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FLAW ACCEPTABILITY ASSESSMENT DETECTED IN HSLA STEEL WELD JOINTS

OCENITEV SPREJEMLJIVOSTI NAPAK ODKRITIH V ZVARNIH SPOJIH VISOKOTRDNOSTNIH JEKEL

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The flaw size in weld joint can be determined by non destructive examination (NDE). Because of different materials, and loading as well as because of the possible effect of corrosive envirnoment the question arises how to assess reliably the allowable flaw size in different weld joint parts. The presence of flaws is obvious but the possibilities of their revealing are limited and not always possible. The flaws size and distribution are the essential parameters for the structure capacity of bearing under high loading the weld joint. The larger is the allowable flaw size anticipated, the safer is the welded structure, and the easiest is the detection of the flaw size by NDE methods. Thus, for assessing the safety of complex loaded welded structure, machine parts or equipment life time, it is obligatory to consider the requirements of different "Fitness for Purpose" systems. The article presents the possibility of assessing the detected flaw by means of NDE if the material fracture toughness of the area where the fatigue crack tip located is known. The fatigue crack represents the severest discontinuity that can occur in a welded joint. The principles of IIW Guidance on Assessment of The Fitness for Purpose of Welded Structures - IIW/IIS-SST-1157-90 and BS PD 6493 and separately ETM that treats mis-matched weld joints are shown and used.

Key words: weld joint, allowable flaw size, fracture toughness, strength mis-match, fitness for purpose

Že desetletja lahko dovolj dobro in natančno z neporušnimi metodami določamo in diagnosticiramo napake v zvarnih spojih. Glede na raznolikost materialov in njih izkoriščenost ter vrste obremenitve ob prisotnosti različnih medijev v zahtevnih nosilnih konstrukcijah, stopa vse bolj v ospredje problem kako zanesljivo oceniti dopustno velikost napake v raznih delih zvarnih spojev. Vemo, da zvarni spoji niso brez napak, vendar je možnost njihovega odkrivanja omejena, odkrivanje pa ni vedno izvedljivo. Za nosilnost visoko obremenjene varjene konstrukcije je torej bistvena velikost dopustne napake. Čim večja je, tem varnejša je konstrukcija in tem lažje jo odkrijemo z neporušnimi preizkavami. Zato je za ocenitev varnosti zelo zahtevno obremenjene konstrukcije, strojnega dela ali opreme potrebno upoštevati priporočila, ki jih podajajo različni sistemi znani pod mednarodnim izrazom "Fitness for Purpose". V prispevku je prikazan primer, kako je možno na osnovi poznavanja lomne žilavosti materiala, v katerem se nahaja konica utrujenostne razpoke, ki predstavlja najostrejšo možno nezveznost, na osnovi poznavanja zakonitosti elasto-plasto mehanike loma, določiti, ali je dopustna z defektoskopskimi metodami odkrita napaka v zvarnem spoju. V ta namen so prikazani in uporabljeni principi priporočila BS PD 6493 in posebej še ETM (Engineering Treatment Model), ki obravnava trdnostno heterogene zvarne spoje (mis-matching).

Ključne besede: zvarni spoj, dopustna velikost napake, lomna žilavost, trdnostna heterogenost, primernost za uporabo

1 INTRODUCTION

At the present state of the art available NDE equipment enable to detect the flaws in welded joints by combination of one or more methods. The codes and standards for welded structures with high bearing capacity prescribe with respect to the loading and the utilisation of construction details or engine parts, the type and size of allowable flaws for quality control. Only separated pores or non-metallic inclusions are permitted. Planar discontinuities (cracks, lack of fusion, lack of penetration, etc.) are not permitted. Problem arises when the quality of a welded joint is limited by the possibilities and capabilities of NDE existing methods. Practical experience confirms that the confidence of flaw detection is about 60 to 70% of all present flaws in welded joints. If the flaw acceptance and quality of weld joints are assessed by the concept of "Fitness for Purpose" it has to be kept in mind that non detectable flaws are also present. For this reason, it is essential to know the critical flaw size (or at least the order of its size) which can cause non-stability or, in the worst case, a catastrophic fracture of a severe loaded welded structure.

If the fracture toughness properties at the top of a sharp planar discontinuity are determined, an allowable flaw size can be predicted or the allowability of the detected flaw can be assessed.. An essential important understanding is the larger the allowable flaw determined by the "Fitness for Purpose" concepts, the higher the safety in the welded structure in case of a sudden over-loading. On the other hand, the confidence of detection of a flaw, which appears as consequence of a poor welding procedure, is easier and more efficient. To realise the explained concept it is necessary to determine the following parameters: to measure fracture toughness, to set the dimensions of the detected flaw, to analyse the stress state around the crack tip at the limit loading condition, and to take into account also the overloading stresses using the fracture mechanics rules and the safety factors, to determine through thickness half crack length and at the end to transform this value into an allowable planar crack size (length and depth of surface or embeded flaw). In this article the procedure to determine the mentioned parameters will be shortly explained with the final target to forecast the order of magnitude of allowable planar discontinuity in a welded joint.

2 FRACTURE TOUGHNESS DETERMINATION

Usually, the fracture toughness of welded joints is measured on the whole thickness and at the lowest construction operating temperature. For ductile micro-alloyed and Q+T steels and their weld joints the elastic-plastic concept CTOD (Crack Tip Opening Displacement) is used. The fracture toughness parameter at the onset of crack initiation as δ_i or at the moment of instability as δ_c or δ_u is determined from R-curves provided by testing on specimens which size and shape are prescribed in the recently issued standard BS 7448:Part 2:1997 which addresses also the mis-matched weld joints[1], and other standards valid for uniform materials (BM) in latest modification[2,3]. An example of specimen instrumentation for the CTOD test before testing is presented in **Figure 1**. The procedure requires first to saw cut the specimen at the weld joint desired area with the micro-structure of the weld metal (WM) and heat affected zone (HAZ) of interest, than to fatigue it to produce a sharp crack tip. Fracture toughness standards are useful for welded joints only under specific

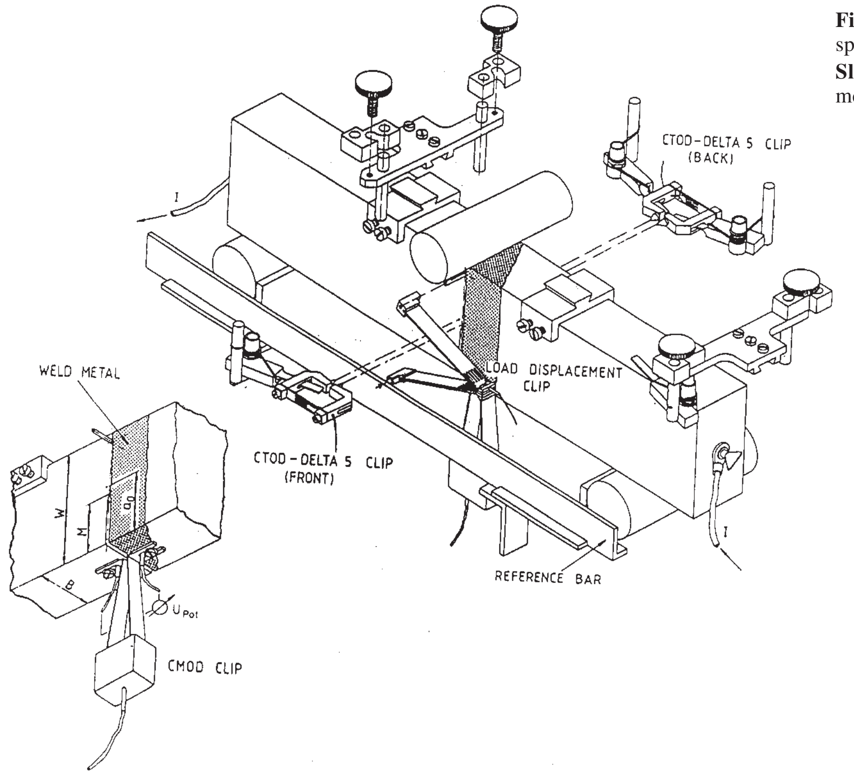


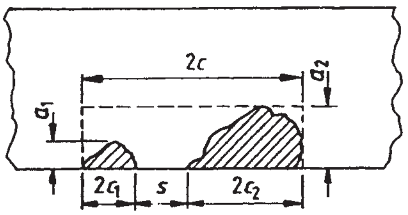
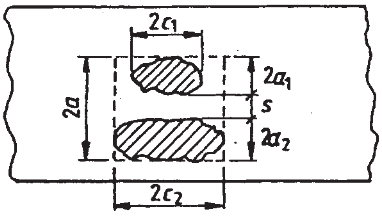
Figure 1: Instrumentation of fracture toughness specimen for HAZ testing

Slika 1: Instrumentirani preizkušanec za merjenje lomne žilavosti v TVP

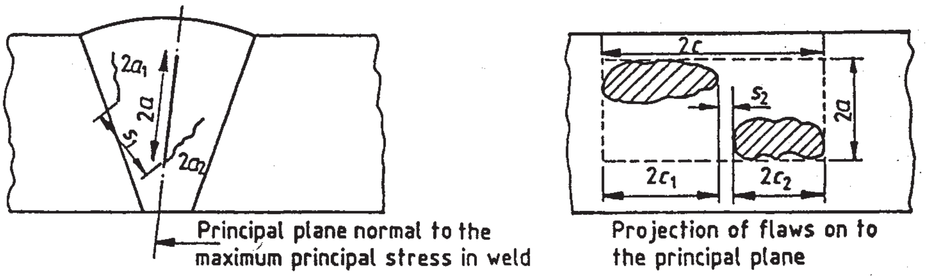
Table 1: Single and average CTOD values and WM/BM hardening exponents

Tabela 1: Posamezne in povprečne CTOD vrednosti in koeficienti utrjevanja za SZ/OM

Testing location	CTOD(BS) (mm)		CTOD(δ_5) (mm)		Hardening exponent n_W, n_B
	a/W=0.5 (δ_c) Bx2B	a/W=0.26 (δ_u) BxB	a/W=0.5 (δ_c) Bx2B	a/W=0.26 (δ_u) BxB	
WM	0.085	0.214	0.116	0.233	0.061 - cap
	0.128	0.185	0.123	0.229	0.056 - root
	0.090	(0.046 δi)	0.085	(0.026 δi)	
	0.098	0.303	0.099	0.366	
	0.104	(0.008 δc)	-	(0.019δc)	
	0.086		0.079		
	0.130	0.234 av.	0.117	0.276 av.	
	0.100 av.		0.103 av.		0.059 - av.
BM	0.123 δi		0.211 δi		0.097 - av.
	0.150 δi		0.151 δi		
	0.137 av.		**0.181 av.**		

Schematic flaws	**Criterion for interaction**	**Effective dimensions after interaction**
1 Coplanar surface flaws  	$s \leq 2c_1$ $(c_1 < c_2)$	$a = a_2$ $2c = 2c_1 + 2c_2 + s$
2 Coplanar embedded flaws  	$s \leq a_1 + a_2$	$2a = 2a_1 + 2a_2 + s$ $2c = 2c_2$

2 Adjacent non-coplanar embedded flaws



3 Adjacent non-coplanar surface and embedded flaws

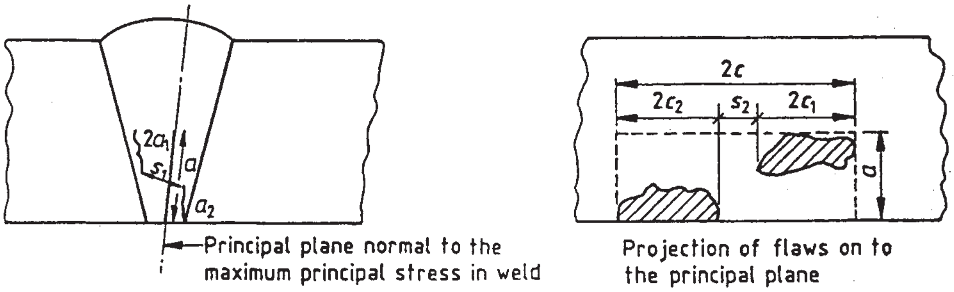


Figure 2: Planar flaw interactions
Slika 2: Vzajemno delovanje planarnih napak

corrections and additional measures such as: special procedure for obtaining the fatigue crack, yield stress determination of the region where the crack tip is located, the consideration of the mis-match properties between (WM) and (BM), and the crack depth a/W = 0.5. This matter is extensively described in ref.[4,5,6].

In **Table 1** the fracture toughness CTOD results calculated by prescribed BS procedure[1] and GKSS proposed direct CTOD-δ_5 measurement[7] are presented. A good correlation between both CTOD determinations concepts is found. A large disagreement between CTOD values determined on specimens with the standardised crack (a/W=0.5) and specimens with shorter crack (a/W=0.26) can be also recognised. As already known, the loading constraint conditions are higher in small standardised specimens with standardised crack size (a/W=0.5) than in weld joints with planar flaws found in a construction loaded by yielding. To overcome this problem and to handle with more realistic fracture toughness data the correlation between fracture toughness K_{IC} and Charpy impact toughness energy valid for wide plate tested specimens[8] was used to determine the critical CTOD-δc by following procedure.

The improved Barsom-Rolfe correlation between K_{IC} and the absorbed energy valid for wide plate test in original form is:

$$\left(\frac{K_{IC}}{100}\right)^2 = 300\left(\frac{\nu E}{\sigma_y}\right) \tag{1}$$

In the correlation the following units are used:

K_{IC} - kp/mm$^{3/2}$

vE, 2mm Charpy energy - kpm

σ_y - kp/mm^2

By vE=60 J at -10°C and σ_y=848 MPa the K_{IC} value is:

$$K_{IC}=147 \text{ MP m}^{1/2} \text{ at } -10°\text{C}$$

Introducing K_{IC} into equation:

$$\delta_c = \frac{K_{IC}^2}{E\sigma_y} \tag{2}$$

the WM CTOD valid for wide plate test can be obtained:

$$\delta_c=0.121 \text{ mm at } -10°\text{C}$$

and for BM δ_c=0.163 mm at -10°C

Comparing these fracture toughness values with fracture toughness values obtained by testing of small standardised CTOD specimens, higher toughness is found as affect of lower constraint conditions in wide plate loaded specimens. It seems that this differences at moderate fracture toughness level are not significant.

Presently a, project of measuring CTOD fracture toughness on Wide plate specimen, Small standardised CTOD specimens and Charpy toughness specimens to determine the correlations among them is in realisation.

The calculated hardening coefficients n[9,10] for BM and WM are added in **Table 1** as well.

3 EFFECTIVE FLAW SIZE

Single weld joints flaws are rarely found and few flaws can be found in a specific region. Flaws could be parallel to each other or can even overlap to some extent and influence load caring capacity differently. The recommendation PD 6493-91[7] distributes the discontinuities into coplanar and non-coplanar embedded or surface flaws, as shown in Figure 2a, 2b and 2c, for example. The interaction effect and the proposed new effective flaw size can be seen clearly. For flaw acceptance analysis it is necessary to know the following dimensions: 2a- for a trough thickness crack, a- and 2c- for a surface crack and 2a- and 2c- for an embedded crack (see the symbols in **Figures 2**).

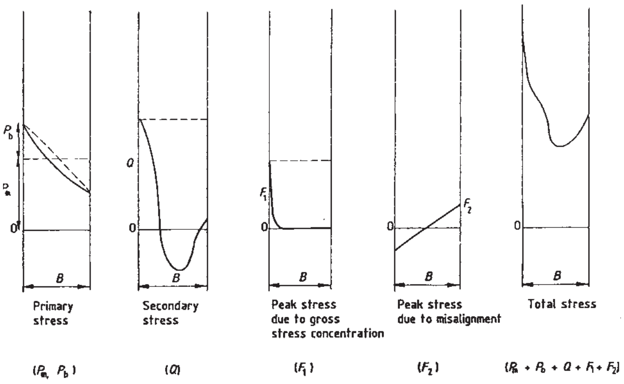


Figure 3: Schematic representation of stress distribution across section

Slika 3: Shematski prikaz porazdelitev napetosti preko preseka

4 CIRCUMSTANCES DETERMINATION AT THE TRANSVERSALLY FULLY LOADEC CRACK TIP

To assess the allowance of detected flaws or to predict the allowable flaw size it is necessary to determine the stress field in which the crack is situated. The stresses which should be taken into account are schematically presented in **Figure 3** and are:

- Membrane stress-**Pm**,
- Bending stress-**Pb**,
- Secondary stress-**Q** (residual and thermal stresses)
- Peak stress-**F** (stresses due to concentrations at local discontinuities-nozzles, weld misalignment-angular distortion and offset, holes notches, sharp angles etc.).

The resulting real stress is a the sum of stresses which can act at the planar crack tip.

5 ALLOWANCE OF PLANAR FLAWS

For easier understanding a simplified assessment will be presented. The analysis shows (Level 1) whether the planar flaw is a risk for fracture appearance or it can be assessed as allowable without employing a more complex assessment of allowability (as Level 2 or Level 3). This access incorporates a safety factor of about 2. The allowable planar through thickness flaw size takes into account the loading conditions at the crack tip $\sigma_1/\sigma_y>0.5$. It can be calculated from:

$$\bar{a}_{\max} = \frac{\delta_{mat} E}{2\pi\left(\frac{\sigma_1}{\sigma_y} - 0.25\right)\sigma_y} \tag{3}$$

σ_1= max. applied tensile stress (Pm+Pb+Q+F) in MPa

σ_y= yield stress

or determined from **Figure 4**. The allowable trough crack size a_m is:

$$\bar{a}_m = C\left(\frac{\delta_{mat} E}{\sigma_y}\right) \tag{4}$$

and C is calculated for ferritic steel as:

$$C = \frac{1}{2\pi\left(\frac{\sigma_1}{\sigma_y} - 0.25\right)} \tag{5}$$

or determined graphically, as shown in **Figure 4**. The factor C represents the loading conditions of a weld joint. The calculated value should be checked for the possible plastic collapse. The planar flaw is allowable if:

$$\sqrt{\delta_r} < \frac{1}{\sqrt{2}} < 0.707 \tag{6}$$

By the CTOD fracture ratio of:

$$\sqrt{\delta_r} = \sqrt{\frac{\delta_1}{\delta_{mat}}} \tag{7}$$

with δ_I as applied CTOD (driving force), and
δ_{mat} as the measured CTOD by specimen testing

$$\delta_1 = \frac{K_1^2}{E\sigma_y}\left(\frac{\sigma_y}{\sigma_1}\right)\left(\frac{\sigma_1}{\sigma_y} - 0.25\right) \tag{8}$$

with σ_y=weld metal yield stress in MPa and

$$K_I = \sigma_1 \sqrt{(\pi a)} \tag{9}$$

with σ_I as max. applied tensile stress (Pm+Pb+Q+F) in MPa and the a according to equation (3)
the calculation is acceptable by the ratio of plastic collapse Sr<0.8, as it is shown in **Figure 5**.

To determine the ratio S_r it is necessary to take into account the stress σ_n, acting as net- section stress and the interaction between tension and bending which effects the collapse behaviour:

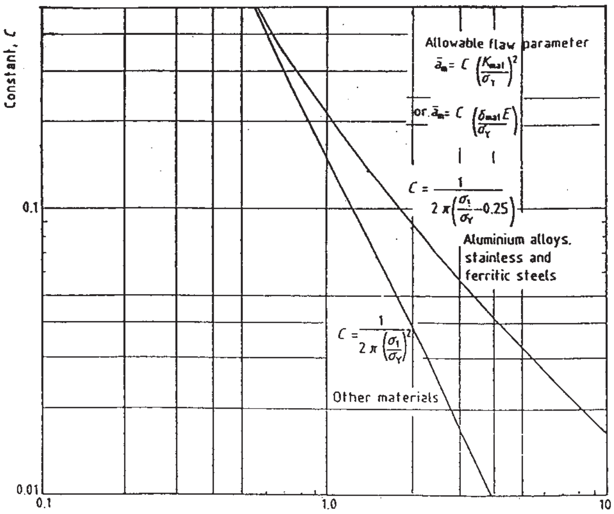


Figure 4: Values of constant C for different loading conditions-level 1
Slika 4: Vrednosti za konstanto C za različne obremenitvene primere-stopnja 1

$$S_r = \frac{\sigma_n}{\sigma_f} \tag{10}$$

with σ_n=net section stress in MPa and
σ_f=flow stress of the material in MPa

The flow strength is the average of the yield stress and of the tensile strength up to a maximum $1.2\sigma_y$. For the net section stress simple equations are derived, which take into account a straight plate, a shell of an penstock, or a pressure vessel for planar through thickness as welded surface or and embedded flaw. For a bended plate which represents a shell of a pressure vessel the σ_n in accordance with the appendix of as a reference[11] can be determined as:

$$\sigma_n = 1.2 M_T P_m \tag{11}$$

The non-dimensional factor for stress raising M_T is calculated as:

$$M_t = \left\{1 + 3.2\left(\frac{a^2}{DB}\right)\right\}^{0.5} \tag{12}$$

and the material flow strength σ_f as:

$$\sigma_f = \frac{\sigma_y + \sigma_m}{2} \tag{13}$$

Determination of allowable flaw size in the weld joint of a severe loaded penstock

As an example the pressurised penstock assembled by SMAW and SAW welding procedures on quenched

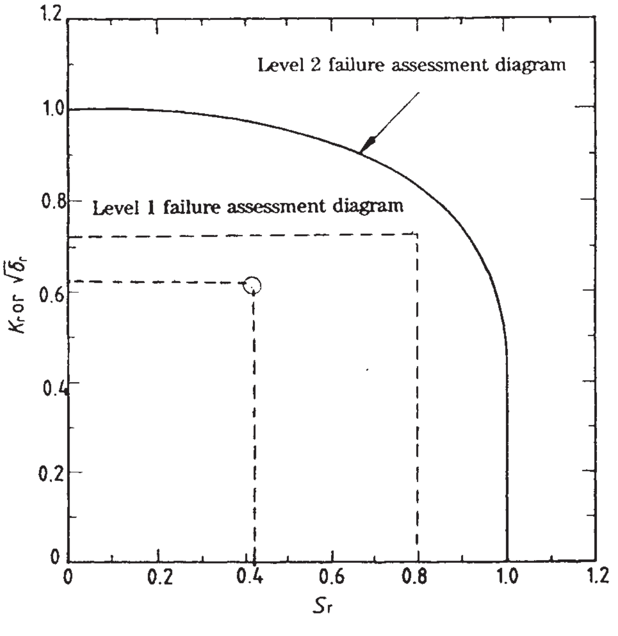


Figure 5: Level 1 and level 2 failure assessment diagram
Slika 5: Ocenitveni diagram napak po stopnji 1 in stopnji 2

and tempered (Q+T) steel grade HT80, was treated. The main data are following:

- Thickness, B: 40 mm
- Pipe diameter, D: 4200 mm
- BM yield stress : σ_y=693 MPa
- BM tensile strength: σ_m=838 MPa
- WM yield stress: σ_y=848 MPa
- WM tensile strength: σ_m=917 MPa
- Tested BM CTOD at -10°C: δ_{mat}=0.163 mm
- BM impact toughness at -40°C: a_k=50 J/cm^2
- Membrane stress: Pm=315MPa
- Bending stress: Pb=100MPa
- Residual stresses: Q=700MPa
- Local stress concentrations: F=150 MPa
- Tested WM CTOD at -10°C: δ_{mat}=0.121 mm
- WM impact toughness at -40°C: a_k=40 J/cm^2
- Mis-match factor: $M=\frac{\sigma_{y_{WM}}}{\sigma_{y_{BM}}}=1.21$

Due to beyond equations the values for allowable WM planar flaws size are as follows:

- Allowable planar through thickness flaw size $\bar{a}_m$=3.8 mm, derived from equation (3) and Figure 4, by C=0.128 and the tensile stress ratio Pm+Pb+Q+F/σ_y=1.492
- The planar through thickness flaw size of 2 mm is chosen, because of a possible plastic collapse and in accordance with the calculation by using equations (6), (7), (8), (9) and (10)
- Plastic collapse ratio from equation (10) Sr=0.43
- CTOD fracture ratio $\sqrt{\delta_r}$=0.623, by using equations (7), (8) in (9)
- The planar flaw size according to Level 1[11] is allowable because S_r<0.8 and $\sqrt{\delta_r}$<0.707. As shown in Figure 5 the flaw size is in the permitted field framed by the assessment line and no additional partial safety factors are required.

Determination of the equivalent part thickness flaw size

The transformation from through thickness to part thickness is obtained according to reference[11] after having obtained a_m and if the term $\bar{a}_m>\bar{a}$ is fulfilled according to parameters in **Figure 6**.

If the ratio $\bar{a}$/B=2.0/40=0.05 is assumed the allowable dimension of the a planar surface flaw using Figure 6 is as shown in Table 2.

From Table 1 it can be recognised that the allowable planar flaw size, as crack, lack of fusion or lack of root penetration are small and not easy detectable by NDE methods and particularly difficult by X ray wxamination, if the locations of the cracks in WM and HAZ are inclined to the X-ray beam by an angle larger than 20° and the thickness is higher than 20 mm.

Table 2: Allowable planar surface flaw sizes
Tabela 2: Dopustne dimenzije površinskih napak

a/2c	a/B	a allow. (mm)	2c allow. (mm)
0.0	0.037	1.48	∞
0.1	0.044	1.76	17.6
0.2	0.055	2.20	11.0
0.3	0.062	2.48	8.30
0.4	0.090	3.60	9.00
0.5	0.113	4.52	9.10

6 USE OF ENGINEERING TREATMENT MODEL (ETM) FOR MIS-MATCHED WELD JOINTS

By high BM tensile strength (800 MPa) a high WM toughness is generally not obtained (higher than BM) and the reliability of a welded joint is assessed by means

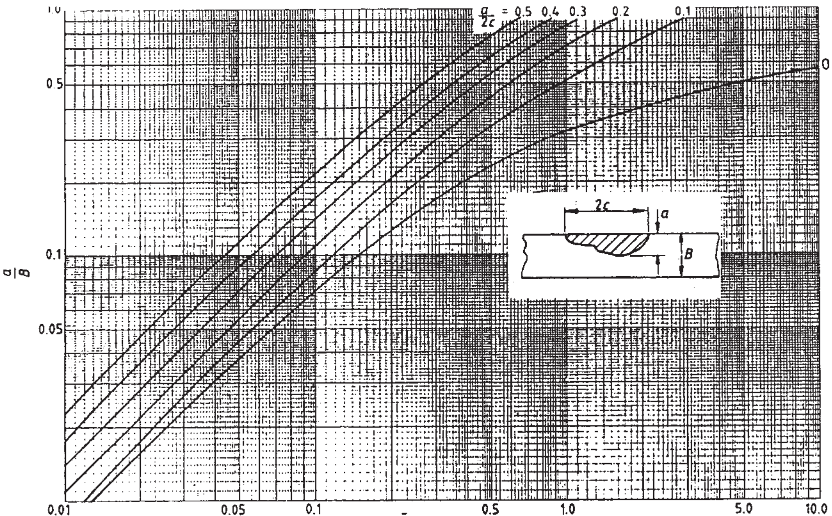


Figure 6: Relationship between actual flaw dimensions and the parameters of surface flaws
Slika 6: Odnos med dejansko velikostjo napake in parametri površinske napake

of ETM developed by K.-H. Schwalbe at the GKSS (12,13).

The principle of the model is the mis-match ratio between yield stress of WM and BM which results in a different hardening ability of both materials. In the treated case the mis-matching factor M>1 (M is the ratio between weld metal yield stress and base material yield stress) and the weld joint is in over-matched condition. This behaviour can be used for the assessment of small WM planar flaws in elastic stress in over-loading condition, while the BM is strained. The size of the acceptable planar flaw can be larger than that determined using reference[11]. This difference will grow in proportion to the mis-matching factor M. In **Figure 7**, an example of mis-matching loading ranges and of the WM fracture toughness requirements according to mis-match condition M (1>M>1) in each range is shown. The formulations for the calculation of the driving force δ_W are added.

Driving force ratio δ_R for the over-matched weld joint

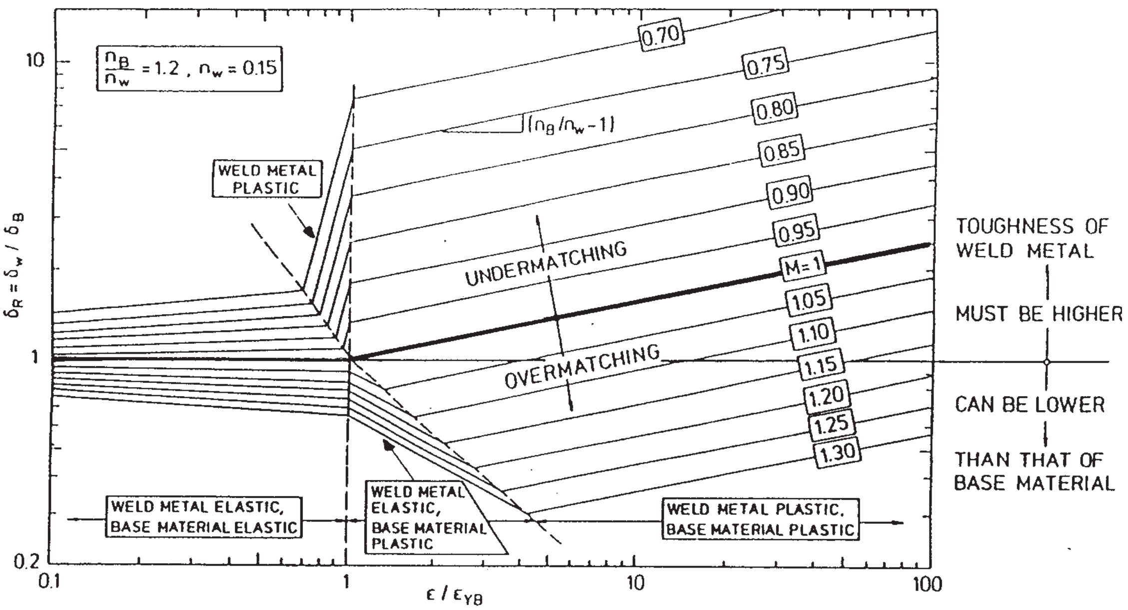
The crack driving force ratio for a weld metal $\delta_R = \delta_W/\delta_B$ can be calculated using the equations (14), (15), and (16) from Figure 7, while the base metal driving force is expressed as $\delta_B = 1.5\,\pi a \varepsilon_B$. For three loading ranges and for an over-matched weld joint the crack driving force ratio can be expressed as function of the lower and the upper limit loading as follows:
Loading range 1:

For the lower limit $e/e_{yB} \Rightarrow 0$

$$\delta_R = \frac{1}{M} < 1 \tag{17}$$

and for the upper limit $e/e_{yB} \Rightarrow 1$

$$\delta_R = \frac{2M^2 + 1}{3M^3} < 1 \tag{18}$$



Loading range 1:
Base material and weld metal material are deformed bellow their respective yield strength, $0<F<F_{yB}$. The weld metal CTOD driving force in terms of nominal strain, ε, is

$$\delta_w = \frac{\pi a \sigma_{yB}}{2M^3 E}\left(\frac{\varepsilon}{\varepsilon_{YB}}\right)\cdot\left[2M^2 + \left(\frac{\varepsilon}{\varepsilon_{yB}}\right)^2\right] \tag{14}$$

Loading range 2:
Base material deforms plastically, whereas the weld metal is still elastic, $F_{yB}<F<F_{yW}$. The weld metal CTOD driving force is

$$\delta_w = \frac{\pi a \sigma_{yB}}{E}\cdot\frac{1}{M}\cdot\left(\frac{\varepsilon}{\varepsilon_{YB}}\right)^{2n_B}\cdot\left[1 + \frac{0.5}{M^2}\cdot\left(\frac{\varepsilon}{\varepsilon_{yB}}\right)^{2n_B}\right] \tag{15}$$

Loading range 3:
Both, base material and weld metal deform plastically, $F>F_{yW}$. The weld metal CTOD driving force is

$$\delta_w = \frac{1.5\pi a \sigma_{yB}}{E}\cdot M^{\left(1-\frac{1}{n_w}\right)}\cdot\left(\frac{\varepsilon}{\varepsilon_{YB}}\right)^{\frac{n_B}{n_w}} \tag{16}$$

Figure 7: ETM for mis-matched weld joints and crack driving force
Slika 7: ETM za zvarne spoje s trdnostno heterogenostjo in gonilna sila odpiranja razpoke

Loading range 2:

The lower limit is equal to the upper limit of loading range 1

For the upper limit $\frac{\varepsilon}{\varepsilon_{yB}} = M^{\frac{1}{nB}}$

$$\delta_R = M^{(1-\frac{1}{n_B})} < 1 \tag{19}$$

Loading range 3:

The lower limit is equal to the upper limit of loading range 2.

If the strain ε_W in weld metal is used as the global strain $\varepsilon = \varepsilon_B$, the plastic properties of WM and BM yield the δ_R as term of the normalised applied strain according to the following equations:

$$\frac{\varepsilon_w}{\varepsilon_{yw}} = (\frac{\varepsilon}{\varepsilon_{yB}})^{\frac{n_B}{n_w}} \frac{\sigma_{y_B}}{\sigma_{y_w}}^{\frac{1}{n_w}}$$

$$\delta_R = M^{(1-\frac{1}{n_w})} \cdot \left[\frac{\varepsilon}{\varepsilon_{yB}}\right]^{\left[\left(\frac{n_B}{n_w}\right)-1\right]} \tag{20}$$

These equations give the required minimum toughness of the WM compared to the BM if the following solution is satisfied:

$$\frac{\delta_{cw}}{\delta_{cB}} > \frac{\delta_w}{\delta_B} = \delta_R \tag{21}$$

In such a case the toughness performance of weld joint with over-matching WM is equal to or even better than that of BM.

In **Figure 8** the driving force ratio δ_R is shown as function of the normalised strain e/e_{yB} for a treated over-matched weld joint. For all over-matched conditions the driving force ratio δ_R is smaller than the measured material fracture toughness ratio and the requirement in equation (21) is fulfilled.

Normalised driving force δ_W for the over-matched weld joint*

For the design curve consideration the formalism proposed in the British CTOD Design Curve[11,13] can be applied. The normalised applied CTOD is defined in weld metal as the driving force δ_C related to the local weld metal stress σ_1. When δ_C is the critical CTOD and a_m is the defect size equal to one half of the defect length a_C:

$$\delta_c^* = \frac{\delta_c E}{2\pi a_m \sigma_y} = \left(\frac{\sigma_1}{\sigma_y}\right)^2 \text{; for } \frac{\sigma_1}{\sigma_y} < 0.5 \tag{22}$$

and the normalised applied CTOD in the weld metal is defined as:

$$\delta_w^* = \frac{\delta_w E}{2\pi\sigma_{yw}} = \frac{\delta_w E}{2\pi M \sigma_{yB}} \tag{23}$$

Loading range 1:

Combining equation (14) from Figure 7 and equation (18) and having in mind a small $\varepsilon/\varepsilon_{yB}$ ratio it can be set:

$$\delta_w^* = \frac{1}{M^2} = \left(\frac{\varepsilon}{\varepsilon_{yB}}\right)^2 \tag{24}$$

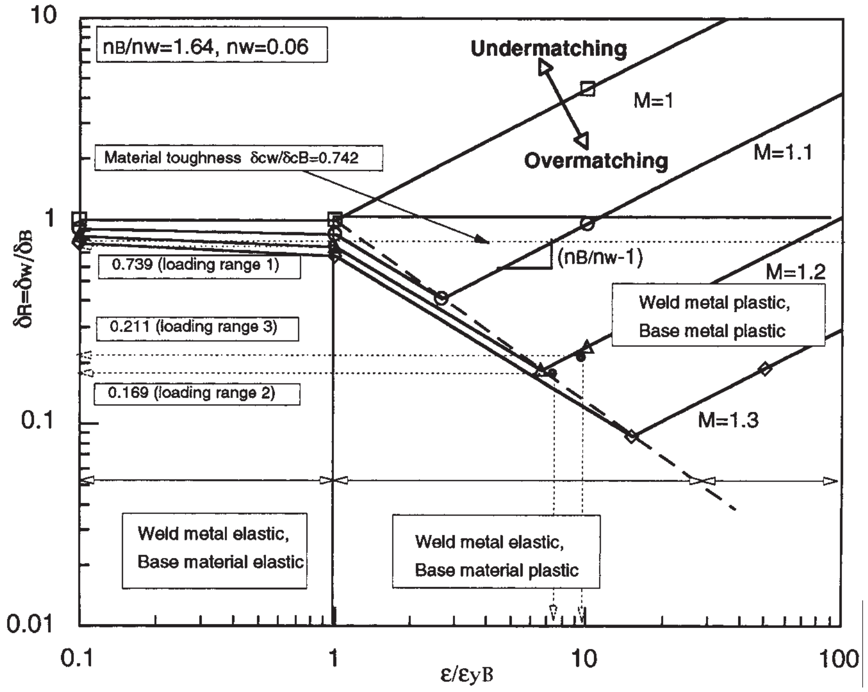
For the upper limit given by $\varepsilon = \varepsilon_B$ the solution is:

$$\delta_w^* = \frac{1}{M^2} = \left[1 + \frac{1}{2M^2}\right] \tag{25}$$

Table 3: Driving force ratio δ_R, driving force δ_W and normalised driving force of weld metal CTOD δ_{cW}*

Tabela 3: Odnos gonilne sile δ_R, gonilna sila δ_W in normalizirana gonilna sila strjenega zvara CTOD δ_{cW}*

Loading stress (MPa)	$\varepsilon/\varepsilon_{yB}$	M	δ_R	δ_W (mm)	δ_W*
Loading range 1	0.1	1	1	0.0030	0.0100
	0.1	1.1	0.909	0.0026	0.0080
lower limit	0.1	1.2	0.833	0.0022	0.0069
$\sigma<\sigma_{yB}<\sigma_{yw}$	0.1	1.3	0.769	0.0025	0.0061
	1	1	1	0.4980	1.5
upper limit	1	1.1	0.856	0.3870	1.1670
	1	1.2	0.748	0.3110	0.9350
	1	1.3	0.665	0.2440	0.7350
Loading range 2	1	1	1	0.498	1.5
upper limit	2.679	1.1	0.411	0.548	1.5
$\sigma_{yw}>\sigma>_{yB}$	6.589	1.2	0.182	0.598	1.5
	15.077	1.3	0.086	0.647	1.5
Loading range 3	10	1	4.410	21.90	66.17
	10	1.1	0.959	4.345	13.08
$\sigma_{yW}<\sigma>\sigma_{yB}$	10	1.2	0.238	0.989	2.978
	50	1.3	0.186	0.292	0.761



Toughness of a over-matched weld metal is equal to or even better than that of base material if the following toughness requirements is met:

$$\frac{\delta_{cw}}{\delta_{cB}} \ge \frac{\delta_{w}}{\delta_{B}} = \delta_{R}$$

This requirement is met at the loading range 1 (when ε/εy=1 or bellow), at the loading range 2 (when ε/εy=M1/nB=7.76 or bellow) and at the loading range 3 (when for instance ε/εy=10 or bellow).

Data: weld joint mis-match M=1.21, σyB=639 MPa, σyw=848 MPa, δcw=0.121 mm and δcB=0.163 mm at -10°C, nB=0.097, nw=0.059.

Figure 8: Driving force ratio as a function of normalized strain ε/εy for treated over-matched weld joint

Slika 8: Odnos gonilne sile v odvisnosti od normalizirane deformacije za obravnavani zvarni spoj

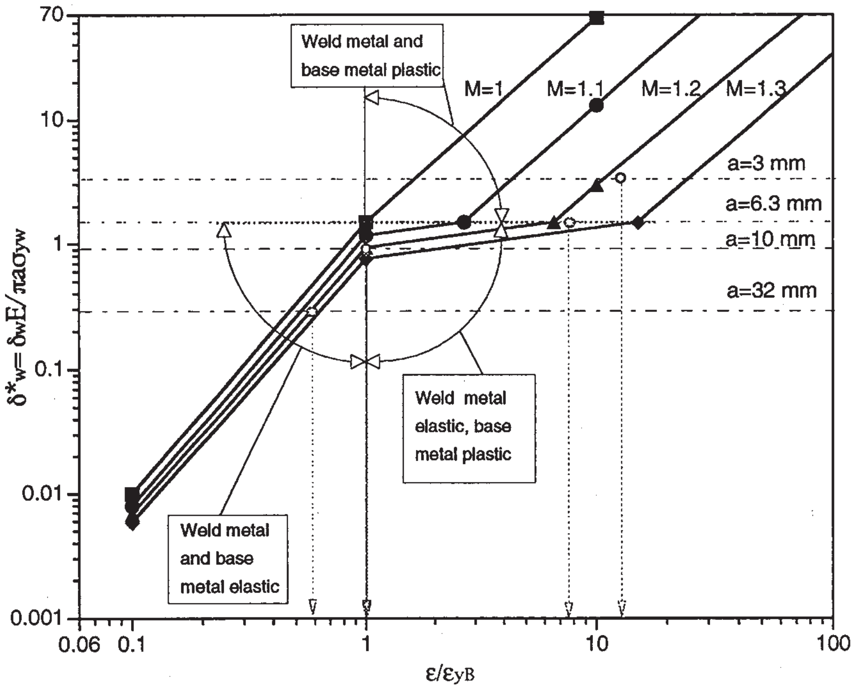


Figure 9: Assessment of WM critical crack size in loading ranges 1, 2 and 3 in the as-welder over-matched weld joint M=1.21

Slika 9: Ocenitev velikosti napake v strjenem zvaru v področjih obremenitev 1, 2 in 3 zvarnega spoja s trdnostno heterogenostjo M=1.21

Loading range 2:

Combining equation (15) for δ_W from Figure 7 and equation (18) we obtain for the upper limit given by $\varepsilon/\varepsilon_{yB} = M^{1/nB}$ the constant value:

$$\delta_w^* = 1.5 \tag{26}$$

Loading range 3:

Combining equation (16) from Figure 7 and equation (18) the normalised form is obtained as:

$$\delta_w^* = 1.5\left[\frac{1}{M}\right]^{\frac{1}{n_w}}\left[\frac{\varepsilon}{\varepsilon_{yB}}\right]^{\frac{n_B}{n_w}} \tag{27}$$

By fully plastic condition δ_W can be written as $\delta_W = 1.5\pi a\varepsilon_W$. The normalisation of the equation (18) leads to

$$\delta_w^* = 1.5\left(\frac{\varepsilon_\omega}{\varepsilon_{yw}}\right) \tag{28}$$

The values for normalised weld metal CTOD δ_W^* as the function of the applied normalised global strain for treated over-matched weld joint is presented in Figure 9.

In Table 3 all data for the driving force ratio δ_R, the driving force δ_W and the normalised driving weld metal CTOD δ_{cW}^* for different weld joint over-matching conditions are given as function of the applied normalised global strain.

7 CRITICAL CRACK LENGTH ESTIMATION

Inserting the measured δ_W=0.121 mm and yield stress σ_y = 848 MPa for over-matched weld metal into the normalised CTOD driving force expression δ_W^*(18) the normalised critical crack length a* can be derived:

$$\delta_w^* = \frac{\delta_w E}{2\pi\sigma_{yw}} = \frac{\delta_w E}{\pi\alpha M\sigma_{yB}} \tag{29}$$

$$a^* = \frac{a_c \pi\sigma_{yw}}{\delta_{cw} E} = \frac{1}{\delta_w^*} \tag{30}$$

Hence, the absolute value a_c can be derived with δ_W^* for the appropriate loading ranges.

$$a_c = \frac{a\delta_{cw} E}{\pi\delta_{yw}\delta_w^*} \tag{31}$$

In **Figure 9** the loading ratios $\varepsilon/\varepsilon_y$ are presented as function of a different selected critical crack length (a = 32, 10, 6.3 and 3 mm) by as welded over-matched condition M=1.21 and by the critical weld metal CTOD value δ_{cW}=0.121 mm. The values for δ_W^* are as follows:

$\delta_W^* = \delta_W E/a\pi\sigma_{yW}$ = 0.298 valid for CTOD δ_c=0.121 mm at -10°C if a = 32 mm

$\delta_W^* = \delta_W E/a\pi\sigma_{yW}$ = 0.953 valid for CTOD δ_c=0.121 mm at -10°C if a = 10 mm

$\delta_W^* = \delta_W E/a\pi\sigma_{yW}$ = 1.514 valid for CTOD δ_c=0.121 mm at -10°C if a = 6.3 mm

$\delta_W^* = \delta_W E/a\pi\sigma_{yW}$ = 3.170 valid for CTOD δ_c=0.121 mm at -10°C if a = 3 mm

The allowable planar trough thickness flaw sizes shown in Figure 9 are due to three different weld joint loading ranges.

By transforming this flaw size into a part through flaw size, as mentioned above, the WM allowable planar crack size in the weld joint operating in mis-matched condition can be determined. In Table 4 the allowable planar surface crack size for through flaw size a=6.3 mm (for a/B=6.3/40=0.158) and overloading by Pm+Pb+Q+F/σ_y=7.6 is presented.

By comparing allowable surface crack sizes in **Table 2** and **Table 4** one can recognise that a 6-8 times larger flaw size much easier to detect by NDE is permissible due to over-matching condition M=1.21.

Table 4: Allowable part thickness planar flaw sizes determined by ETM for weld joint with M>1

Tabela 4: Dopustna velikost površinske napake določena po ETM za zvarni spoj z M>1

a/2c	a/B	$a_{allow.}$ (mm)	$2c_{allow.}$ (mm)
0.0	0.105	4.20	8
0.1	0.131	5.24	52.4
0.2	0.168	6.72	33.6
0.3	0.215	8.60	28.6
0.4	0.255	10.2	25.5
0.5	0.320	12.0	24.0

8 CONCLUSIONS

The following conclusions are proposed:

- The acceptability of planar discontinuities in a weld joint can be determined on the basis of the knowledge of the material properties and of the stress field in which the discontinuity is located.
- By using of recommendations, such as BS PD 6493-91, IIW Guidance on Assessment of the Fitness for Purpose of Welded Structures and ETM the detected weld joint flaws can be assessed and the allowable flaw size before NDE can be determined. The larger is the determined allowable flaw size, the safer is the welded structure and at the same time the higher is the certainty of revealing the flaw size by the NDE inspection.
- Usually, (due to codes and standards roles) planar discontinuities are not permitted because due to a poor welding procedure or incorrect welding technique used. In case of impossibility of repairing the flaw, the fracture mechanics assessment is very valuable.
- Especially important and pretending is the assessment of planar flaw acceptance of

mis-matched welded joints. In such a case the assessment in accordance with ETM is unavoidable.

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