THE ESTIMATION OF TRANSITION TO BRITTLE BEHAVIOUR OF HIGH STRENGTH STEELS WELDMENTS

OCJENA PRELASKA U KRTO STANJE ZAVARENIH SPOJEVA ČELIKA VISOKE ČVRSTOĆE

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Ključne riječi: krti lom, mehanika loma, prijelazne temperature plastičnosti, temperatura nulte plastičnosti, eksplozivna proba

Key words: brittle fracture, fracture mechanics, transition temperatures, nil ductility temperature, explosion bulge test

Sažetak: U radu je prikazan postupak ocjene ponašanja prema krtom lomu zavarenih spojeva čelika visoke čvrstoće sa stanovišta utjecaja brzine opterećenja na otpornost ka lomu. Analiza krtog ponašanja je provedena na ručno elektrolučno zavarenim spojevima dva čelika visoke čvrstoće, namjenjenih za posude pod tlakom, primjenom tri različite metode ispitivanja (instrumentirano Charpi klatno, eksplozivna proba i metode mehanike loma). Pored osnovnih mehaničkih osobina zavarenih spojeva, kao prilog ocjeni zavarljivosti, određivana je i prijelazna temperatura krtosti po kriteriju 50% vrijednosti apsorbitane energije udara na Charpy klatnu i preko temperature nulte plastičnosti. Analizirani su i uporeďivani rezultati ispitivanja osnovnog materijala, metala šava i zone utjecaja toplote. Rezultati primjene ovih metoda su prikazani u cilju ocjene utjecaja brzine i uvjeta opterećenja na otpornost ka lomu zavarenih spojeva dva čelika visoke čvrstoće za posude pod tlakom: čelik HY 100 i čelika japanske proizvodnje SUMITEN 80. Zaključeno je da primjenjene metode ne samo što ne isključuju jedna drugu, već one daju rezultate koji se dopunjavaju i pomažu da se bolje razumije odnos prema krtom lomu zavarenih spojeva kao važan dio globalne ocjene zavarljivosti.

Abstract: The procedure for brittle fracture behaviour of high strength steels has been given from the point of view of loading rate effect on fracture resistance. The evaluation of brittle fracture behaviour of two high strength pressure vessels steels weldments were tested. Three different testing methods (instrumented impact, explosion bulge test and fracture mechanics tests) had been applied for brittle fracture behaviours of base metal and welded joints, produced by manual arc welding. Basic properties of weldments and transition temperatures i.e. 50% Charpy impact energy and nil ductility drop weight test temperature were evaluated too as a contribution of weldability testing. The results, obtained for BM, WM and HAZ are analyzed and compared. In this paper the results of application of listed methods are presented in order to assess the effect of loading rate and condition on fracture resistance of welded joint of two high strength pressure wessels steels: HY 100 type steel and SUMITEN 80P, produced in Japan. It was concluded that applied testing methods do not exclude each other, since they produce complementary results, helping to understand better brittle fracture behaviour of welded joints as a important part of global weldability assessment.

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1. INTRODUCTION

The application of high strength steels, especially steels for pressure vessels or other structures, is dependent by their formability. The most often used method of forming of these steels is welding. Thus, the application of high strength steels for welded structures depends, besides other factors, on properties of their welded joints.

One of the most important requirements for service safety of welded structures, produced of high strength steel, is to achieve corresponding level of toughness in all three weldment constituents: base metal (BM), weld metal (WM) and heat-affected-zone (HAZ). The evaluation of weldments toughness is very complex, because of microstructures heterogeneity of WM and HAZ, as well as the heterogeneity of their mechanical properties. Charpy test, although very old method is generally accepted for the evaluation of the impact toughness due to its simplicity. Recently developed instrumentation of Charpy test significantly extended its capacity (1), enabling not only the separation of energy portions required for crack initiation and crack propagation, but also the evaluation of loading during the fracture process. Specifications for heavy loaded welded structures normally include impact energy values for BM and WM, as well as transition temperature when service at low temperature is expected. However, there is still the problem how to evaluate toughness of HAZ, since it is difficult to position notch root precisely in HAZ region of lowest toughness.

In order to establish more severe testing loading, explosion bulge test had been introduced (2). Fast loading rate and notched brittle bead, welded on the plate specimen assured severe testing conditions. Applied to welded joint specimens (3), this test enables to determine the most critical region in weldment, in which fracture would occur. In this way by the global test critical local property could be defined.

Further improvement in crack resistance testing is offered by introduction of fracture mechanics tests, that involved pre-cracked specimens. The application to welded joints allows for convenient determination of crack resistance of BM and WM, but it is followed again by uncertainty in defining of critical crack tip position in HAZ (4), since in prescribed preparing method fatigue crack would follow the path of notch root rather than direction of critical HAZ region.

The application of all three above described methods for the evaluation of brittle behaviour of welded joints, performed of high strength pressure vessels steels by manual arc welding, are presented in the paper.

1. BASIC PROPERTIES OF TESTED WELDED JOINTS

Two kinds of high strength steels were used in these tests: HY100 type steel produced in Jesenice, d=35 mm thick, designed in next text as "A", and Japanese SUMITEN 80P, d=46mm thick, designed as “B” in next text. Their typical chemical composition and tensile properties are given in Table 1.

	Chemical composition, wt %											
Steel	C	Si	Mn	P	S	Cr	Ni	Mo	V	Al	Cu	B
A	0.1	0.27	0.35	0.014	0.012	1.11	2.65	0.26	0.1	0.05		
B	0.1	0.3	0.9	0.01	0.008	0.48	1.01	0.47	0.03		0.24	0.0016
	Mechanical properties											
	Yield strength			Ultimate tensile strength			Elongation		Reduction of cross section area			
Steel	YS, MPa			UTS, MPa			A, %		Z, %			
A	780			825			18		68			
B	775			820			26		70			

Table 1. Chemical composition and tensile properties of tested steels

Welding of steel "A" had been performed using Tenacito 80 covered basic electrode.
Chemical composition of Tenacito 80 is (%):
C: 0. 06 Si: 0. 50 Mn: 1. 80 Cr: 0. 35 Ni: 2. 20 Mo: 0. 40
Yield strength of all weld metal Tenacito 80 is above 750 MPa, its ultimate tensile strength 810 to 910 MPa, and elongation > 16 %.
The basic coated low hydrogen electrode LB 118, produced by "Cobe steel", Japan was selected for welding of steel "B". The chemical composition of LB 118 electrodes is (%):
C: 0.1 Si: 0.3-0.7 Mn: 5-7 P: 0.035 S: 0.013 Cr: 19-22 Ni: 9.5-10.5 Ti: 0.2-0.5.
Yield strength of all weld metal is min 720 MPa, ultimate tensile strength min 820MPa, elongation > 22%.

Welding specimens were performed by approved welders according to the qualified procedures. Direction of welded joint was transverse to steel rolling direction. Base mechanical properties of tested welded specimens are given in Table 2.

Welded joint	Welded joint		Weld metal tensile properties			Hardness (HV 30)		Bend test (^{0})	
	Y.S. MPa	Fracture position	Y.S. MPa	U.T.S. MPa	Elongation (%)	HAZ	Weld metal	Around face	Around root
Steel A	800	W.M.	750	810	16	260-330	258-290	180	180
Steel B	761	HAZ	796	848	22	220-334	255-275	180	180

Table 2. Results of tensile and bending tests of welded joints and hardness of welded joints

Results of hardness measurements along welded joints are given in Figure 1.(5).

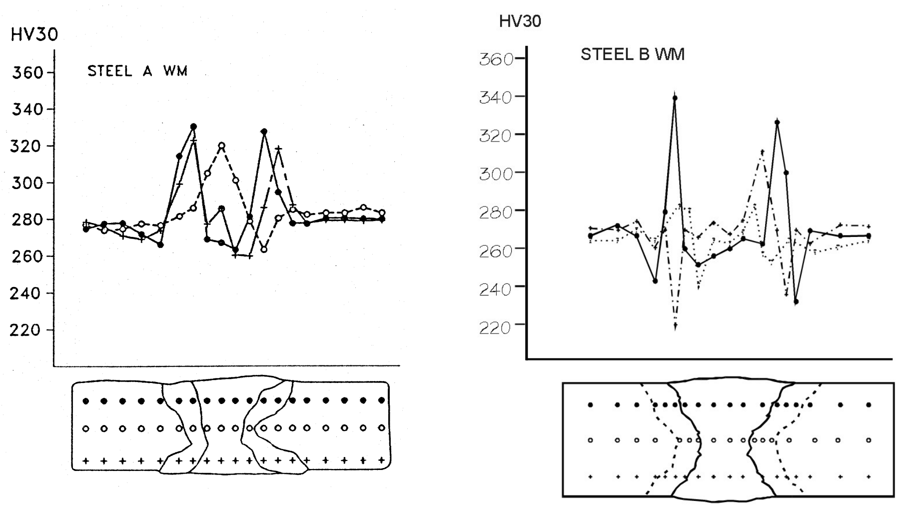


Figure 1. Results of hardness measurements along welded joints.

2. RESISTANCE TO BRITTLE FRACTURE

Brittle fracture resistance of both steels and theirs welded joints is evaluated by instrumented impact, explosion and fracture mechanics tests, performed for BM, WM and HAZ.

3.1. Instrumented Charpy test

The conventional Charpy test measures the total energy absorbed in fracturing the specimen. Additional information can be obtained if the impact tester is instrumented to provide a load-time history of the specimen during the test (6). Figure 2. shows an idealized load-time curve for an instrumented Charpy test. With this kind of record it is possible to determine the energy required for initiating fracture (crack) and the energy required for propagating fracture. It also yields information on the load for general yielding, the maximum load, and the fracture load.

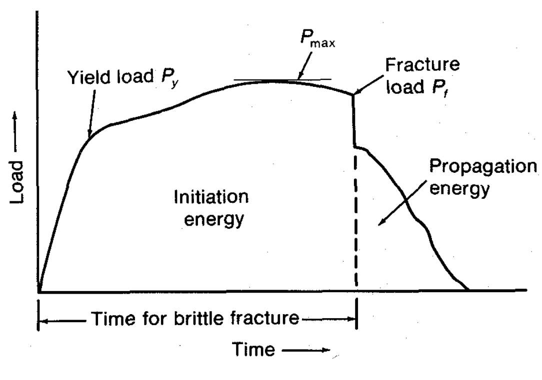
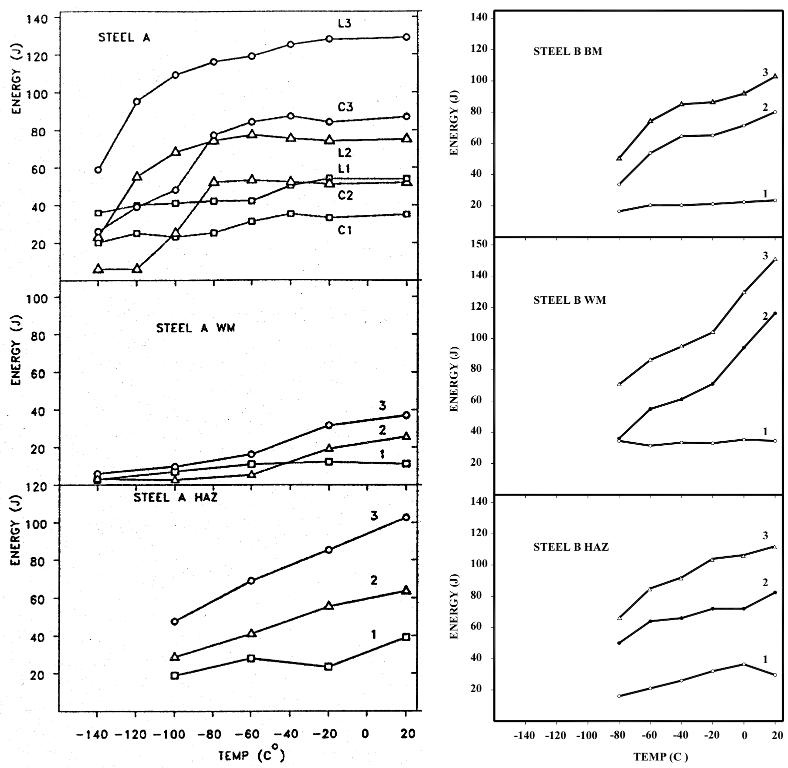


Figure 2. Load-time history for an instrumented Charpy test

Charpy V specimens were tested at different temperatures in the instrumented impact test. Parent plate specimens, for steels "A" were cut in the rolling (L) and in transverse direction (C) with notches normal to these directions. For steel "B" only the rolling direction specimens were tested. The notches in weldment specimens were positioned in WM and in HAZ. Typical results are presented in Fig. 3. (5).



WM- weld metal
HAZ- heat affected zone
1 crack initiation energy, 2 crack propagation energy, 3 total energy
L- notch in cross-rolling direction
C- notch in rolling direction

Figure 3. Instrumented impact test results obtained with Charpy V specimen

3.2. High rate impact test

Probably the chief deficiency of the Charpy impact test is that the small specimen is not always a realistic model of the actual situation. Not only does the small specimen lead to considerable scatter, but a specimen with thickness of 10 mm cannot provide the same constraint as would be found in a structure with much greater thickness. The situation that can result is shown in Fig. 4. At a particular service temperature the standard Charpy specimen shows a high shelf energy, while actually the same material in a thick-section structure has low toughness at the same temperature. The most logical approach to this problem is the development of tests that are capable of handling specimens of extended thickness (e.g. explosion bulge test, drop weight test).

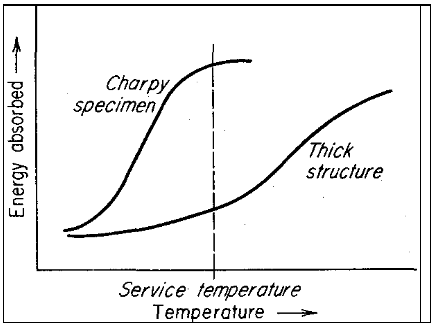


Figure 4. Effect of section thickness on transition-temperature curves

3.2.1. Explosion bulge test

The basic need for large specimens resulted from the inability to produce fracture in small laboratory specimens at stresses below gross yield stress, whereas brittle fractures in ship structures occur at service temperatures at elastic stress levels, as experienced with Liberty ships. The development of such tests and their rational method of analysis has been chiefly the work of Pellini (7) and his co-workers at the Naval Research Laboratory.

The explosion bulge test, developed in the U.S. Naval Research Laboratory (NRL) to study the problem of brittle fracture in structural steels used in welded ship hulls, is presented in Fig. 4. Die support (rig) with the base allows bulging of properly positioned test plate (specimen). Cast explosive charge of specified mass and power should be applied at properly determined distance, obtained by cardboard box over the test plate. Test assembly during shot is presented on the right. High rate of explosion loading contributes to brittle fracture of test plate.

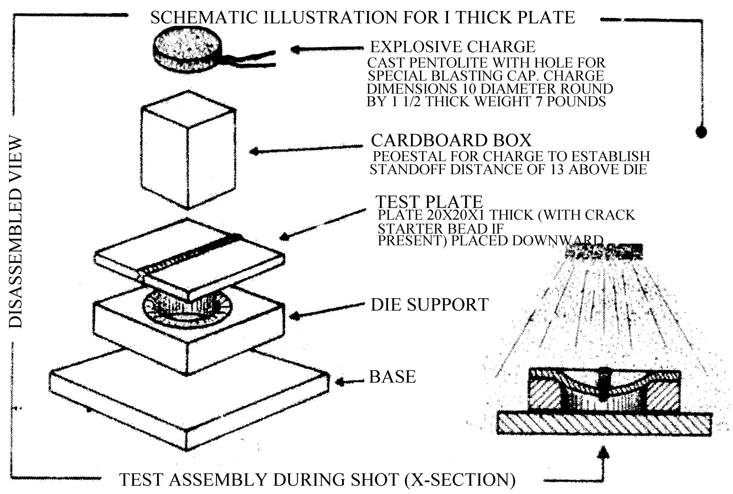


Figure 5. Explosion bulge test, developed in the U.S. Naval Research Laboratory (NRL)

Explosion bulge test specimens (8,9) were 500x500xd mm. Brittle bead was welded in the rolling direction of base metal (BM) and direction of tested weldment (WM), and the notch as crack starter was normal to the bead direction. Test results are given in Fig. 6., expressed by bulge development B and thinning ΔR with explosions number. Typical development of crack in explosion tests is presented in Fig. 7. for welded joint specimens.

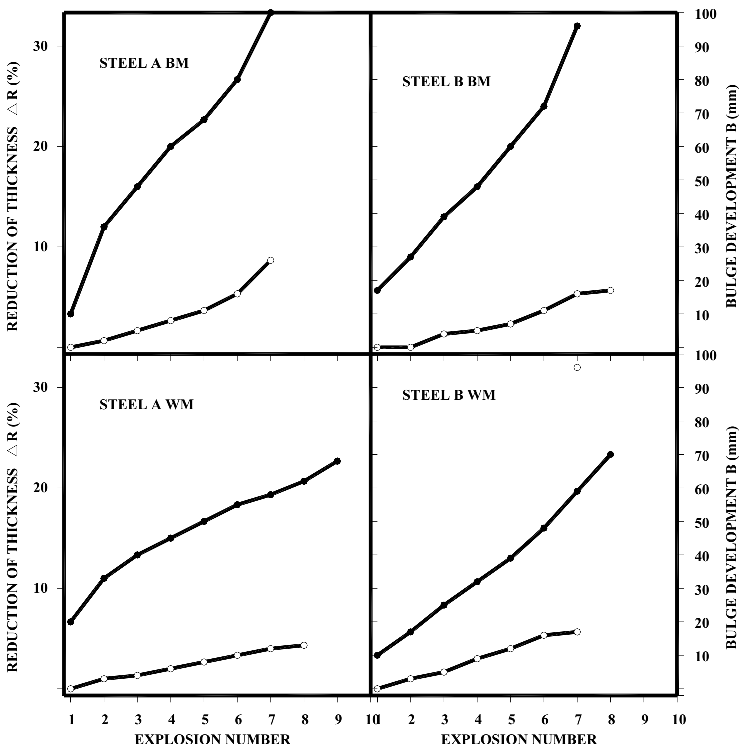
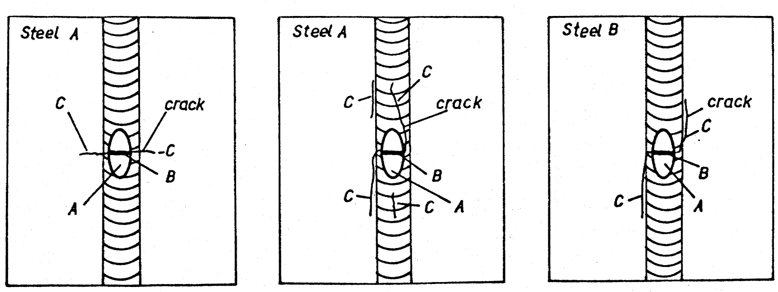


Figure 6. Typical results of explosion bulge test, expressed by reduction of thickness ΔR and bulge development B vs. number of explosions indicated specimens



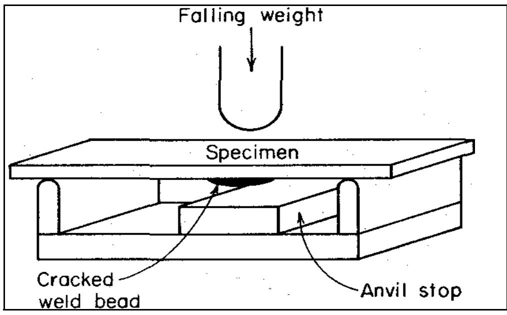
A- brittle bead
B- notch-crack starter
C- crack

Figure 7. Scheme of crack propagation in explosion bulge test

3.2.2. Drop weight test

Experience gathered with the explosion bulge test in NRL has led to the development of drop-weight test, intended to avoid the explosion. The energy for DWT is obtained from potential energy of falling mass (weight). Due to significant weight of the tup and height of device, much more energy can be obtained compared to Charpy pendulum.

The drop weight test (DWT) was developed (10) specifically for the determination of the NDT temperature on full thickness plates (Fig. 8.). The simplicity of the drop-weight specimen, the apparatus for applying load and the interpretation of results, contributed to wide use of this test. The stress applied to the specimen during the impact loading is limited to the yield point by a stopping block attached to the anvil below the specimen (Fig. 9.). This is the practical device for evaluating the ability of the steel to withstand yield point loading in the presence of a small flaw.
The specimens may be oxygen-cut from a parent plate and additonally machined. When thinner specimens are prepared from a very thick plate, the original tolled surface is to be employed on the welded (tension) face of the specimen. Since the specimen is a wide beam loaded in three-point bending, this restriction limits the stress on the tension face of the plate to a value that does not exceed yield stress. A short bead of brittle weld metal, taken from explosion bulge test, is deposited on the plate surface, 15 to 25 mm thick, typically sized 80x350 mm (Fig. 10.).



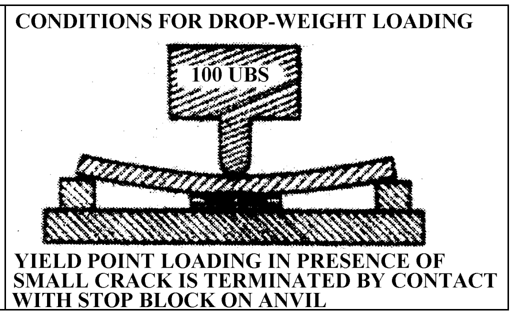


Figure 8. Drop weight test configuration Figure 9. The anvil stop

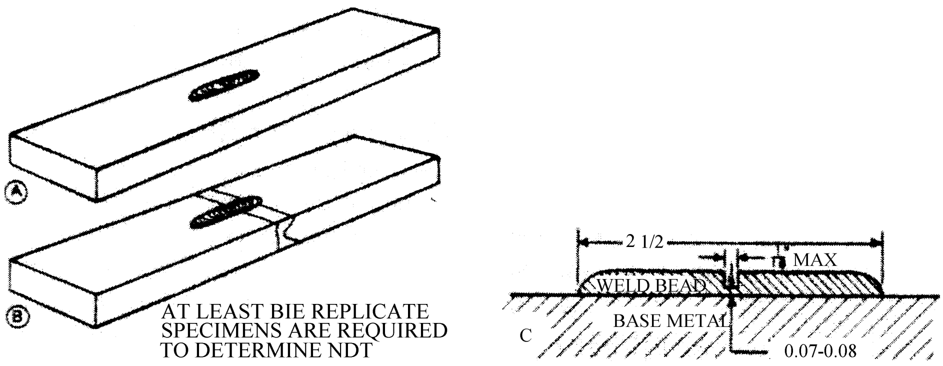


Figure 10. Drop weight test specimen

The drop-weight test was devised for testing relatively heavy structural sections, and is not recommended for base metal pieces less than 12.5 mm thick. A complete description of the standard method for conducting the NRL Drop-Weight Test is presented in ASTM E 208.
Nill-ductility-transition temperatures, determination for 50% upper shelf impact energy and from explosion test, are listed in Table 3.

	Steel A				Steel B			
	L	C	WM	HAZ	L	C	WM	HAZ
50% Charpy V impact energy	-138	-100	-52	-94	>-80	>-82	-79	>-80
Drop-weight test		-103	-85			-113	-100	

Table 3. Nill-ductility-transition temperatures, ^oC

3.3. Fracture mechanics test

Fracture mechanics parameters were tested on SEN (B) specimens 14x28 mm cross-section for steel "A", its WM and HAZ, using single specimen J_{IC} procedure. Critical crack-opening displacement δc for maximal load could also be determined in this test. The results of fracture mechanics tests are listed in Table 4.

	BM			WM			HAZ		
Critical J integral J_{IC}, kN/m	195	209	257	94		105	176		320
Critical crack-opening displacement δc, μm	63	85	103	66	80	90	167	183	208

Table 4. Critical J integral J_{IC} and critical crack-opening-displacement δc for base metal (BM) steel A, its weld metal (WM) and heat affected zone (HAZ)

4. DISCUSSION

The obtained results can be considered from two standpoints. One of them is related to brittle fracture properties of welded joints constituents, the second is the comparison of three test methods.

Steel "A" impact toughness is satisfactory in both directions, and its behaviour at low temperatures is also satisfactory. Anyhow, this is not the case with its weld metal, because NDT temperature for impact energy of 27 J is only -25 °C, higher than the value for 50% upper shelf energy. Heat-affected-zone in this test was found to be superior compared to weld metal.

For similar strength of steel "B", impact energy values are satisfactory, including transition temperature. Higher impact values of WM compared to BM corresponds to high alloy consumable. The results for HAZ are comparable to BM results.

High quality of both steels and welded joint is proved in explosion bulge test. The cracks, emanated from brittle bead notch, are arrested in base metal (Fig. 7.a) in most specimens, and in some cases fusion line of HAZ was critical welded, joint region as regard brittle fracture (Fig. 7.b). No significant difference was found comparing base metal and welded joint specimens, e.g. after sixth shot thinning and bulge developments were comparable (Fig. 7.a, 7.b) for same explosive charge. No significant difference was found comparing both steels and corresponding welded joints.

In all tested welded joint specimens fracture was limited to base metal, but the case is possible limited fracture in weld metal (Fig. 4.c), due to lower strength of WM.
Hardness values in Fig. 1 correspond to the expected levels for both (steel "A" and "B") welded, joints, some scatter in WM of steel "A" can be attributed to multipass welding.

The results of fracture mechanics tests (Table 4.) show that best crack resistance is typical for HAZ, and the lowest for WM. Since the precise position of crack tip in HAZ cannot be defined, this behaviour can be considered as an average result. Comparing to impact test results, some disagreement can be found, since they have shown best resistance in BM, and not in HAZ. General view of fracture appearance, Fig. 7.b, 7.c, indicates that HAZ can be critical region, but this conclusion scarcely could be described by fracture mechanics test, or impact test.

5. CONCLUSIONS

In this paper the procedure for testing of material for pressure vessels has been given from the point of view of loading rate effect on fracture resistance.
Taking into account obtained results one can conclude that the applied procedure for testing of high strength material, as presented in this paper and applied to fabrication of pressure vessels, has proved to be selective. On the other hand side, results obtined by using fracture mechanics methods and Charpy test are compatible with the results of explosion bulge test. Also, the indication of the weakest region of welded joint, obtained by fracture mechanics laboratory testing or by Charpy test, has been verified by the experimental testing in real condition.

It was concluded that applied testing methods do not exclude each other, since they produce complementary results, helping to understand better brittle fracture behaviour of pressure vessel steels welded joints for different strain rate (static, impact and dynamic).

The introduced procedure can be used also for the selection of material and methods of its forming into a desirable structures.

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