UDK 621.791.05:539.42:539.55
Izvirni znanstveni ~lanek

ISSN 1318-0010
KZLTET 33(6)437(1999)

ROLE OF RESIDUAL STRESSES ON FRACTURE PROPERTIES OF UNDER-MATCHED BUTT WELD

VLOGA ZAOSTALIH NAPETOSTI NA LOMNE LASTNOSTI TRDNOSTNO NI@JEGA STRJENEGA ZVARA

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Prejem rokopisa – received: 1999-11-17; sprejem za objavo – accepted for publication:1999-11-22

Under-matched weld joints were adopted for producing a penstock of 47 mm wall thickness and 4200 mm diameter, to improve the weldability. The isothermal Robertson wide plate test on the under-matched weld joints, where the allowable stress level was 0.6 of the yield stress, proved that the longitudinal stresses caused the crack propagation along the weld joint to deviate into tough base material where it was arrested. The arrest temperature was between -10 and -20°C. The behaviour of the crack propagation was the reason to omit the thermal stress relieving of the pipe sections and on circumferential weld joints executed at the site. One can always take into consideration the role of axial residual stresses when assessing whether to use, or not, under-matched weld joints in severer loaded structures.

Key words: under-matched weld joint, residual stresses, fracture path, arrest properties, fracture toughness

Izbran je bil zvarni spoj z ni`jo mejo te~enja v strjenem delu zvara za izdelavo tla~nega cevovoda z debelino stene 47 mm in premerom cevi 4200 mm zaradi izbolj{ave varivosti. Izotermni Robertsonov preizkus izveden na zvarnem spoju obremenjenem z dopustno napetostjo 0.6 od meje te~enja je dokazal, da so vzdol`ne zaostale napetosti povzro~ile odmik {irjenja razpoke v `ilav osnovni material, kjer se je lom ujel. Temperatura ujetja je bila med -10 in -20°C. To dognanje je bilo vzrok za izpustitev termi~nega popu{~anja zaostalih napetosti na sekcijah cevi in na radialnih zvarnih spojih izvedenih na monta`i. Zaostale vzdol`ne napetosti je vedno mo`no upo{tevati pri ocenitvi uporabe strjenega zvara z ni`jo mejo te~enja od osnovnega materiala za visoko obremenjene konstrukcije.

Klju~ne besede: strjeni zvar z ni`jo mejo te~enja, zaostale napetosti, potek loma, lastnosti ujetja , lomna `ilavost

1 INTRODUCTION

The common philosophy in designing the weld joints for welded structures is to provide a weld metal (WM) when over-matched mechanical properties. The intention is to prevent the instability of short planar faults arising during the welding in the WM while the base material (BM) is straining when overloading occurs. This idea is based on the weld joint fracture toughness data received from the small scale CTOD tests in accordance with BS 7448[1] and the concept of CTOD driving force calculation on wide plates (WP) using the Engineering Treatment Model (ETM) intoduced by Schwalbe et al.[23] not taking into account the residual stresses. Thus, lower toughness in the WM is needed to operate the welded structure safely. But for weldability reasons, high preheating is necessary to prevent cold cracking.

To reduce the preheating, or even to eliminate it, in order to improve the weldability, WM under-matching properties could be used. Considering the above mentioned statement, this solution requires a high WM toughness to enable small planar faults to remain stable or to arrest a possible propagated (running) crack. When taking into account the axial residual stresses, which are higher than nominal stresses (near the yield stress in the as-welded condition), it was supposed that a more moderate WM toughness could also be satisfactory. The reason might be the "crack deviation phenomenon" appearing as a consequence of the high level of the residual stresses acting in the weld joint axial direction when the low stress brittle fracture is initiated and propagated. It can happen, as proposed for instance in the ETM loading range 1, where the effect of the mis-match weld metal on the driving force δ_R is small and depends only slightly on the applied strain[2]. This supposition was proven by the testing of an under-matched (M=0.84) butt weld joint made of 47 mm thick, 700 MPa yield stress, high strength, low alloy (HSLA) quenched and tempered (Q+T) steel (grade HT 80). The isothermal Robertson wide plate tests were used.

To assess the allowable planar fault size CTOD, the fracture toughness in accordance with BS PD 19[4] was measured on the specimens precracked from the weld joint surface side. The CGHAZ, which is the worst part of the weld joint, was hit with the crack tip line. The allowable planar fault size was calculated by the use of Burdekin's and Dawes' references[5,6,7]. These planar faults were introduced into the pipe longitudinal weld joints and their stability was proven by the full scale model test. The results have been reported previously by Kuder et al[8]. The nominal stress level caused by the external loading is much higher in the circumferential direction than in the longitudinal direction.

On the basis of the obtained results the under-matched weld joints were chosen for the

Table 1: Chemical composition of materials used

Elements in wt. %	C	Si	Mn	P	S	Cr	Ni	Mo	Pcm
Materials									
HT 80 steel	0.10	0.28	0.85	0.013	0.008	0.44	1.02	0.47	0.245
Deposited WM	0.05	0.34	1.89	0.020	0.011	0.44	0.14	0.72	0.217

Table 2: Mechanical properties of BM, weld joint and deposited WM

Designation	Y.P. (MPA)	T.S. (MPA)	EL. (%)	R.A. (%)	Fracture position/M	Impact toughness (J) at -40°C
BM	827.5	863	17	-	-	217
Transverse butt weld joint	-	810		-	WM	HAZ 31 WM 65 bond middle
Deposited WM, ϕ bars	693.5	797.5	22.5	61	M=0.84	-

production of a penstock used in a reversible hydro-power plant (pxD=323 bar m). The weld joints were not stress relieved in the workshop or on the site. The penstock has been operating for many years without any difficulties.

2 MATERIAL PROPERTIES AND WELDING PROCEDURE

HSLA Q+T steel with wall thickness from 26 to 47 mm was used to produce pipes for the penstock. Steel plates were cold rolled to a pipe diameter of 4200 mm using a special upright rolling device. The cylindrical shells were assembled by the tack weld passes. In the workshop at the site the longitudinal and circumferential weld joints were executed to produce pipe parts by the multi-pass submerge arc welding procedure (SAW). The circumferential weld joints for joining the pipe parts to erect the penstock were performed on site by manual arc welding (MAW).

The chemical composition of the BM and SAW deposited consumable (all-weld metal) are presented in **Table 1**. Mechanical properties of BM plates and SAW WM are presented in **Table 2**. The welding procedure data, preheating temperature of the MAW and SAW are presented in **Table 3**. To reduce the possible harmful effects of CGHAZ on the as-welded joints a special welding procedure was provided on the weld joint cup passes to reduce grain size at the weld toe[7].

3 EXPERIMENTAL DETAILS

Besides the mentioned tests for determination of mechanical properties, fracture mechanics tests were conducted on SENB specimens to measure CTOD fracture toughness at room temperature and at the freezing point. The aim was to gain an impression as to how a sharp crack in the HAZ of the weld joint will behave at the lowest possible penstock operating temperature.

Table 3: Welding procedure data

Designation	MAW	SAW
Powder/electrode drying	350°C, 1 hour	350°C, 1 hour
Hydrogen content ml/100g	1.1	< 0.1
Preheating temp. (°C)	75	< 20
Inter-pass temp. (°C)	150 - 170	130 - 150
Heat input (kJ/cm)	14 - 18	36 - 40
Electric source	DC	DC
Number of passes	36	10
HAZ max. hardness (HV10)	340	327

SENB specimens were notched at the surface side up to the CGHAZ of an X-shaped weld joint. The ratio a/W was approx. 0.5. The fracture mechanics tests have been performed in the year 1976 in accordance with the proposed method specified in BS DD19[4]. In all cases the "pop-in" event appeared after some extention of the slow crack growth. Due to the WM under-match properties the fracture path was similar in all specimens. After the crack initiation at the CGHAZ the slow crack propagation was deviated into a softer WM region. The results of CTOD fracture toughness tests are shown in **Table 4**. In accordance with[5], the lowest CTOD value at the instant fracture measured at the lowest possible temperature was used for calculation of the allowable planar defect size. Thus, the allowable surface crack size 2c=20 mm (crack length) and a =8 mm (crack depth) was adopted in accordance with the references[6,7] as the reference for acceptance or rejection of the faults by the non-destructive examination (NDE).

Table 4: CTOD data of BM and HAZ

Designation	Testing temp. (°C)	Specimen thickness Bx2B (mm)	Crack depth (mm)	CTOD, δ_u (mm)	"Pop-in" appearance
BM	+20	47x 94	31.4	0.80	yes
ME1	+20	"	23.4	047	yes
ME 2	0	"	24.2	0.21	yes
ME 3	2	"	22.91	0.30	yes
ME 4	3	"	22.32	0.28	yes

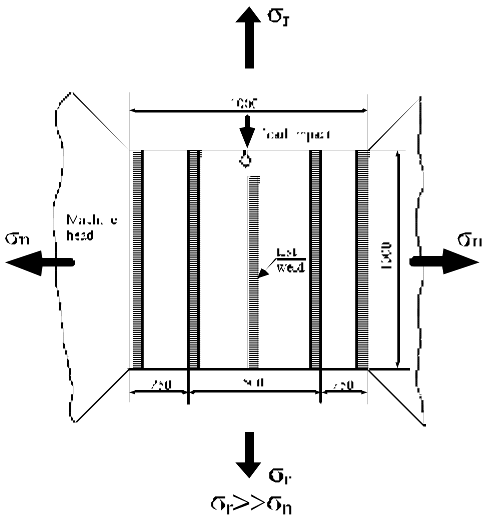

Figure 1: Dimensions of the specimen and its assembly in the tensile machine for isothermal Robertson test

Slika 1: Izmere preizku{anca in namestitev v trgalni stroj za izotermni Robertsonov preizkus

Two main objectives of the present investigation were:

- to establish how the initiated fracture in the under-matched weld joint behaves;
- and to assure a crack running along the longitudinal weld joint to arrest to check the nominally stressed overall properties of the joint the residual stresses were not relieved (as-welded condition).

To answer these questions, the isothermal Robertson wide plate tests were conducted at different testing temperatures on a 60 MN tensile machine. The specimens were assembled into the tensile machine and loaded to the penstock operating stress of 420 MPa in the as welded condition. One can assume that the longitudinal residual stresses were around 700 MPa at the level of the WM yield stress.

The fracture initiation points at the end of each specimen were saw cut in the HAZ of the tested weld joint (composite notch). The specimens were cooled to the testing temperature, while the initiation point was additionally cooled with liquid air. A brittle fracture was then initiated by a hammer impact. The scheme of the specimen preparation and the assembling into the tensile machine can be seen in **Figure 1**. The results of the Robertson tests executed at different temperatures are shown in **Table 5**.

The results of Robertson tests on the treated 47 mm thick under-matched weld joints made on the HT 80 steel plates stressed at a level of nominal stress of 420 MPa show that the crack arresting temperature in the as-welded condition is between -20 and -10°C. Despite of the under-matched weld joint properties (M=0.84) the fracture (the running crack) deviated from the WM/HAZ initiating area into the tough BM and was arrested even at a temperature of -20°C.

4 DISCUSSION

The results of the Robertson tests on 47 mm thick Q+T 700 MPa HSLA steel and the results of the full scale model testing reported in reference (6) led during the penstock designing, manufacturing and erection to an important insight into the problem and led to a beneficial explanation.

Table 5: Robertson test results

Designation	Testing Temperature (°C)	Fracture path
PD. 1-1	-22	After HAZ fracture initiation, at a distance of approximately 100 mm the fracture deviated mainly into the BM but did not arrest there until the end, see **Fig. 2**
PD. 1-2	0	After HAZ fracture initiation, at a distance of approximately 100 mm the fracture deviated into the BM and arrested at distance of 660 mm from the plate edge end, see **Fig. 3a and 3b**
PD. 1-3	-10	After HAZ fracture initiation, at a distance of approximately 20 mm the fracture deviated into the BM and arrested at a distance of 170 mm from the plate edge end, see **Fig 4**
PD. 1-4	-20	After HAZ fracture initiation, fracture deviated at a distance of 50 mm from the plate edge end into the BM, propagated in the BM until approx. 240 mm from the plate edge end and then deviated to the under-matched WM, the specimen fractured over its entire length, see **Fig. 5a and 5b**

Despite the penstock butt weld joints being provided in the under-matched condition it was recognised that the longitudinal residual stresses act beneficially. The level of the longitudinal stresses is the BM yield stress, R_e>700 MPa, while the level of the allowable nominal design stress is only 420 MPa. The longitudinal residual stresses caused deviation of the fast fracture initiated at the lower temperature into the BM of high toughness. It

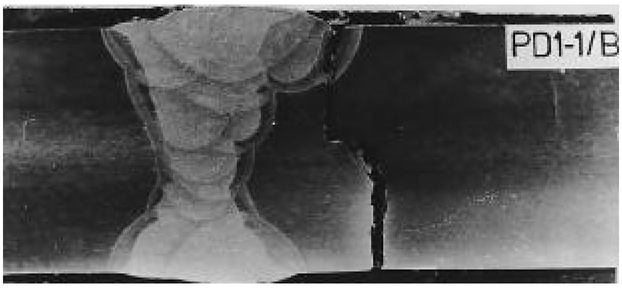

Figure 2: Macrograph of specimen PD.1-1 at a distance of 300 mm from the lower edge plate

Slika 2: Makro posnetek preizku{anca PD.1-1 pri oddaljenosti 300 mm od spodnjega roba plo{~e

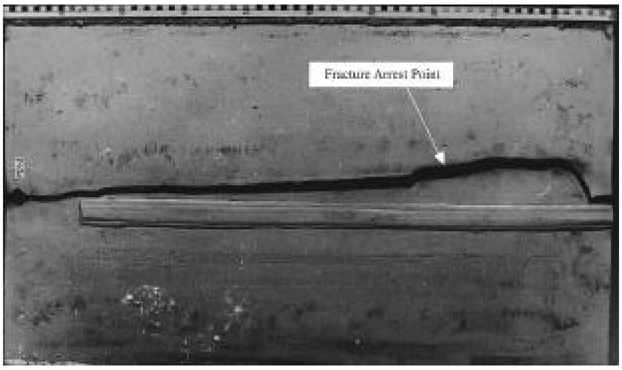

Figure 3a: Specimen PD.1-2 after testing
Slika 3a: Preizku{anec PD.1-1 po preizku{anju

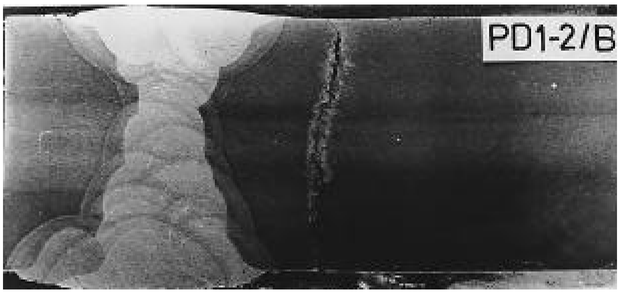

Figure 3b: Macrograph of specimen PD.1-2 at a distance of 300 mm from the HAZ saw cut notch
Slika 3b: Makro posnetek preizku{anca PD.1-2 na razdalji 300 mm od zareze name{~ene v TVP

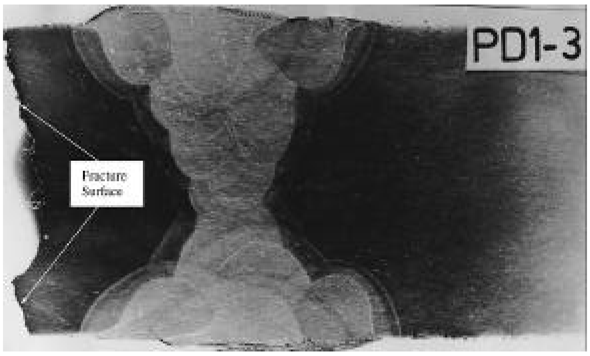

Figure 4: Macrograph of specimen PD.1-3 at a distance of 150 mm from the HAZ saw cut notch
Slika 4: Makro posnetek preizku{anca PD.1-3 na razdalji 150 mm od zareze v TVP

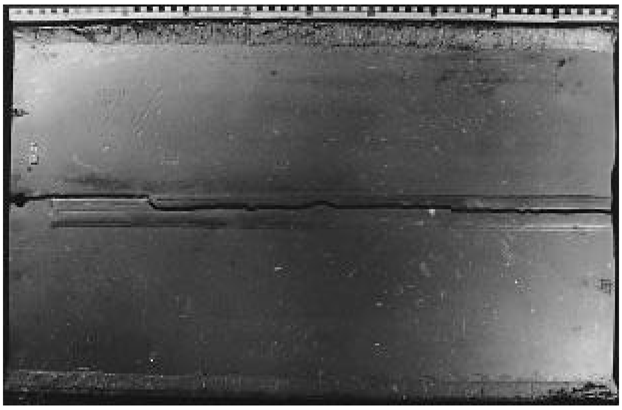

Figure 5a: Fracture path of specimen PD.1-4 after the Robertson test at -20°C
Slika 5a: Potek loma v preizku{ancu PD.1-4 po Robertsonovem preizkusu pri -20°C

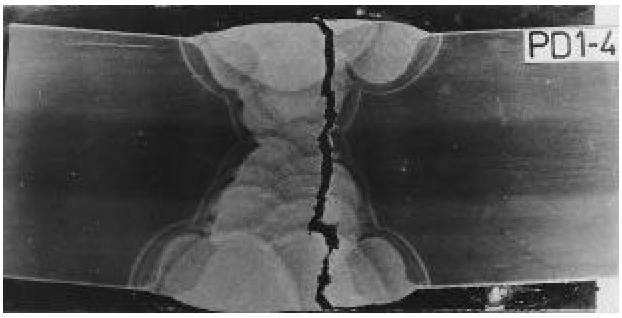

Figure 5b: Macrograph of specimen PD.1-4 at a distance of 500 mm from th upper edge of the plate
Slika 5b: Makro posnetek preizku{anca PD.1-4 na razdalji 500 mm od zgornjega roba plo{~e

arrested there between -10 and -20°C. Below -20°C BM it was not able to arrest the propagated crack despite the BM impact toughness energy of 200 J at -40°. According to current knowledge such a level of impact toughness is thought to be excellent. The above mentioned behaviour of the crack propagation was the first reason for omitting the weld joint thermal stress relieving.

The second reason to omit the thermal stress relieving was the existing residual stresses caused by the pipe shell forming. Because the plates were cold bent the residual stresses in the pipes are self evident. As was shown in ref. (8) these residual stresses enable pipe straining in the circumferential direction before stresses caused by loading reach the BM yield stress. This is very convenient in the case of overloading. These residual stresses act as a shock absorber because a large amount of energy is absorbed when stresses grow beyond the nominal allowable stresses and should not be omitted.

From the point of view of weldability of the HSLA structural steels it is easier to produce under-matched weld joints. Lower preheating is necessary and a lower restraining during the welding of the first root passes at the beginning of the welding is achieved too. In this way, the sensitivity to cold cracking is reduced.

Considering the under-matched weld joint from the point of view of the longitudinal residual stresses and their effect on the "crack deviation phenomenon" it offers a new philosophy for understanding its use. The most important is that the penstock was not stress relieved, despite exceeding a wall thickness of 38 mm, below which the stress relieving can be omitted.

It would be convenient to extend the "Fitness for Purpose Criteria" by taking into account the beneficial effect of the residual stresses in the under-matched weld joints when low stress brittle fracture is expected due to the "pop-in" appearance in the specimens CTOD testing.

5 CONCLUSIONS

On the basis of the obtained results, under-matched weld joints were used for manufacturing the penstock for the reversible hydro-power plant. The weld joints were not stress relieved. The penstock has been operating in the power plant for many years without any difficulties.

We state that the omitting of stress relieving may have the following beneficial effects:

- the prevention of the reheat cracking or the toughness reduction in the HAZ;
- the shell residual stresses due to cold bending enable straining at a stress level below the yield stress. They act as an additional safety factor in the case of penstock overloading;
- in the case of brittle fracture initiation in the weld metal or the HAZ longitudinal weld joint residual stresses enable fracture deviation into the BM.

We are convinced that when assessing whether to use under-matched weld joints, or not, the influence of the axial residual stresses can be taken into consideration to prevent the low stress brittle fracture. From the welding procedure point of view, the execution of under-matched weld joints is simpler.

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