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ASSESSMENT OF THE BEHAVIOUR OF FATIGUE LOADED HSLA WELDED STEEL JOINT BY APPLYING FRACTURE MECHANICS PARAMETERS

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Abstract: In discussion of the welded joints from fracture mechanics point of view, it is assumed that the welded joint is pre-cracked and that therefore fatigue life of the pre-cracked structure is determined by the period of crack growth under variable loading. Experimental data obtained by testing provide a substantial foundation for better understanding and explanation of the phenomenon of fatigue of a material. Low-cycle fatigue (LCF) occurs during charging and discharging of the reactors, pressure vessels and pipelines; it can be accelerated by additional negative effect of temperature variation and aggressive effect of vessel contents during exploitation of the equipment in processing industry.

In present paper, the results of measurement of *J*-integral of weld metal made of low-alloy high-strength steel, used for manufacture of the pressure vessels in the process of powder welding, at LCF have been presented.

Keywords: LCF, *J*-integral, HSLA steel, process equipment

1. INTRODUCTION

Material fatigue can be clarified to a large extent using the results obtained by experimental examination, particularly so when one should understand the behaviour of a crack in a material with heterogeneous structure such as welded joint. Thus, we should conduct fatigue testing of fracture mechanics of the specimens with notch and crack for determination of the stress-intensity factor, K_I and crack opening displacement, *COD*, or for determination of energy parameter, *J*-integral. In addition, one should compare conditions for crack propagation at high-cycle fatigue (HCF) and low-cycle fatigue (LCF) on one hand, and behaviour of the welded joint on the other hand. Based on it, one can get a picture of behaviour of the welded joint affected by fatigue loading, and the possibility of application of *J*-integral as a universal parameter of elastic and plastic behaviour of a material with a crack, and their effect on the problem of fatigue-crack propagation.

In present paper, measurements of *J*-integral at LCF for the specimens made of low-alloy high-strength HSLA steel (PM) and weld metal (WM) of their welded joints have been presented.

2. MATERIAL

For these tests, HSLA steel of NIONIKRAL 70B designation with welded joints made in submerged arc-welding (SAW) process with US-80B wire was chosen.

Chemical composition of tested material has been presented in Tab. 1 and chemical composition of the wire for the SAW process in Tab. 2, respectively.

Table 1 Chemical composition of tested batch of NIONIKRAL 70B steel (weight %)

C	Si	Mn	Cr	Ni	Mo	P	S
0.19	0.4	1.11	1.06	2.59	0.25	0.019	0.024

Table 2 Chemical composition of US-80B wire for SAW of NIONIKRAL 70B steel (weight %)

C	Si	Mn	Cr	Mo	P	S
0.09	0.19	2.15	0.49	0.84	0.014	0.013

Tensile properties of HSLA steel of NIONIKRAL 70B designation have been shown in Tab. 3 and tensile properties of WM of the welded joint weld in the SAW process with US-80B wire have been shown in Tab. 4.

Table 3 Tensile properties of NIONIKRAL 70B steel

Ultimate tensile strength, MPa	Yield stress, MPa	Elongation A_5, %	Reduction of cross section Z, %
842	707	16	56.5

Table 4 Tensile properties of WM of tested welded joint

Ultimate tensile strength, MPa	Yield stress, MPa	Elongation A_5, %	Reduction of cross section Z, %
848	701	17	46.2

3. PLAN OF THE EXPERIMENT

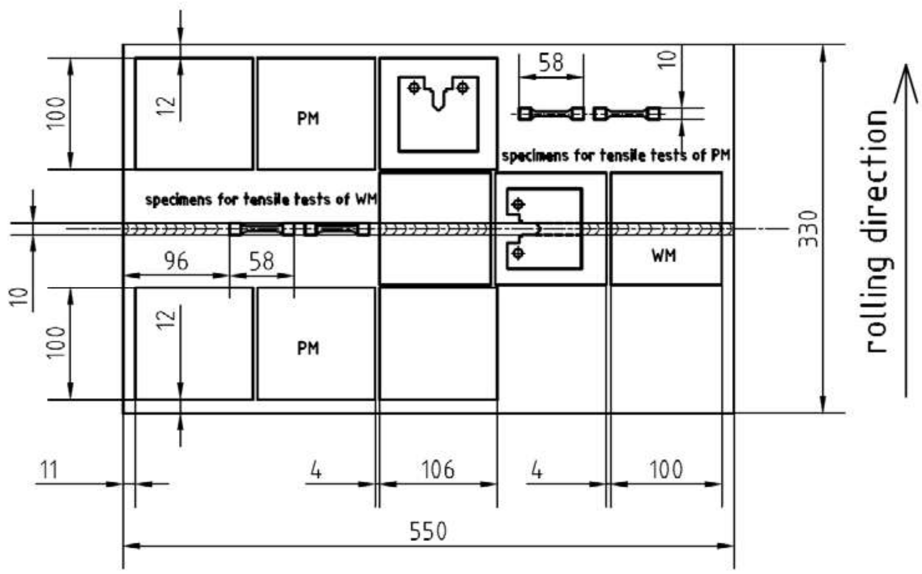
Welded plates, specimens to be cut from the plates, order of cutting of the specimens and their testing are defined by the work plan.

Experimental examination of the behaviour of NIONIKRAL 70B and WM of its welded joint included the following:

1. determination of the properties of PM and WM (the results have been shown in Tabs 3 and 4);
2. determination of fatigue-crack growth at HCF;
3. measurement of compliance of a specimen and determination of dependence of compliance and crack length;
4. establishment of dependence of fatigue-crack growth rate (increase of crack length per cycle) and range of stress-intensity factor;
5. determination of J_R-curve and critical value of J_{IC}-integral, and
6. monitoring of J-integral value at LCF.

According to the plan for cutting shown in Fig. 1, from two welded plates dimensions of which were 550 x 330 x 12 mm round specimens for tensile tests and CT specimens for testing of fracture mechanics were made.

Figure 1 Plan for cutting of CT specimens and specimens for tensile tests cut from



PM and WM of SAW welded joint

In this paper, the results of monitoring of J-integral value at LCF will be presented; other results can be found in [1].

4. THE RESULTS OF TESTING OF J_R-CURVES WITH LCF PHASES

For application of HSLA steel in welded structures, its behaviour when affected by LCF is important, especially when a part of the structure contains a crack, [2-6].

4.1. TESTING OF SPECIMENS FROM PARENT METAL

CT specimens (B=11.85 mm; W=86 mm; a_0=32 mm) from PM were tested for resistance to cracks based on J_R-curves with phases of one-direction LCF for analysis of the effect of LCF on shape of J_R curves and value of J_{IC}. The data on testing of the subject specimen have been shown in Tab. 5.

As one can see from Tab. 5, testing was conducted in a few phases shown in Fig. 2. Taking into consideration noticeable proportion of LCF, in these tests residual strain, measured by the magnitude of residual COD, was monitored.

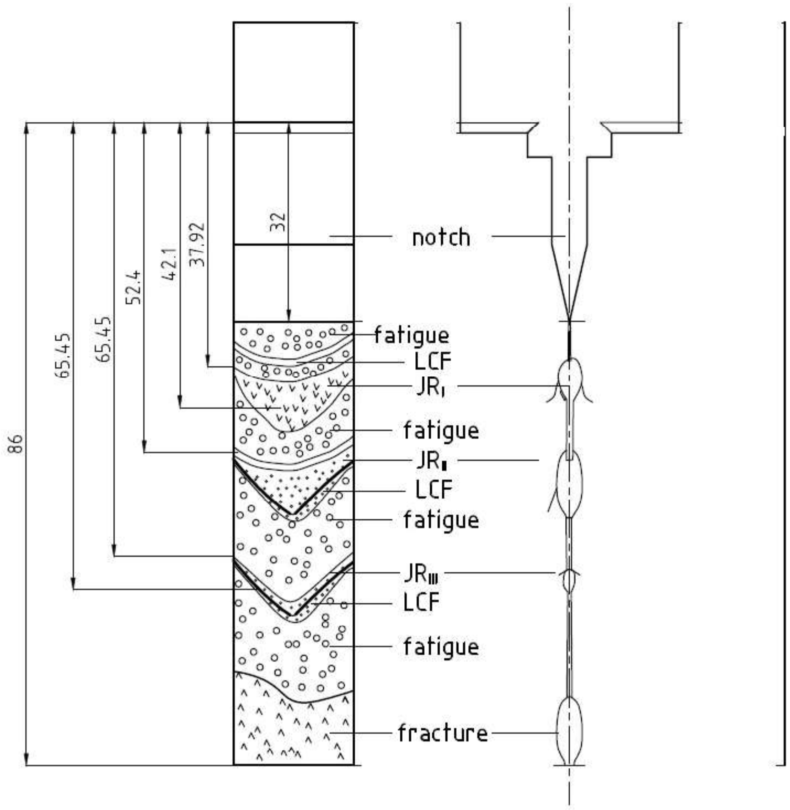


Figure 2 Fracture surface of CT specimen cut from PM

Table 5 Data on complex tests for determination of J_R –curves with phases of LCF for CT specimens taken from PM

	FATIGUE								COMPLIANCE				
										CRACK OPENING DISPLACEMENT (*COD*)			
Test phase	Upper force, F_{max}, kN	Lower force, F_{min}, kN	R=F_{max}/F_{min}	Frequency, f, Hz	Increase, No. of cycles, ΔN, cycle	Total No. of cycles, N cycle	Increase, crack length, Δa, mm	Total crack length, a, mm	Max static force, kN	Residual, μm	Current, μm	Total, μm	Compliance C, μm/kN
A								32	50		408	408	8.16
								32	70		576	576	8.23
								32	30	67	244	311	8.13
								32	50	67	408	475	8.16
B	36.1	5.1	0.14	26	5000	5000	2.7	34.7	70	67	597	664	8.53
	50	5.7	0.11	1	300	5300	1.2	35.9	50	96	435	531	8.7
	36.1	5.1	0.14	28	10^4	15300	2.02	37.92	30	96	280	376	9.33
C							4.18	42.1	89	96	3808	3904	
D									40	2816	504	3320	12.6
	32	4.8	0.15	21	2000	2000	0.5	42.6	40	2816	512	3328	12.8
	32.2	5.6	0.17	21	5000	7000	1.8	44.4	40	2816	608	3424	15.2
	32.2	4.8	0.15	21	5000	12000	3.1	47.5	40	2864	741	3605	18.53
	32.2	4.8	0.15	21	5000	17000	3.8	51.3	40	2920	939	3859	23.46
	40	4	0.1	0.9	100	17100	1.1	52.4	40	2934	1019	3953	25.74
E								53.6	45.5	2994	2568	5562	
	43.5	3.5	0.08		30		0.22	53.82	43.5	4426	160	4586	
								54.65	41.75	4558	2400	6958	
	35	5	0.14		18		0.4	55.05	39	5806	128	5934	
F	24.9	5.3	0.21	20	4200	4200	9.35	64.4	10	5878	688	6566	68.8
G							0.7	65.1	18.75	5966	2760	8726	
	18.5	2	0.11		30		0.15	65.25	18	7454	152	7606	
							0.2	65.45	17.25	7482	2416	9898	74.3
H	11.25	1.25	0.11	20	5010	5010	4.05	69.5					
	8.7	0.85	0.11	20	2100	7110	7.3	76.8					

A-static tension for determination of compliance; B-fatigue-crack propagation a_{0I} with determination of; C-J_R-curve; D-fatigue-crack propagation a_{0II} with determination of compliance; E-J_{RII}-curve with LCF phases; F-HCF; G- J_{RIII}-curve with LCF phase; H-HCF

4.2. TESTING OF SPECIMENS FROM WELD METAL

The plan of testing of CT specimen (B=11.8 mm; W=86 mm; a_0=32 mm) with a notch in WM differs from the previous one, as in this testing LCF has had the most important role. The data from this testing are presented in Tab. 6, but it should be noted that monitoring of the data on testing was stopped after the second LCF (R≈0.5).

5. DISCUSSION

5.1. TESTING OF SPECIMENS FROM PM

Starting compliance of the specimen with a notch in PM was determined by static loading (test phase A in Tab. 5).

Table 6 Data on complex tests for determination of J_R –curves with phases of LCF for CT specimens taken from WM

		FATIGUE								COMPLIANCE				
											CRACK OPENING DISPLACEMENT (*COD*)			
Test phase	Registered data point	Upper force F_{max}, kN	Lower force F_{min}, kN	$R=F_{min}/F_{max}$	Frequency, f, Hz	Increase No. of cycles, ΔN, cycle	Total No. of cycles, N cycle	Increase, crack length, Δa, mm	Total crack length , a, mm	Max. static force, kN	Residual, µm	Current, µm	Total, µm	Compliance C, µm/kN
A	1								32	35		242	242	6.93
B	2	36	3.6	0.1	25	200	200	0.5	32.5	35		252	252	7.2
	3	33	3.3	0.1	25	27600	27800	1.5	34	35		261	261	7.46
	4	33	3.3	0.1	25	14600	42400	2.4	36.4	35		280	280	8
C	5							4.1	40.5	88	944	915	1859	10.4
D	17	71	7.1	0.1	0.5	50	50			70		840		12
	18	70.5	7.05	0.1	0.5	50	100			69		862		12.5
	19	69	6.9	0.1	0.5	50	150			67		911		13.6
	20	66	6.6	0.1	0.5	50	200			62		992		16
	21	62	6.2	0.1	0.5	50	250			57		1049		18.4

	22	57	5.7	0.1	0.5	50	300			54		1064		19.7
	23	53	5.3	0.1	0.5	50	350			48		1113		23.2
	24	46	4.6	0.1	0.5	50	400			41		1148		28
	25	38	3.8	0.1	0.5	50	450			32		1145		35.8
	26	27	2.7	0.1	0.5	50	500	21	61.5	19	1500	906	2406	47.7
	27	19.84	9.9	0.5	0.5	50	50			22		1084		49.3
	28	21.92	10.96	0.5	0.5	50	100			21.6		1080		50
	29	21.52	10.76	0.5	0.5	50	150			213		1075		50.5
E	30	21.36	10.68	0.5	0.5	50	200			21.2		1087		51.3
	31	20.96	10.48	0.5	0.5	50	250			20.8		1096		52.7
	32	20.64	10.32	0.5	0.5	50	300			20.6		1092		53
	33	20.16	10.08	0.5	0.5	50	350			20		1094		54.7
	34	19.68	9.84	0.5	0.5	50	400	5.3	66.8	19.4	1800	1100	2900	56.7
F								8.2	75					

A- static tension; B-HCF with determination of compliance; C-J_R curve; D-LCF immediately after determine of J_R curve; E-LCF R≈0.5; F-final HCF.

Residual strain at the point at which the data were registered, 3, resulted from exceeded yield stress limit and small extension of the root notch. In phase B, fatigue crack 37.92 mm-long was initiated, with initial and final HCF between which 300 cycles of LCF, designated in Fig. 2, were realized. Fatigue was interrupted from time to time, for measurement of compliance. After that, standard determination of J_{IC} in phase C using J_{RI} curve followed. Crack propagation in phase C was 4.18 mm and the value obtained, J_{IC} = 212.78 kJ/m^2, was in accordance with the results of previous testing. Upon completion of phase C, measurement of COD was resumed from zero (knife edges that support the gage arms were moved, as the full working range of the COD-measuring device of 4 mm was exceeded). It was then that testing of the specimen was interrupted for the first time. In the next phase, D, the specimen was again subjected to fatigue, with determination of compliance at intervals. After 4 cycles of HCF, 100 cycles of LCF followed. The specimen prepared in that way, with initial fatigue-crack length a_{02}=52.4 mm, was subjected to complex testing, phase E, by applying monotonous loading and successive unloading.

5.2. TESTING OF SPECIMENS FROM WM

The testing started with three successive HCF, during which an increase of physical crack length of 4.4 mm was attained, so that static loading *F-COD* was conducted with initial fatigue crack of 36.4 mm. After sufficient number of unloading points for determination of the value of plane-strain fracture toughness was obtained, LCF was tested with minimum force – maximum force ratio *R*≈0.1. When the value of amplitude of upper force dropped below 20 kN, testing of LCF was resumed at *R*≈0.5. To mark attained crack length, we resumed with HCF until specimen fracture. In Fig. 3, the appearance of fracture surface is given, showing the differences in behaviour of WM induced by heterogeneous structure and existence of the defects. Face of the fatigue crack is blocked in development on one side, probably because of the existence of some defect in the structure (surface A in Fig. 3). That is why the crack face under static loading had the shape of an irregular triangle (surface B in Fig. 3), with clear flat fracture in the crack plane, that only after crack growth of 1.4 mm deflects at an angle of 45° in the direction of maximum tangential stresses (plane stress state). In initial phase of LCF, surface C in Fig. 3, the crack first propagates along the edges of the specimen, face line becomes more regular in shape and fatigue crack propagates, but still under conditions of plane stress state. The effect of the fusion line becomes apparent. Namely, at the side surfaces fracture develops at the boundary between heat-affected zone (HAZ) and WM. One should also observe the surface D, on which fracture is partially brittle due to structural defects in WM. HCF characteristic for the crack length shows similar fracture surface, and it is only in the final stage of fracture that shear lips forms again.

6. CONCLUSION

In present paper, experimental procedure for analysis of material crack resistance using the parameters of fracture mechanics for three types of effective loadings (HCF, monotonously increasing loading and LCF), as well as at combined loading (monotonously increasing loading with LCF phases), has been presented. By applying the above-specified loadings to PM of HSLA steel NIONIKRAL 70B and its WM obtained by SAW welding procedure, the properties relating to resistance of these two constituents of a welded joint were determined and compared. The values obtained, $J_{IC}\approx 210$ kJ/m^2 for PM and $J_{IC}\approx 90$ kJ/m^2 for WM, indicate degradation of the properties of the joint in WM. More inferior properties of the joint in WM are also indicated by decrease of the value of J-integral in the phases of LCF.

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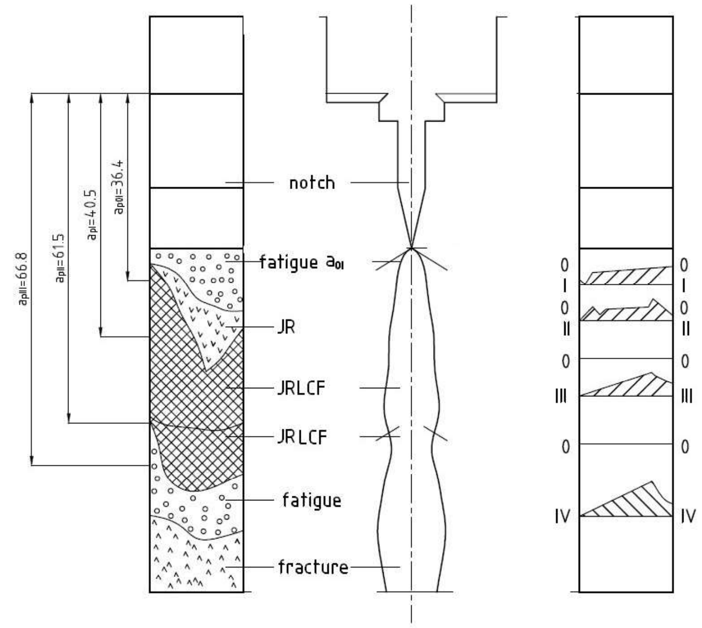

Fig. 3 Fracture surface of CT specimen cut from WM

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