STATIC AND DYNAMIC FRACTURE MECHANICS PARAMETERS OF MATERIAL IN THE HEAT-AFFECTED-ZONE

S. Sedmak [1], K. Gerić[2], V. Grabulov[3], Z. Burzić[3], A. Sedmak[4]
[1] Faculty of Technolgy and Metallurgy, Belgrade, Serbia
[2] Faculty of Technical Sciences, Novi Sad, Serbia
[3] Military Technical Institute, Belgrade, Serbia
[4] Mechanical Engineering Faculty, Belgrade, Serbia

ABSTRACT

The behaviour of heat-affected-zone (HAZ) in welded joints of structural steels with different chemical composition and different strength class (yield strength ranged from 450 to 700 MPa) has been evaluated, applying two approaches. In the first approach two types of specimens were used, one taken from simulated different microstructural regions in HAZ, and the other from the real welded joint with crack tip positioned in different microstructural regions. Impact toughness was determined by instrumented Charpy test and different fracture mechanics parameters were tested including single specimen method applied to measure J integral. The results of simulated specimens testing indicate that M/A microconstituents significantly reduce toughness and crack resistance in HAZ. The results obtained on specimens made from the real welded joint indicate higher crack resistance, due to multi-pass welding procedure and to the size effect as well, since the brittle microstructure region containing M/A microconstituents are surrounded by regions of higher toughness, capable to arrest crack growth. In the second approach the crack properties of parent metal, weld metal and HAZ in real welded joint are compared. Superior properties in HAZ compared to weld metal can be contributed to the high quality of parent metal, but also this can be an indication that crack tip in HAZ was in more ductile, and not in brittle microstructure. Extension of investigation can be achieved by numerical method, as it is proposed by J integral model for HAZ.

1 INTRODUCTION

The fracture parameters of three welded joint constituents: parent metal (PM), weld metal (WM) and heat-affected-zone (HAZ) are required for the evaluation of welded joint crack resistance Parent metal is a structural steel itself, with uniform microstructure and mechanical properties, corresponding to its chemical composition and manufacturing procedure. Weld metal is obtained by crystallization of base metal and electrode material mixture, melted by heat introduced during welding. Its microstructure is of cast type, less uniform in microstructure compared to PM. By proper selection of welding procedure and electrode it is possible to obtain WM strength close to the strength of PM, indicating satisfactory matching – evenmatching. Generally, WM of higher strength compared to PM is required (overmatching), in order to direct initial plastic deformation to the PM. It is well known that overmatching is beneficial for welded structure regarding strength, but also offers better crack resistance by shielding the crack effect (Božić[1]). For weldable high strength steels, e.g. high-strength low-alloy (HSLA) steel, of yield strength above 700 MPa so called undermatching is recommended in order to avoid the occurrence of cold cracks, that means the strength of WM is designed to be lower compared to PM. It is possible to conclude that welded joint is heterogeneous on the global level due to difference in WM and PM strength.

Following temperature gradient during welding from melting point to the level at which no more transformation is possible the microstructure is continuously changed. This part is heat-affected-zone (HAZ). Depending on chemical composition and steel strength, different microstructures and mechanical properties can be obtained in HAZ, expressing its heterogeneity at local level.

In design the differences in welded joint material properties are neglected. The basic approach in design is to exclude the occurrence of plastic yielding and to allow only elastic deformation in structure, that it is far from real behaviour of welded structure in service. In order to avoid plastic deformation designer accept safety factor, e.g. 1.5 compared to yield strength. It is also general practice to neglect the crack existence in design stage. However, in service condition welded structures can fail, and they do. To prevent the failure, welding is defined as "special process" in ISO 9000 standards series because the welded joints quality cannot be verified on the product but has to be built-in in the product. By acceptability criteria in standard ISO 5817 "Guidance on quality levels for imperfections", cracks as most severe defects in welded joint, are not allowed, except cracks in the crater of low quality welded joints and microcracks less than 1 mm^2 cross section. It is not possible to detect reliably cracks of that size by available equipment for nondestructive testing, what means that equipment can operate in real conditions with such imperfections. With this in mind, the full description of welded joint and welded structure requires the data for static and dynamic fracture mechanics parameters of material in the heat-affected-zone. Together with the data of impact toughness they can be used as comparative indication in case studies.

2 FRACTURE MECHANICS PARAMETER DETERMINATION FOR MATERIAL IN THE HEAT-AFFECTED-ZONE

Stress concentration (fatigue pre-crack) is typical requirement for fracture mechanics specimens in order to produce plain strain condition. In some cases it can be achieved by notch, e.g. by Charpy V specimen. High velocity (impact, drop weight or explosion tests) contributes to fast fracture. These test methods correspond to homogeneous material, but not properly for welded joint and HAZ.

The thermal simulation procedure can help to get closer insight in the properties of individual microstructures of HAZ. It is possible to define critical microstructure by simulation and to predict its position in the HAZ. Anyhow, HAZ in welded joint is a continuous metal, and there is no clear boundary between individual microstructures, identified by simulation. This effect can produce important disagreement between the test results of simulated samples and welded joint, more expressed for local parameter, such as fracture toughness, than for yield or tensile strength.

The main idea in welded joint toughness testing is to find critical microstructural region and to determine minimum toughness. For Charpy V impact test this can be achieved by positioning notch radius in different location (PM, WM, HAZ). Notch radius is large comparing the size of different microstructural regions in HAZ, and obtained result in that case must be taken with precaution. Better results can be obtained by pre-cracked specimens. They can be tested by quasi-static load, following standard test methods and by impact load for determination of dynamic fracture mechanics parameter. In preparing the specimen, crack tip can be located in selected HAZ micro structural region, but there is no guaranty that the crack will grow through the same microstructure, and again the results have to be accepted with precaution in both, quasi-static and impact testing. Even if the properties of different micro structural regions are known, the question of crack resistance of welded joint and welded structure cannot be prescribed completely.

Three micro alloyed steels (Table 1 and 2) has been selected for experimental testing.

Table 1: Chemical composition of tested micro alloyed steels

Steel	C	Si	Mn	P	S	Al	Cu	Nb	Cr	Ni	Mo	V
P	0.20	0.51	1.42	0.020	0.010	0.018	0.035		0.018	0.574	0.017	0.180
V	0.07	0.43	1.43	0.012	0.012	0.037	0.043	0.031	0.018		0.17	0.087
A	0.1	0.27	0.35	0.014	0.012	0.05			1.11	2.65	0.26	0.1

Table 2: Mechanical properties of tested microalloyed steels

Steel	Yield strength, MPa	Tensile strength, MPa	Elongation, %	Impact toughness, J	Hardness, HV5
P	547	738	28.6	130.2	242
V	462	596	32.7	142.7	204
A	780	825	19.6	126	260

First one is normalized V microalloyed steel (P), the second one is thermomechanically control rolled Nb+V microalloyed steel (V) and the third is quenched and tempered steel (A).

The analysis of HAZ properties of steels P and V has been performed on both simulated and welded joint samples. The microstructures of different regions in HAZ had been simulated on Smitweld LS1402 device. The samples, 11x11x60 mm (Fig. 1) had been exposed to different temperatures (1350°C-coarse grains formation, 1100°C-fine grains formation, 950°C-fine grains region above A_{c3}, 850°C-partial transformation between A_{c1} and A_{c3} temperatures) for 15 s as cooling time $\Delta t_{8/5}$. These temperatures are typical for microstructural transformations in HAZ of tested steels. Some samples had been obtained by two successive simulations: first at 1350°C, followed by 750°C or 650°C. Sample central part, 20 mm long, was measuring region for hardness test (HV5), tensile test (Φ4.5 mm specimen), Charpy V impact and fracture mechanics tests.

Microstructures of HAZ regions had been analyzed by light microscopy (Fig. 2 and 3).

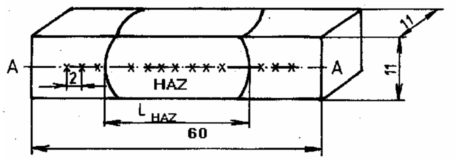

Figure 1: Simulated sample and positions (x) for hardness measurement

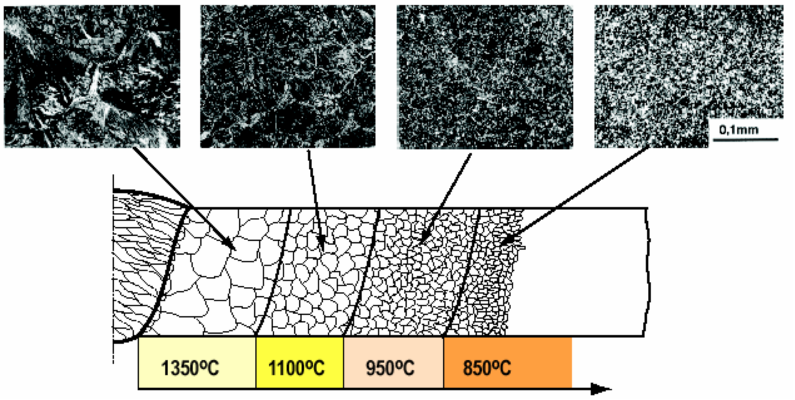

Figure 2: Microstructures in simulated samples of steel P

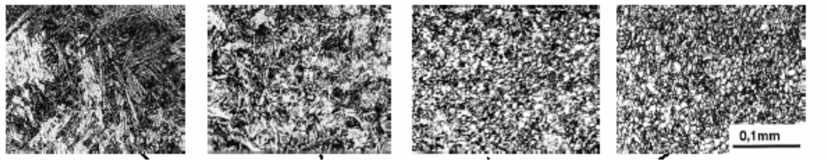

Figure 3: Microstructures in simulated samples of steel V

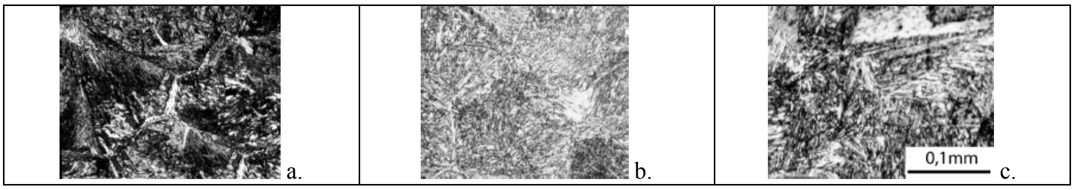

Figure 4: Steel P microstructure simulated at 1350°C (a), at1350°C/750°C (b) and at 1350°C/650°C

Roughly presented heterogeneous microstructure in Fig. 2 corresponds in general to the real situation in a one pass welded joint, but of course their is no clear boundary between different microstructure. The second and next passes have a beneficial effect regarding toughness, since previous passes are tempered by the exposure to given temperature, as it can be seen in Fig. 4.

Impact toughness was determined with standard V Charpy specimen. Applying pre-cracked specimens in this test dynamic fracture mechanics parameters can be determined, commonly accepted in the form of dynamic J-R curve. Standard fracture mechanics testing was performed applying a single specimen compliance technique for J - integral evaluation, according to ASTM E1737. Charpy size specimens (10x10x55 mm), produced from simulated samples (Fig. 1), with V notch, had been fatigue pre-cracked on Crackthronik pulsator, by variable loading with the ratio R = 0.1 and a bending moment of 40 Nm, to produce 1 mm long fatigue crack for about 80000 cycles. In this way the specimens with crack ratio a/W = 0.3 were obtained (total crack length 3 mm).

Coarse microstructure, corresponding to 1350°C, is found to be critical in toughness in both P and V steels. Ccomparison of microstructures of these two steels and of their HAZes indicate substantial difference. The reason is found in (1) carbon content (0.2% in steel P, bellow 0.1% in steel V) and in manufacturing procedure (steel P is normalized, steel V is control rolled). In spite of different carbon content, microstructures of steels P and V, heated to 1350°C are similar on light microscope. Anyhow, microstructure of steel P is coarser, and hardness according to KH diagram indicates presence of martensite (Fig. 2), whereas corresponding microstructure of steel V is of bainitic type (Fig. 3). This reflects to mechanical properties and fracture toughness values.

Testing results of steel P (Table 3) indicated the regions of very high strength, and brittle behaviour had been experienced with the specimens treated at 1350°C and 1100°C, but increased strength and reduced ductility compared to parent metal had been found also for the other simulation temperatures. High hardness in simulated samples of steel P corresponds to 0.2%C content. Increasing hardness and tensile strength of simulated samples can be contributed to martensitic microstructures with M-A constituents. Beneficial effect of subsequent welding passes could be recognized for specimens P5 and P6.

The changes in properties in steel V are not critical, even at the temperature of 1350°C.

Table 3: Test results of simulated samples testing of steel P and steel V

	Simulation temperature, °C	Yield strength, MPa	Tensile strength, MPa	Elongation, %	Impact toughness, J	Hardness, HV5
P1	1350	1101	1101	-	7.7	480
P2	1100	943	1189	12.6	10.6	418
P3	950	818	1036	18.0	46.2	353
P4	850	660	936	11.8	31.6	338
P5	1350/750	815	889	7.3	57.5	364
P6	1350/650	948	1035	12.6	25.2	395
V1	1350	660	726	18.0	64.7	287
V2	1150	534	675	21.7	60.7	265
V3	950	453	631	28.0	169.7	252
V4	850	459	672	31.3	187.5	232

Results from Table 3 show that crack brittle behaviour can be expected for specimens of highest hardness (P1, P2 , P6), while the specimens P3, P4, P5 and also steel V specimens can be more ductile. For brittle specimens plain strain fracture toughness K_{Ic} can be applied and for other specimens J integral is applicable, and crack opening displacement (δ) was measured for all cases. Brittle behaviour of samples P1 and P2 is confirmed by low values of crack parameters, samples

P3, P4 and P5 exhibited better crack resistance, and the value of 2621 N/mm$^{3/2}$ for specimen P6 is higher than K_{Ic}, since testing condition were not fulfilled (Table 4). The values of δ_u and J integral for samples of steel V are satisfactory, indicating ductile behaviour. For specimens V3 and V4 fracture occurred after maximum load achieved (Table 5).

Table 4: Crack opening displacement and fracture toughness for simulated samples of steel P

Parameter	Sample	P1	P2	P3	P4	P5	P6
Crack opening displacement, δ_c	mm	0,007	0,008	0,164$^{\#}$	0,130$^{\#}$	0.095	0.017
Plane strain fracture toughness, K_{Ic}	N/mm$^{3/2}$	1890	1498	-	-		(2621)

$^{\#}$ corresponds to crack opening displacement, δ_u, achieved before fracture.

Table 5: Crack parameters for simulated samples of steel V

Parameter	Sample	V!	V2	V3	V4
Crack opening displacement, δ_u	mm	0,178	0,260	0,536#	0,510#
J integral	kJ/m^2	140	205	675	574

$^{\#}$ corresponds to δ_m crack opening displacement at maximum load.

Crack resistance had been measured by crack opening displacement (COD) on the welded joint specimens. Figure 5a presents location of crack tip, and the microstructure of steel P coarse and fine grains zones in cross-section A-A (Fig. 5b). Obtained COD values are given in Table 6.

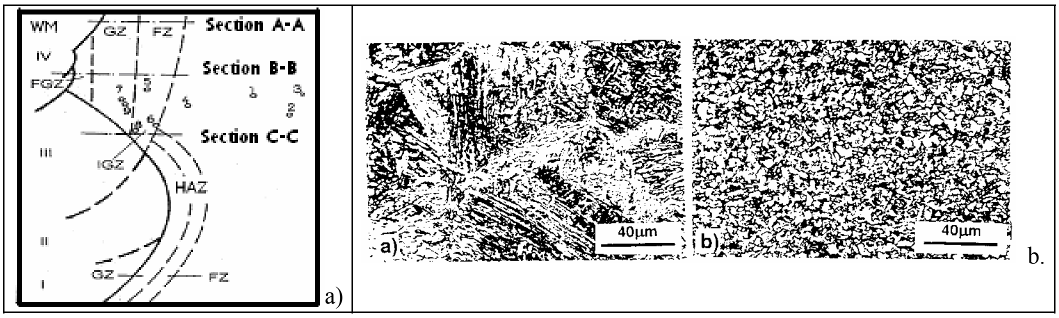

Figure 5: Crack tip locations (a) in steel P welded joint for specimens in different HAZ regions of welding runs I - IV and microstructures (b) in coarse and fine grains zones (section A-A)

Table 6: Crack tip opening displacement values for welded joint specimens

Steel		P						V			
Distance from fusion line	mm	3.1	2.6	1	0,4	0.32	0	4	3.2	0.8	0
Crack opening displacement, δ	mm	0.56	0.42	0.45	0.39	0.41	0.21	0.32	0.38	0.20	0.32

The approach applied in testing welded joint of high strength steel A (Table 1, 2) is different. The main goal was to prove structural integrity of welded joint and for that fracture mechanics test of PM, WM and HAZ had been supported by explosion crack starter global testing of welded joint. Fracture mechanics parameters were tested on SEN (B) specimens 14x28 mm cross-section for PM, WM and HAZ, using single specimen J_{Ic} procedure, following the specified procedure for welded joint characterization. Critical crack opening displacement δ_c for maximal load was also determined in this test. The results of fracture mechanics tests are listed in Table 7.

Table 7: Critical J integral J_{Ic} and crack-opening-displacement δ_c for steel A welded joint

Welded joint constituent		PM			WM			HAZ		
Critical J integral, J_{Ic}	kN/m	195	209	257	94		105	176		320
Critical crack opening displacement, δ_c	μm	63	85	103	66	80	90	167	183	208

Scheme of crack propagation in explosion crack starter test is given in Fig. 6. The cracks, emanated from brittle bead notch, are arrested in parent metal (Fig. 6a) in most specimens, and in some cases fusion line of HAZ was critical welded joint region as regard brittle fracture (Fig. 6b). The difference in this test was between parent metal and welded joint specimens is negligible, e.g. after sixth shot thinning and bulge developments were comparable for same explosive charge.

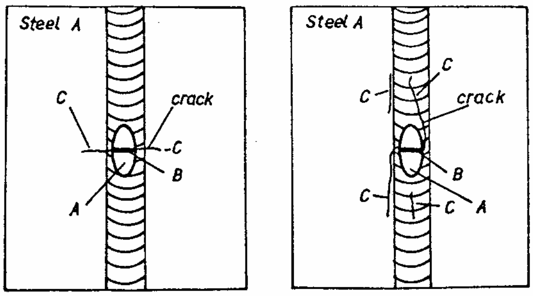

Figure 6. Scheme of crack propagation in explosion crack starter test
A- brittle bead, B- notch-crack starter, C- developed crack

3 TESTING RESULTS ANALYSIS AND CONCLUSION

The testing of steel P revealed the existence of brittle region close to fusion line in welded joint. This explained in-service failures of welded structure, produced of this steel. Satisfactory behaviour of steel V welded joint is confirmed by acceptable differences in strength of HAZ regions, saving sufficient toughness and crack resistance. High quality of steel A welded joint is proved locally by fracture mechanics testing, and globally, by explosion crack starter testing.

For detailed analysis the modified J integral model for a weldment is introduced as for a multi-material body (Fig. 7), containing four regions of different material properties: PM, WM and two HAZ regions, fine grain (FG) and coarse grain (CG), using the data from performed simulation.

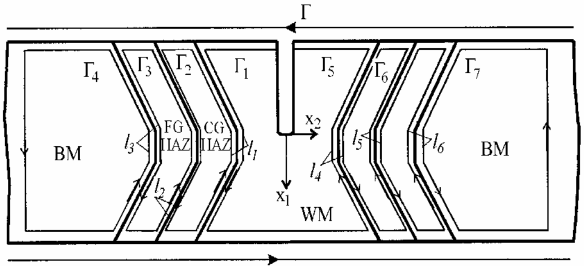

Figure 7: Model for the J integral integration paths for welded joint

4 REFERENCES

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