after welding.
Tabela 4. Hemijski sastav posle zavarivanja

Steel	Location	C	Si	Mn	P	S	Cr	Cu	Mo	Ni	Ti	CE
S690QL	BM	0.146	0.167	0.962	0.010	0.005	0.299	0.125	0.400	0.084	0.030	0.46
	WM	0.100	0.382	1.450	0.010	0.005	0.315	0.007	0.289	1.310	0.025	0.55
S890QL	BM	0.147	0.176	1.450	0.010	0.005	0.506	0.125	0.260	0.020	0.046	0.55
	WM	0.110	0.660	1.630	0.010	0.007	0.394	0.125	0.486	0.710	0.045	0.61

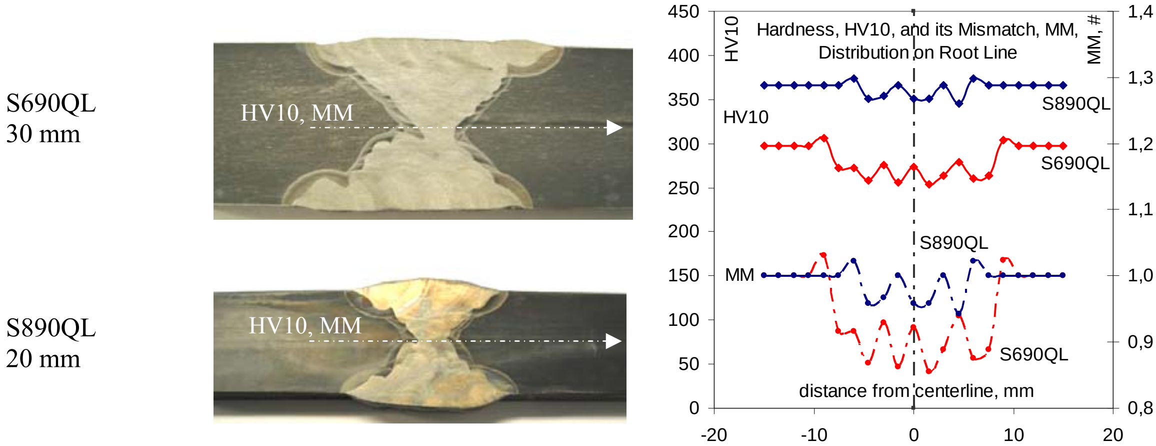


Figure 2. Macro-section, hardness HV10 distribution and matching levels, MM, of S690QL and S890QL welds.
Slika 2. Makroizbrusak, raspodela tvrdoće HV10 i odnos mečinga, MM, spojeva na S690QL I S890QL

Table 5. Tensile testing results.
Tabela 5. Rezultati ispitivanja zatezanjem

 Specimen LS, S690QL welded joint, fracture in WM				 Specimen LS, S890QL welded joint, fracture in HAZ		
Range of tensile testing results (Lateral specimens, LS, normal to welded joint)						
Specimen/Steel	S690QL			S890QL		
	BM	WM	LS	BM	WM	LS
Yield strength, $R_{p0.2}$, MPa	750–775	695–720	723–740	935–962	878–915	870–937
Matching ratio, $R_{p0.2(WM)}/R_{p0.2(BM)}$	0.93		–	0.94–0.95		–
Tensile strength, R_m, MPa	857–878	770–779	782–787	1016–1024	963–984	974–999
Strength ratio, $R_{p0.2}/R_m$ (Y/T)	0.88	0.91	0.93	0.93	0.92	0.92
Elongation, A_f, %	15.3–15.9	14.4–16.4	10.9–11.5	12.6–13.1	17.8–18.7	10.5–11.1
Cross section contraction, Z_f, %	72.4–75.5	61.2–61.7	50.6–57.8	63.3–67.2	58.4–59.9	32.5–38.5

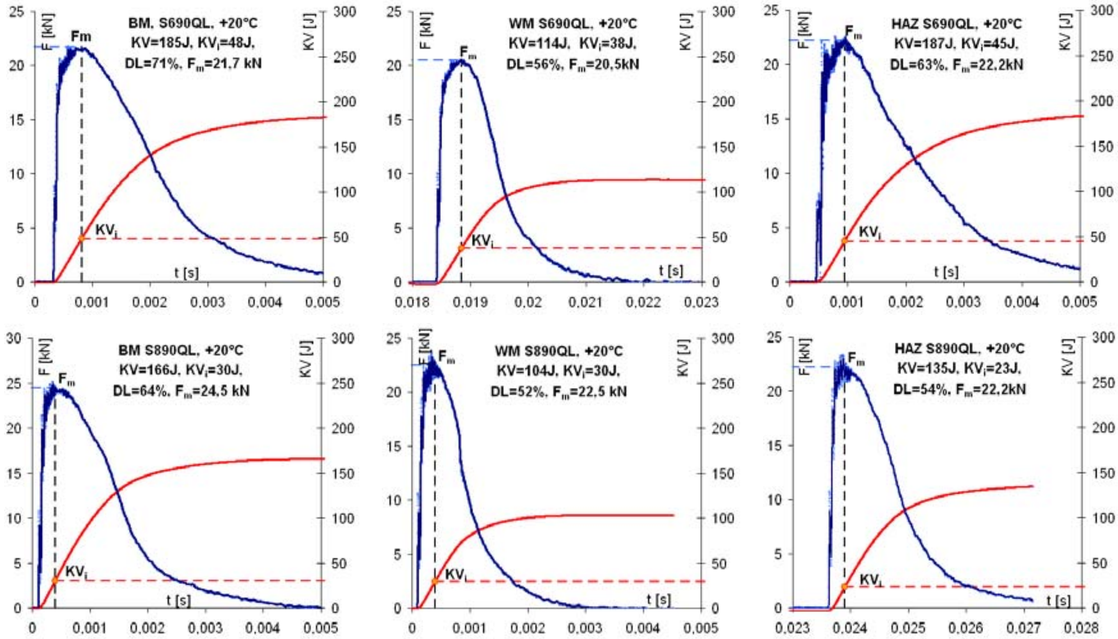


Figure 3. Typical results of instrumented Charpy testing of impact energy for base metal, weld metal, and HAZ at room temperature.
Slika 3. Tipični rezultati ispitivanja na instrumentiranom Šarpi klatnu za osnovni materijal, metal šava i ZUT na sobnoj temperaturi

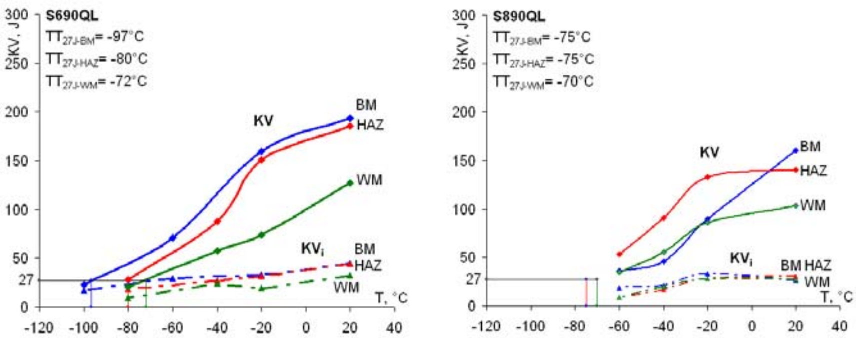


Figure 4. Results of impact toughness vs temperature testing of weld zones.
Slika 4. Rezultati ispitivanja udarne žilavosti u zavisnosti od temperature za uzorke zavarenih spojeva

Table 6. Dimensions of SEB specimen and view (S890QL steel, WM).
Tabela 6. Dimenzije SEB epruvete i izgled (čelik S890QL, WM)

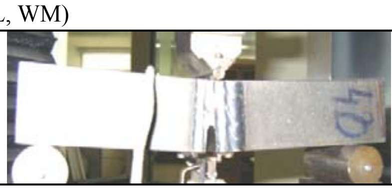
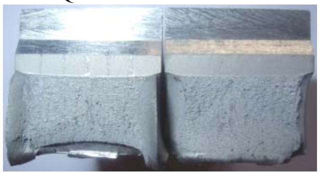
Specimen	S690QL		S890QL		
	BM	WM	BM	WM	
Width, B, mm	25	30	15	20	
Thickness, W, mm	25	30	30	40	
Initial crack length, a_0, mm	11.82–12.70	15.35–17.98	13.73–14.26	22.46–25.16	

Table 7. Typical appearance of fracture surfaces of FM specimens (initial crack length a_0, mm).
Tabela 7. Tipični izgled površine preloma FM epruveta (početna dužina prsline, a_0, mm)

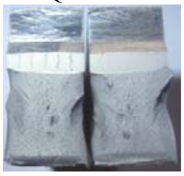
S690QL



BM, a_0 = 11.90 mm

WM, a_0 = 17.17 mm

S890QL



BM, a_0 = 14.03 mm

WM, a_0 = 22.46 mm

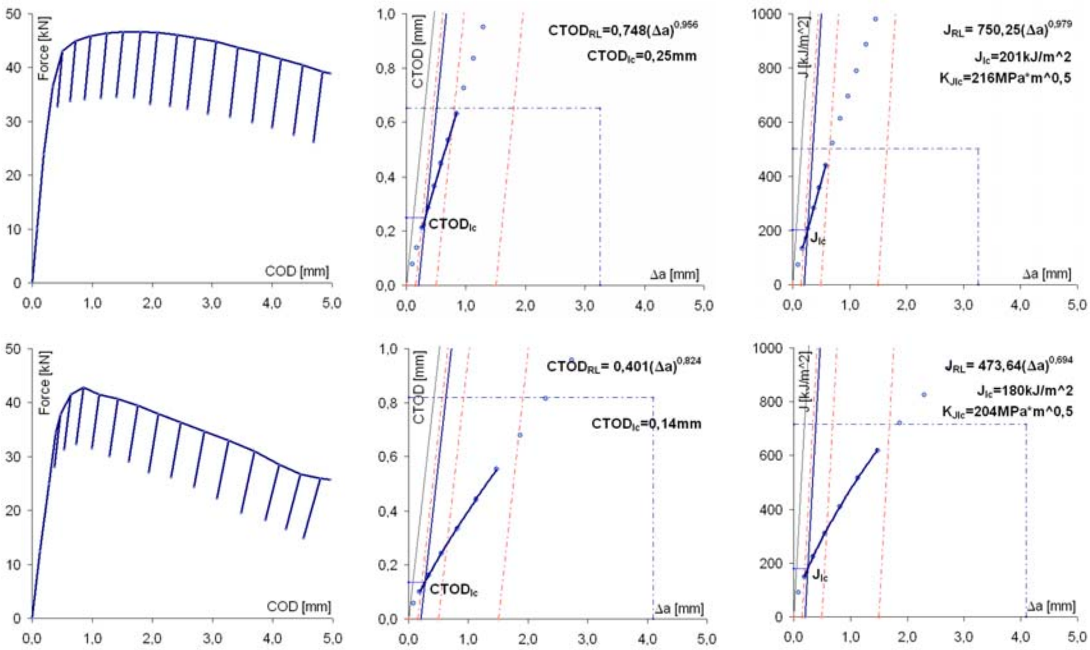


Figure 5. Typical testing results of EPFM parameters for base metal of S690QL (up) and S890QL (down).
Slika 5. Tipični rezultati ispitivanja EPFM parametara za osnovni materijal S690QL (gore) i S890QL (dole)

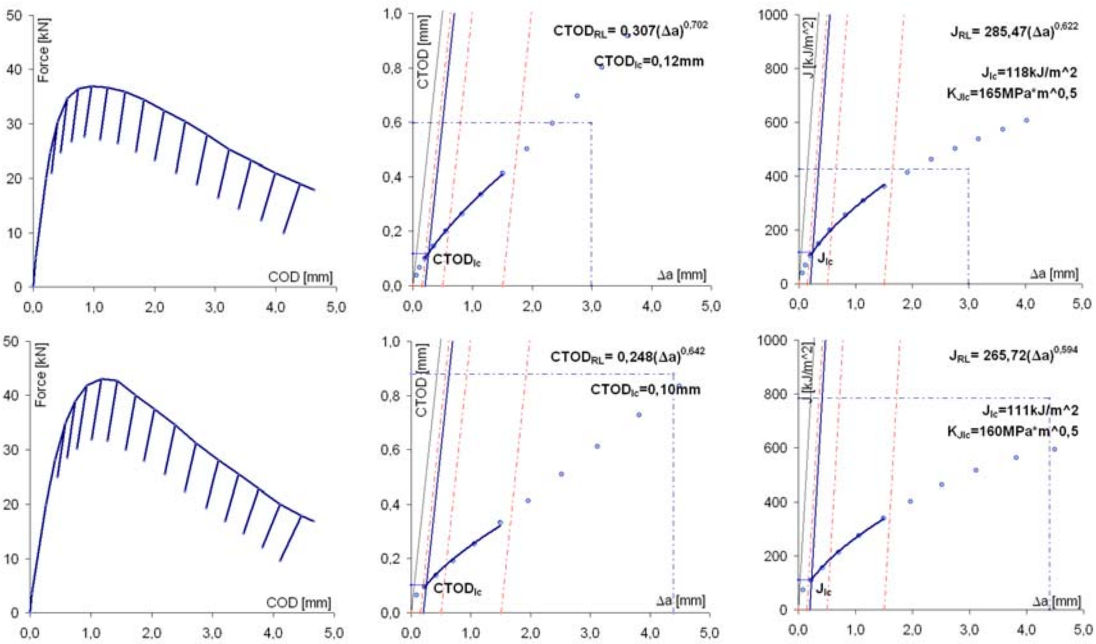


Figure 6. Typical testing results of EPFM parameters for weld metal of S690QL (up) and S890QL (down).
Slika 6. Tipični rezultati ispitivanja EPFM parametara za metal šava S690QL (gore) i S890QL (dole)

Applying qualification ranges for CTOD, J-integral, and crack growth Δa, regression lines (Table 8) and crack growth resistance, R-curves (Table 9) are determined. Using qualified J_{Ic} values, the corresponding K_{JIc} calculation is performed, since plane strain conditions for K_{Ic} determination are not satisfied.

Table 8. Typical results of regression lines, or EPFM R-curves.
Tabela 8. Tipični rezultati regresionih krivih, ili EPFM R-krivih

Steel	Crack in	a_0/W	R-curve, regression line, Δa, mm	
			CTOD, mm	J, kJ/m^2
S690QL	BM	0.476	$0.748(\Delta a)^{0.956}$	$750(\Delta a)^{0.979}$
	WM	0.601	$0.307(\Delta a)^{0.702}$	$285(\Delta a)^{0.622}$
S890QL	BM	0.461	$0.401(\Delta a)^{0.824}$	$474(\Delta a)^{0.694}$
	WM	0.561	$0.248(\Delta a)^{0.642}$	$266(\Delta a)^{0.594}$

Table 9. Results of critical EPFM and LEFM parameters.
Tabela 9. Rezultati za kritične EPFM i LEFM parametre

Steel	Initial crack in	a_0/W	EPFM parameters		LEFM parameter
			$CTOD_{Ic}$, mm	J_{Ic}, kJ/m^2	K_{JIc}, MPam$^{0.5}$
S690QL	BM	0.476–0.512	0.250–0.275	201–238	216–235
	WM	0.512–0.601	0.119–0.146	118–132	164–175
S890QL	BM	0.453–0.473	0.136–0.146	173–180	200–204
	WM	0.561–0.629	0.102–0.109	111–126	160–170

CONCLUSIONS

In accordance to EN 10025-6, the tested standard HSQT steels S690QL and S890QL have good combination of high strength, acceptable ductility and satisfactory impact toughness at moderate sub-zero temperature.

Welded joint heterogeneity and mismatching effect may significantly influence HSQT steel structure design and performance. Therefore, an appropriate hardness, tensile, impact, as well as fracture mechanics parameters testing of both BM and WM are of utmost importance.

Chemical analysis of investigated steels show that main differences are in higher Ni and Mn content of WM in comparison to BM. Values of CE are 0.46 for BM and 0.55 for WM for S690QL steel, and 0.55 and 0.61 for S890QL, respectively. However, even WM exhibits higher CE compared to BM, both steels have undermatched welds, or UM = 0.93 for S690QL, and 0.95 for S890QL.

Steel S690QL shows better fracture resistance, both, in impact (KV, KV_p, T_{27J}) and FM parameter values (CTOD, J-integral) than S890QL. Crack impact initiation energies, KV_i, mostly remain similar for both steels for the testing temperature range.

High impact toughness values (KV and T_{27J}) of HAZ, even at some temperatures better than BM for S890QL steel, may be explained with initial notch sampling dominantly within normalised or fine-grained, FG-HAZ zone. Therefore, it is of particular importance the investigation of coarse-grained, CG-HAZ microstructure, which could be possible by use of welding thermo-cycle simulation techniques, better than sampling specimens from real welds.

Critical EPFM values that define initiation of stable ductile tearing of BM have quite higher values of $CTOD_{Ic}$, J_{Ic} and K_{JIc}, in comparison to WM. Thus, WM of S690QL steel has almost half (50%) of crack growth resistance of BM, while in S890QL this difference is lesser (WM/BM, 70%). In addition, BM of S690QL has almost two times better $CTOD_{Ic}$, compared to S890QL. Other two critical values, J_{Ic} and K_{JIc}, for BM do not show so high difference between two steels (lower than 15%). Such difference is lesser while comparing WM values. Moreover both WM(s) show similar crack-growth resistance.

All FM tested specimens have showed ductile fracture and load maximum in the load-displacement curves, and thus considerable resistance to ductile tearing.

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