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## Določanje odpornostnih krivulj elasto-plastične mehanike loma na upogibnih preizkušancih s plitvimi in globokimi razpokami

### The Determination of Elasto-Plastic Fracture Mechanics Resistance Curves on Bend Specimen with Shallow and Deep Cracks

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Poglavitni cilj obširnega eksperimentalnega programa, ki je delno predstavljen v tem članku, je bila študija vpliva velikosti in geometrijske oblike preizkušancev na odpornostne krivulje CTOD in integral J. Material, ki smo ga izbrali za te raziskave, je mikrolegirano jeklo s površino trdnostjo (HSLA) NIONICRAL 70A, ki ga pridobiva Železarna Jesenice. Preizkusi so bili opravljeni na različnih upogibnih preizkušancih z enostransko zarezo na robu preizkušanca (SEN-B) z različnimi razmerji dolžine razpoke proti višini preizkušanca ( $a/W$ ). Za določanje rasti razpoke med samim preizkusom sta bili uporabljeni dve metodi: metoda elastične popustljivosti pri delnem razbremenjevanju preizkušanca in metoda, ki temelji na merjenju padca električnega potenciala.

The aim of this paper is to present a part of an experimental program being carried out to study size and geometry effects on CTOD and J resistance curves. The material selected for this investigation was high strength low alloy (HSLA) steel, called NIONICRAL 70A produced by Steelworks Jesenice in Slovenia. The experiments were performed on various single edge notch bend (SEN-B) specimens with different crack depth to specimen width ratio ( $a/W$ ). The unloading compliance and the DC potential drop methods to determine the crack growth during the test were used.

#### 0 UVOD

Za opisovanje obnašanja telesa z razpoko ima mehanika loma v elasto-plastičnem območju na voljo dva parametra: kritično vrednost integrala J in kritično velikost odpiranja konice razpoke CTOD. Oba parametra sta v splošnem priznana kot merilo lomne žilavosti konstrukcijskih materialov.

Odpornostne krivulje so črte, pri katerih je prikazan določen parameter mehanike loma v odvisnosti od prirastka razpoke  $\Delta a$ . V našem primeru sta to integral J in odpiranje konice razpoke CTOD. V začetnem strmem, linearinem delu krivulje se še ne pojavi razdvajanje materiala in nastane prirastek razpoke zaradi zaobljevanja (otopitve) prvotno ostre razpoke. Z naraščajočo obremenitvijo se ostra razpoka zaoblji in doseže svojo kritično vrednost, pride do razdvajanja materiala in pri žilavih materialih do stabilne rasti razpoke. Z rastjo razpoke se spremeni tudi strmina odpornostne krivulje, ki preide v položnejši del. Na presečišču obeh črt se torej pojavi iniciacija razpoke (vrednost  $J_0$ ,  $CTOD_0$ ), vendar se v inženirski praksi običajno uporablja vrednosti  $J_{0,2bl}$  in  $CTOD_{0,2bl}$  [1], [2].

#### 0 INTRODUCTION

Fracture mechanics offers two parameters for the description of cracked body behaviour in an elastic-plastic regime: the critical J-integral value and the critical crack tip opening displacement (CTOD). Both parameters are generally accepted as a measure of fracture toughness of engineering materials.

Resistance curves are lines in which a certain parameter (in our case the J-integral or the crack tip opening displacement CTOD) is plotted over the crack extension  $\Delta a$ . The steep, straight line originating from zero corresponds to the process of crack tip blunting and the second flatter part of the resistance curve resulting from the increase in loading describes the stable crack extension (fig.5) in tough materials. At the intersection of the two lines, the process of stable crack growth is initiated ( $J_0$ ,  $CTOD_0$ ), but the values  $J_{0,2bl}$  and  $CTOD_{0,2bl}$  are usually used to determine an engineering measure of initiation of crack growth [1], [2].

Dolžina razpoke ima odločilen vpliv na izmerjene vrednosti lomne žilavosti in moramo biti pri uporabi laboratorijskih rezultatov, dobljenih na standardnih preizkušancih z globokimi razpokami, zelo previdni.

## I MATERIALI IN PREIZKUŠANCI

Za študij in raziskave izbrano mikrolegirano jeklo s površino trdnosti NIONICRAL 70A, ki ga izdeluje Železarna Jesenice, je ekonomsko zanimiv material za izdelavo kompleksnih nosilnih konstrukcij. Zato je zelo pomembno, kako se obnašajo strojni deli s plitvimi površinskimi razpokami, ki se jim pri različnih zvarnih spojih praktično ne moremo izogniti.

V preglednici 1 so podane osnovne mehanske lastnosti in kemična sestava preizkušanega jekla, na sliki 1 pa je prikazana inženirska krivulja napetost – deformacija, ki smo jo dobili z nateznim preizkusom okroglega nateznega preizkušanca ( $d_0 = 6 \text{ mm}$ ) pri sobni temperaturi in pri počasni stopnji obremenjevanja ( $< 25 \text{ MPa/s}$ ). Zaradi dodatka mikrolegirnih elementov ima to jeklo zelo visoko točko tečenja z razmerjem napetosti tečenja in natezne trdnosti  $R_{p0,2} / R_m = 0,92$  in z nizko vrednostjo eksponenta deformacijskega utrjevanja  $n = 0,06$ .

Preglednica 1: Kemična sestava (v utežnih %) in mehanske lastnosti jekla NIONICRAL 70A

Table 1: Chemical composition (weight percent) and mechanical properties of NIONICRAL steel 70 A

C	Si	Mn	P	S	Cr	Ni	Al	Mo
0,09	0,27	0,25	0,015	0,004	1,12	2,63	0,020	0,25
Modul elastičnosti	Meja plastičnosti			Natezna trdnost		Raztezek pri najv. sili		Raztezek pri zlomu
Modulus of elasticity	Yield strength (0,2% offset)			Ultimate tensile strength		Ultimate strain		Elongation at fracture
E MPa	$R_{p0,2}$ MPa			$R_m$ MPa		$e_n$ %		A %
≈ 198000	718			778		7,4		22,4

Z iste slike je tudi razviden poenostavljen postopek za ocenitev eksponenta deformacijskega utrjevanja ( $n$ ) zadovoljive natančnosti. Če so znani modul elastičnosti ( $E$ ), meja plastičnosti ( $R_{p0,2}$ ), natezna trdnost ( $R_m$ ) in enakomerni inženirski raztezek (relativni raztezek pri maksimalni sili,  $e_n$ ) je mogoče eksponent  $n$  določiti z izrazom:

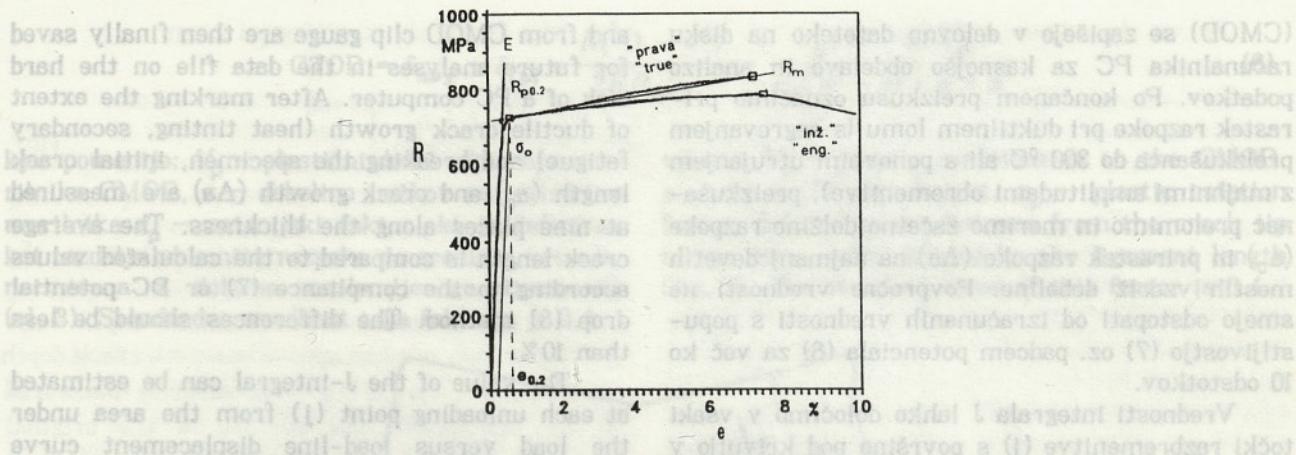
The notch depth of the standard CTOD or J-integral has a significant influence on measured fracture toughness results and should be carefully considered when laboratory test results obtained from deep cracked specimens are related to the service behaviour of the cracked component.

## 1 MATERIALS AND SPECIMENS

The material selected for this investigation was the high strength low alloy (HSLA) steel produced by Steelworks Jesenice, Slovenia. This steel, called NIONICRAL 70A, is an economically interesting material for the manufacture of complex load bearing structures. So the way it behaves in the presence of shallow surface cracks, which cannot be avoided in various weld joints, is very important.

Table 1 indicates its chemical composition and mechanical properties. The engineering stress-strain curve obtained from a standard 6 mm diameter longitudinal tensile test conducted at room temperature and a slow loading rate ( $< 25 \text{ MPa/s}$ ) is shown in fig. 1. Because of the addition of microalloyed elements, this steel has a very high yield point with a yield stress to ultimate tensile strength ratio of  $R_{p0,2}/R_m = 0.92$  and low strain hardening exponent of  $n = 0.06$ .

The same figure also shows an estimation of sufficient accuracy for the strain hardening exponent ( $n$ ) evaluation. If modulus of elasticity ( $E$ ), yield ( $R_{p0,2}$ ), ultimate tensile stress ( $R_m$ ) and elongation at maximum load ( $e_n$ ) are known, the hardening exponent can be determined by:



Sl. 1. Inženirska in prava krivulja napetost – deformacija za jeklo NIONICRAL 70A  
Fig. 1. The engineering stress-strain curve and the true stress-strain curve for NIONICRAL 70A steel

$$n = \frac{\log \frac{R_m(1+e_n)}{R_{p0.2}}}{\log \frac{1+e_n}{e_{0.2}}} \quad (1)$$

kjer je:  $e_{0.2} = \frac{R_{p0.2}}{E} + 0.002$

with:  $e_{0.2} = \frac{R_{p0.2}}{E} + 0.002$

Fiktivna meja plastičnosti pa je:

$$\sigma_0 = R_{p0.2} 10^{n-1}$$

Fictive yield stress follows from:

$$\frac{n}{n-1} \log \frac{E e_{0.2}}{R_{p0.2}} \quad (2)$$

Standardni upogibni preizkušanci z enostransko zarezo na robu in pravokotnega prereza  $18 \times 36$  mm (sl. 4) so bili izrezani iz plošč v smeri valjanja in utrujani do različnih globin razpoke, tako da je bilo začetno razmerje dolžine razpoke in višine preizkušanca približno 0,1, 0,2, 0,3 in 0,5. Vsi preizkušanci pa so bili opremljeni tako, da je bilo mogoče meriti integral  $J$  in CTOD. Nekaterim preizkušancem smo nato naredili bočne zareze do globine 1,8 mm na vsaki strani (20%).

## 2 EKSPERIMENTALNE METODE

V prvem delu eksperimentalnega programa smo uporabili metodo elastične popustljivosti pri delnem razbremenjevanju preizkušanca za določanje vrednosti integrala  $J$  in CTOD na začetku duktilnega loma. Podrobni potek preizkusa je opisan v literaturi [1], [2], [3]. Tukaj samo kratko:

Preizkušanec s poprejšnjo utrujenostno razpoko obremenjujemo z enakomerno naraščajočo silo; med preizkusom pa opravimo več delnih razbremenitev približno za 25% trenutne vrednosti sile. Signali iz meritne obremenilne celice preizkuševalnega stroja, signali iz meritnika pomika prijemalšča sile in iz meritnika odpiranja razpokane

Standard three-point-bend (SENB – single edge notch bend) specimens with a rectangular cross-section of  $18 \times 36$  mm were extracted in the longitudinal orientation with through-thickness notches and then fatigue-cracked to crack depth ratio of approximately 0.1, 0.2, 0.3 and 0.5, and they were all instrumented so that the crack growth could be correlated with the  $J$ -integral and CTOD. Some specimens were side-grooved to a depth of 1.8 mm on each side (20%).

## 2 EXPERIMENTAL PROCEDURES

In the first part of the experimental program, the unloading compliance technique was used to determine the  $J$ -integral and the CTOD values at the onset of ductile tearing. The details of the experimental procedures are fully described in [1], [2], [3]. Here only briefly:

A prefatigued specimen is monotonically loaded and, during the test, partial unloadings up to 25% of the actual load value are performed to measure the specimen compliance. The signals from the load cell of the testing machine, from load line displacement clip gauge machine,

(CMOD) se zapišejo v delovno datoteko na disku računalnika PC za kasnejšo obdelavo in analizo podatkov. Po končanem preizkusu označimo pri-rastek razpoke pri duktilnem lomu (s segrevanjem preizkušanca do 300 °C ali s ponovnim utrujanjem z majhnimi amplitudami obremenitve), preizkušane prelomimo in merimo začetno dolžino razpoke ( $a_0$ ) in prirastek razpoke ( $\Delta a$ ) na najmanj devetih mestih vzdolž debeline. Povprečne vrednosti ne smejo odstopati od izračunanih vrednosti s popustljivostjo (7) oz. padcem potenciala (8) za več ko 10 odstotkov.

Vrednosti integrala  $J$  lahko določimo v vsaki točki razbremenitve ( $j$ ) s površino pod krivuljo v diagramu sila – pomik prijemališča sile z izrazi [1], [2]:

$$J = J_{el} + J_{pl} \quad J_{el} - \text{elastični delež (elastic component)}$$

$J_{pl}$  – plastični delež (plastic component)

$$J_{el(j)} = \frac{K_1^2(1-\nu^2)}{E} \quad (4)$$

$$J_{pl(j)} = \left[ J_{pl(j-1)} + \left( \frac{2}{b_j} \right) \frac{A_{pl(j)} - A_{pl(j-1)}}{B_N} \right] \left[ 1 - \frac{a_j - a_{j-1}}{b_j} \right] \quad (5)$$

kjer so:  $K_1$  – linearno elastični faktor intenzivnosti napetosti,  $B_N$  – neto debelina preizkušanca,  $b = W - a$  – preostali nezloravljeni ligament,  $A_{pl}$  – površina, prikazana na sliki 2.

and from CMOD clip gauge are then finally saved for future analyses in the data file on the hard disk of a PC computer. After marking the extent of ductile crack growth (heat tinting, secondary fatigue) and breaking the specimen, initial crack length ( $a_0$ ) and crack growth ( $\Delta a$ ) are measured at nine places along the thickness. The average crack length is compared to the calculated values according to the compliance (7) or DC potential drop (8) method. The differences should be less than 10%.

The value of the J-integral can be estimated at each unloading point ( $j$ ) from the area under the load versus load-line displacement curve using the following expressions [1], [2]:

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where  $K_1$  is the linear elastic stress intensity factor,  $B_N$  is specimen net thickness,  $b = W - a$  is the remaining ligament and  $A_{pl}$  is area as shown in figure 2.

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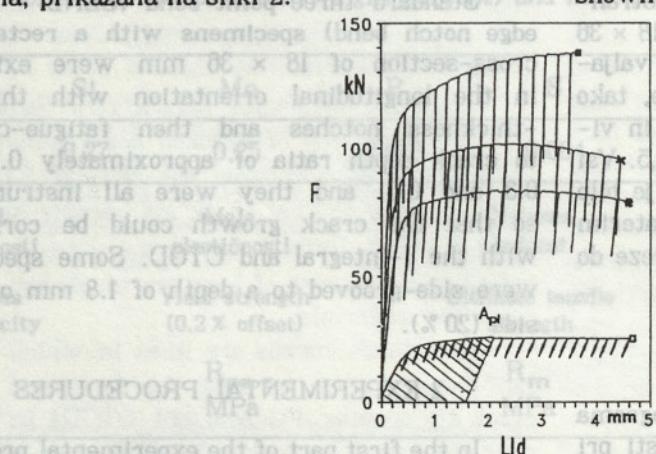
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Most CTOD based studies have used the

british BS 5762 [3] CTOD-CMOD correlation to analyze the behaviour of shallow crack specimens. CTOD is regarded as the sum of small scale yielding and a fully plastic contribution:



Sl. 2. Diagrami sila – pomik prijemališča sile ( $Lld$ ) za upogibe preizkušance  $18 \times 36$  mm z različnimi dolžinami razpoke –  $R = a/W$

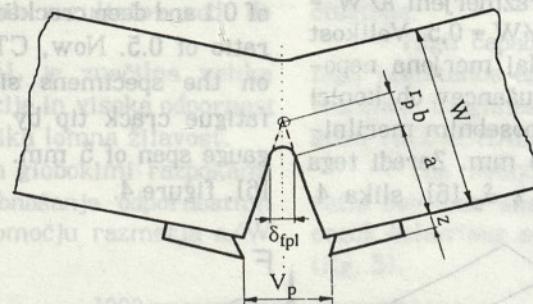
Fig. 2. Load versus load-line displacement records for bend specimens  $18 \times 36$  mm with different crack depth ratios –  $R = a/W$

Večina raziskav odpiranja konic razpoke uporablja CTOD-CMOD korelacijo britanskega standarda BS 5762 [3] tudi za analizo preizkušancev s plitvimi razpokami. Po tem standardu je odpiranje konice razpoke prav tako sestavljeno iz elastičnega in plastičnega deleža:

$$\text{CTOD} = \delta_{ssy} + \delta_{fpl} = \frac{K_1^2(1 - v^2)}{2ER_{p0,2}} + \frac{r_p(W - a)V_p}{r_p(W - a) + a + z} \quad (6),$$

kjer pomenjo:  $V_p$  — plastični delež odpiranja merilnika CMOD,  $z$  — debelino nožkov za pritrditev merilnika  $r_p$  — rotacijski faktor, ki je definiran kot razdalja od konice razpoke do središča vrtenja, normirana z dolžino nezlomljenega ligamenta (sl. 3). Standardna vrednost tega faktorja je 0,4.

je, kakor je razvidno iz razprave, da je faktor  $r_p$  med 0,1 in 0,2. Kadar pa je razprava na krovu, se krivulja J-R na sliki 5, v območju razpone med 0,1 in 0,2.



Sl. 3. Geometrijska oblika za ekstrapolacijo določitve  $\delta_{fpl}$

Fig. 3. Geometry of extrapolation procedure for  $\delta_{fpl}$  determination

Dolžino in prirastek razpoke smo računali z izmerjeno popustljivostjo preizkušanca ( $C_J$ ) med delnim razbremenjevanjem [1], [2]:

Crack length and crack extension were calculated using the specimen compliance ( $C_J$ ) measured during a partial unloading of the specimen [1], [2]:

$$\Delta a = a_J - a_0$$

$$a_J = W(0,999748 - 3,9504 U_x + 2,9821 U_x^2 - 3,21408 U_x^3 + 51,51564 U_x^4 - 113,031 U_x^5) \quad (7).$$

kjer je pomožni faktor  $U_x$  podan z izrazom:

where the auxilliary factor  $U_x$  is given by:

$$U_x = [\sqrt{EBC_J} + 1]^{-1}$$

Metoda za določanje dolžine razpoke med preizkusom, ki sloni na merjenju padca električnega potenciala, uporablja Johnsonovo formulo [4] za računanje dolžine razpoke:

$$a = \frac{2W}{\pi} \arccos \frac{\cos(\pi y/2W)}{\operatorname{ch}\{(U/U_0)\operatorname{area ch}[\cosh(\pi y/2W)/\cos(\pi a_0/2W)]\}} \quad (8),$$

kjer  $U_0$  in  $a_0$  označujeta vrednosti električnega potenciala in dolžine razpoke,  $U$  in  $a$  sta tekoči vrednosti obeh veličin,  $y$  pa je polovčna razdalja, na kateri merimo  $U$ .

Strmino smeri otopitve smo določili po postopku EGF [5] z rezultati nateznega preizkusa:

$$\text{CTOD}_{BI} = \frac{\sigma_0}{0,4d_n} \Delta a \quad \text{in and}$$

DC potential drop method uses Johnson's equation [4] for crack length determination:

where  $U_0$  and  $a_0$  denote the initial values of potential and crack length,  $U$  and  $a$  are the actual values of both quantities and  $y$  is the half gauge span over which  $U$  is measured.

The slope of the blunting line was determined from tensile data using the EGF procedure [5]:

$$\text{CTOD}_{BI} = \frac{\sigma_0}{0,8d_n R_{p0,2}} \Delta a \quad (9).$$

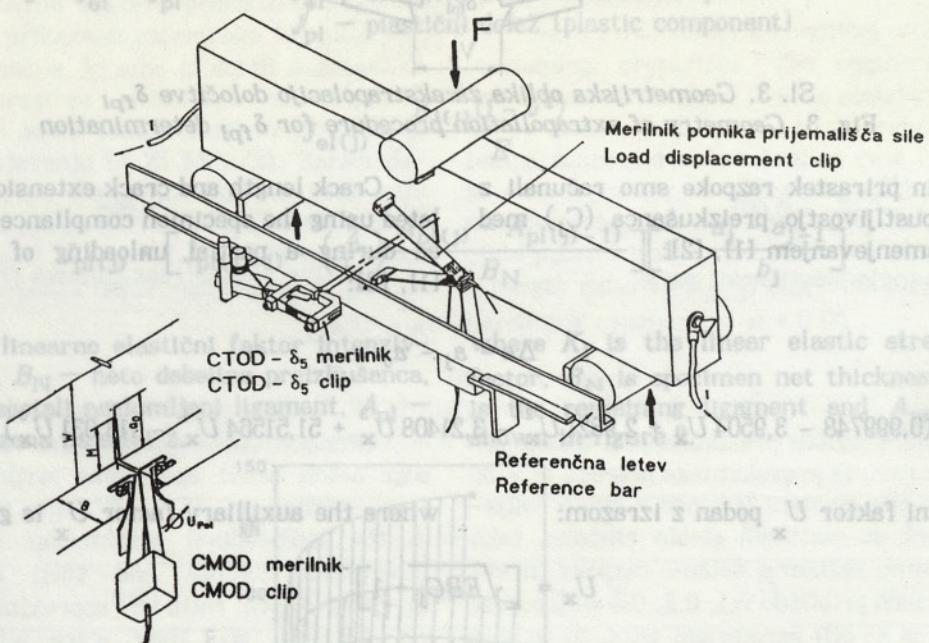
Faktor  $d_n$  dobimo z izrazom:

$$d_n = \frac{1,185 E}{\pi \sigma_0 (1+n)(1-v^2)} \left[ \frac{2\sigma_0}{\sqrt{3}} \frac{1+v}{E} \frac{1+n}{n^{n/(1+n)}} \right]^{(1+n)} \quad (10)$$

V drugem delu raziskav je za določanje dolžine razpoke med preizkusom uporabljena metoda pada električnega potenciala na upogibnih preizkušancih s plitvimi razpokami z razmerjem  $a/W = 0,1$  in globokimi razpokami z  $a/W = 0,5$ . Velikost odpiranja konice razpoke je sedaj merjena neposredno na bočni površini preizkušancev ob konici začetne utrujenostne razpoke s posebnim merilnikom z začetno merilno dolžino 5 mm. Zaradi tega je imenovana veličina označena z  $\delta_5$  [6], slika 4.

The factor  $d_n$  is evaluated from:

In the second part of our investigation, the DC potential drop method as applied on shallow cracked SENB specimens with crack depth ratio of 0.1 and deep cracked specimens with crack depth ratio of 0.5. Now, CTOD was directly measured on the specimens side surface at the original fatigue crack tip by a special clip gauge over a gauge span of 5 mm. It was therefore termed  $\delta_5$  [6], figure 4.



Sl. 4. Upogibni preizkušanec, opremljen za merjenje dolžine razpoke po metodi padca električnega potenciala in z merilnikom za merjenje parametra  $\delta_5$

Fig. 4. Instrumentation of bend fracture specimen for the application of the DC potential drop method and for  $\delta_5$  measurements

Vrednost  $\delta_5$  lahko uporabimo za določitev rotacijskega faktorja ( $r_p$ ) po eksperimentalni poti, in sicer na dva načina:

$$r_p = \frac{\delta_{5pl}(a+z) - V_{pl}(a-a_0)}{(V_{pl} - \delta_{5pl})(W-a)} \quad (11)$$

$$r_p = \frac{(\delta_5 - \delta_{ssy})(a+z)}{(V_{pl} - \delta_5 + \delta_{ssy})(W-a)} \quad (12)$$

Measurements  $\delta_5$  can be used to determine the plastic rotation factor ( $r_p$ ) experimentally in two ways:

po metodi z dvema merilnikoma CMOD  
by the double clip gauge method

z zamenjavo CTOD vrednosti v izrazu po BS z  $\delta_5$   
by substituting CTOD values in the BS formula by  $\delta_5$  (12).

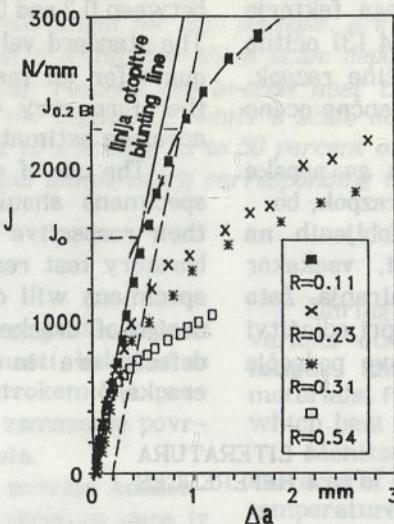
## UDK 538.24:621.77 3 SKLEPI

V delu je obravnavan vpliv razmerja dolžine razpoke in višine preizkušanca na elasto-plastične krivulje odpornosti in na lomno žilavost mikrole-giranega jekla s povisano trdnostjo. Z uporabo izraza CTOD po standardu BS in kombinacijo neposrednega merjenja odpiranja konice razpoke  $\delta_5$  je po eksperimentalni poti določen rotacijski faktor  $r_p$ .

Analiza eksperimentalnih rezultatov vodi do naslednjih ugotovitev:

— Za jeklo NIONICRAL je značilna velika zmožnost plastične deformacije in visoka odpornost proti širjenju razpoke — velika lomna žilavost.

— Meja med plitvimi in globokimi razpokami je, kakor je razvidno iz obnašanja odpornostnih krivulj J-R na sliki 5, v območju razmerja  $a/W$  med 0,1 in 0,2.



Sl. 5. Odpornostne krivulje J za upogibne preizkušance  $18 \times 36$  mm z različnimi dolžinami razpoke —  $R = a/W$

Fig. 5. J-Resistance curves for bend specimens  $18 \times 36$  mm with different crack depth ratio —  $R = a/W$

— Vrednosti parametrov CTOD in integrala J pri iniciaciji žilavega loma, še posebej pa vrednosti njihovih inženirskeh približkov, znatno narastejo pri preizkušancih s plitvimi razpokami (sl. 5).

— Metoda z delnim razbremenjevanjem utegne postati manj primerna pri preizkušancih z zelo kratkimi razpokami, kajti merjenje elastične popustljivosti postane zelo težavno. Plastične deformacije na prosti površini preizkušanca za razpoko, kjer je merilnik CMOD pritrjen, lahko povzročijo znatno napako pri merjenju.

— Pri preizkušancih z bočnimi zarezami dobitimo nižje vrednosti  $J_{0,2}$ , vendar pa to zmanjšuje neto debeline preizkušanca bistveno ne vpliva na vrednost  $J_0$  (sl. 6).

## 3 CONCLUSIONS

The effect of crack depth to specimen width ratio  $a/W$  on elastic-plastic resistance curves and fracture toughness of a HSLA steel was studied. The plastic rotation factor  $r_p$  was experimentally determined by using the CTOD equation of the BS standard in combination with the  $\delta_5$  clip gauge measurements. The analyses of the experimental results lead to the following conclusions:

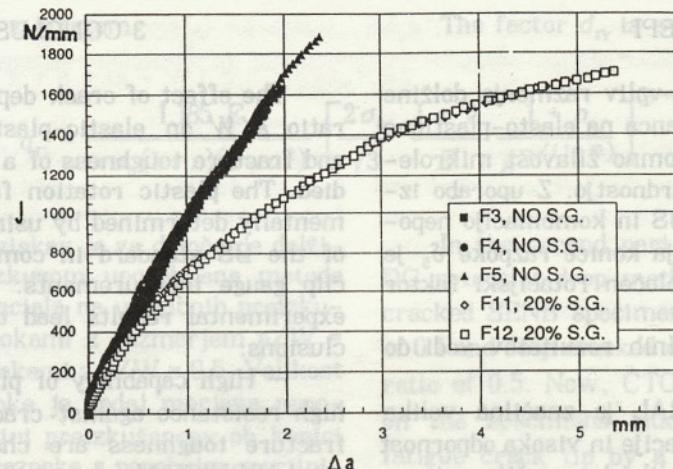
— High capability of plastic deformation and high resistance against crack propagation — high fracture toughness are characteristic of HSLA steel NIONICRAL.

— The boundary value of the crack depth ratio between shallow crack behaviour and deep crack behaviour seems to lie between 0.1 and 0.2 (fig. 5).

— The CTOD, and especially J-integral values at the initiation of ductile tearing (or their engineering approx.  $J_{0,2}b_l$ ), increase considerably with the use of shallow cracked specimens (fig. 5).

— The unloading technique might become inappropriate with decreasing crack depth ratio, because specimen compliance becomes increasingly difficult to measure. The plastic deformation of the free surface behind the crack (where the CMOD clip gauge is attached) can cause an appreciable error in CMOD measurements.

— Side grooving lowers  $J_{0,2}b_l$ , but it has no influence on  $J_0$ . It can be seen from fig. 6 that the R-curves of the side-grooved specimens tend to emerge from the same origin whereas beyond the first exclusion line, they are already split off.



Sl. 6. Vpliv bočnih zarez na odpornostne krivulje J-R in na vrednosti lomne žilavosti

Fig. 6. Influence of side grooving on J-Resistance curves and fracture toughness values

— Za preizkušance s plitvimi razpokami smo dobili precej nižje vrednosti plastičnega faktorja  $r_p = 0,2$  do  $0,3$ . Standardna vrednost  $0,4$  [3] očitno ni primerna za vse materiale in dolžine razpok. Zato je zelo pomembno imeti dovolj natančne ocene faktorja  $r_p$ .

— Pri konstrukcijah, pri katerih se napake pojavljajo v obliki plitvih površinskih razpok, bo uporaba laboratorijskih rezultatov, dobljenih na preizkušancih z globokimi razpokami, vsekakor privedla do konzervativnega dimenzioniranja. Zato je treba pri načrtovanju preizkusov — pri odločitvi o dolžini razpoke — upoštevati njihovo področje uporabnosti.

— The plastic rotation factor was found to be between  $0.2$  and  $0.3$  for shallow cracked specimens. The standard value  $0.4$  [3] is apparently not adequate for all materials and crack lengths. It is therefore very important to have a reasonably accurate estimate of the  $r_p$ .

The use of deep or shallow cracked fracture specimens should be carefully considered with their respective application areas. The use of laboratory test results obtained from deep notched specimens will certainly be conservative for the design of cracked components, where crack-like defects are in the form of shallow surface cracks.

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