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ODREĐIVANJE J KRIVE OTPORNOSTI METODOM DVE TAČKE

DETERMINATION OF J RESISTANCE CURVE BY TWO POINTS METHOD

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Ključne reči
- projektovanje J-R krive
- čelici visoke čvrstoće
- eksperimentalna provera
- metoda dve tačke

Izvod

Predložen je novi pristup projektovanju krive otpornosti prema prslinama i ispitana mogućnost njegove primene. Pristup se zasniva na opisu J_R krive polinomom sa dva koeficijenta. Za određivanje koeficijenta su potrebna dva para vrednosti J integrala i širenja prsline Δa. Jedan od njih je određen eksperimentalno. Usvojeno je da drugi par pripada liniji zatupljivanja, ali su takođe potrebni i dodatni kriterijumi. Razmotrena je mogućnost kako da se uspostave ovakvi kriterijumi za drugi par vrednosti J integrala i širenja prsline Δa.

UVOD

Načelno je prihvaćeno da se zavisnost *J* integrala od rasta prsline Δa može predstaviti polinomskom funkcijom. Između ostalih takva je jed. (1), data u standardu ASTM 1737 /1/, koju karakterišu dve konstante:

$$J = C_1 (\Delta a)^{C_2} \tag{1}$$

Konstante C_1 i C_2 se mogu odrediti pomoću dva para vrednosti *J* integrala i širenja prsline Δa, pod uslovom da je $\Delta a \neq 0$, jer je za $\Delta a = 0$ odgovarajuća vrednost *J* integrala jednaka nuli za bilo koje vrednosti konstanti C_1 i C_2. Statički uslovi opterećenja dopuštaju da se prekine ispitivanje i primeni metoda termičkog obeležavanja rasta prsline Δa_f. Vrednost J_f se može odrediti, bez korekcije *J* integrala zbog širenja prsline, prema jed. (2)

$$J_i = \frac{2U_i}{Bb} \tag{2}$$

gde: J_i–predstavlja vrednost *J* integrala, a U_i–oslobođenu energiju u tački *i*, *B*–debljinu epruvete i b_0–početnu dužinu ligamenta.

U slučaju kada su vrednosti *J* integrala korigovane za širenje prsline, jed. (3), predložena u Preporukama ESIS P2, se može primeniti, /2/,

$$J_i = \frac{2U_i}{Bb_0}\left(1 - \frac{(0,75\eta - 1)\Delta a}{b_0}\right) \tag{3}$$

sa vrednošću $\eta = 2$ za SENB epruvetu. Jednačina za proračun *J* integrala iz ASTM 1737 nije prikladna zbog njenog

Keywords
- J–R curve design
- high strength steel
- experimental verification
- two points method

Abstract

New approach for crack resistance curve design is proposed and the possibility of its application investigated. The approach is based on J_R description by polynomial function with two coefficients. For determining coefficients two pairs of values of J integral and crack extension Δa are necessary. One of them is determined experimentally. It is accepted that the second pair of values belongs to the blunting line, but additional criteria are also required. The possibility to establish these criteria for the second pair of values of J integral and crack extension Δa is considered.

INTRODUCTION

It is generally accepted that the dependence of *J* integral on the crack growth Δa can be presented by a polynomial function. Among others, hear Eq. (1) is given in standard ASTM 1737 /1/, characterized by two constants:

$$J = C_1 (\Delta a)^{C_2} \tag{1}$$

Constants C_1 and C_2 can be determined if two pairs of values of *J* integral and crack extension Δa, under condition that $\Delta a \neq 0$, since for $\Delta a = 0$ the corresponding *J* integral value is zero for any value of constants C_1 and C_2. Static conditions of loading allow to terminate testing and apply the heat tinting method to determine crack extension Δa_f. The J_f value can be determined without the correction of *J* integral for crack extension, according to Eq. (2)

$$J_i = \frac{2U_i}{Bb} \tag{2}$$

where: J_i–represents *J* integral value, U_i–value of released energy in point *i*, *B*–specimen thickness, and b_0–initial ligament length.

In case when *J* integral values are corrected for crack extension, Eq. (3), proposed in ESIS P2 Recommendations, can be applied, /2/,

$$J_i = \frac{2U_i}{Bb_0}\left(1 - \frac{(0.75\eta - 1)\Delta a}{b_0}\right) \tag{3}$$

with $\eta = 2$ for SENB specimen. The ASTM 1737 equation for calculating *J* is not convenient due to its incremental inkrementalnog karaktera, za određivanja plastične komponente J integrala (tačka A1.5.3. navedenog standarda). Razlika u vrednosti J integrala, sračunata prema jed. (2) i (3), je mala do širenja prsline $0,06W$ (W je širina epruvete). Za drugi par vrednosti širenja prsline Δa i J integrala, koji pripada liniji zatupljenja, a potreban je za određivanje konstanti C_1 i C_2, može se koristiti zavisnost

$$J = M\sigma_y \Delta a \quad (4)$$

Može se uzeti da definisani par vrednosti širenja prsline Δa i J integral odgovara proizvoljno izabranoj tački P_1 na sl. 1. Moguće je odrediti J integral na osnovu odgovarajuće vrednosti energije primenom jed. (3), pa se korišćenjem jed. (4) može odrediti širenje prsline Δa. Konstante C_1 i C_2 se određuju korišćenjem dva para vrednosti Δa i J integrala, primenjenih u jed. (1). Vrednost širenja prsline u tački i za poznate vrednosti konstanti C_1 i C_2 se može dobiti iz rešenja jed. (5), izvedene iz jed. (1) i (3):

$$C_1\left(\Delta a_i\right)^{C_2} = \frac{2U_i}{Bb}\left(1-\frac{(0,75\eta-1)\Delta a}{b_0}\right) \quad (5)$$

Za rešavanje jed. (5), primenjena je metoda Njutna, /3/.

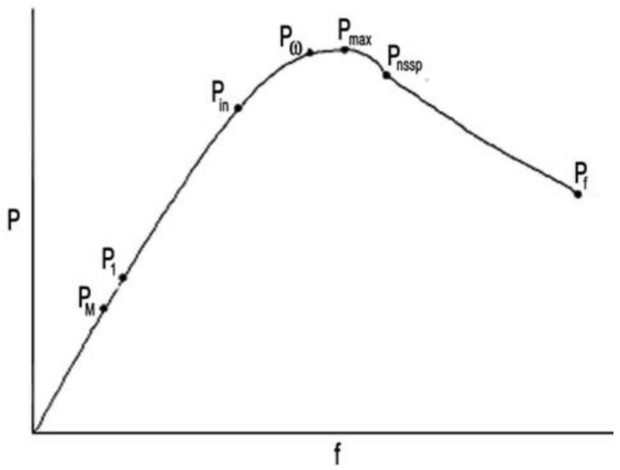
character for determining plastic component of J (clause A1.5.3. in cited standard). The difference in J values, calculated by Eqs. (2) and (3) are small up to the crack extension of $0.06W$ (W is specimen width). For the second pair of crack extension Δa and J integral values, belonging to the blunting line, that are necessary for determining constants C_1 and C_2, the following relationship may be used

$$J = M\sigma_y \Delta a \quad (4)$$

The defined pair of values, crack extension Δa and J, can be assumed to correspond to the arbitrarily chosen point P_1 in Fig. 1. It is possible to determine J integral from the corresponding value of energy by Eq. (3), and using Eq. (4) one can determine crack extension Δa. Constants C_1 and C_2 are determined using two pairs of Δa and J values from Eq. (1). The value of crack extension in point i, for constants C_1 and C_2, can be obtained by solving Eq. (5), derived from Eqs. (1) and (3):

$$C_1\left(\Delta a_i\right)^{C_2} = \frac{2U_i}{Bb}\left(1-\frac{(0.75\eta-1)\Delta a}{b_0}\right) \quad (5)$$

Newton's method, /3/, is used in solving Eq. (5).



Slika 1. Karakteristične tačke na dijagramu sila P–ugib f

Figure 1. Characteristic points on the diagram load P vs. deflection f.

P_M	prethodno zamorno opterećenje	pre-fatigue load
P_1	zatupljivanje	blunting
P_{in}	inicijacija rasta prsline	crack growth initiation
P_ω	tačka koja odgovara nagibu krive ω = 10	point corresponding to curve slope ω = 10
P_{max}	maksimalno opterećenje	maximal load
P_{nssp}	nestabilni rast prsline, /4/	specimen instability point, /4/
P_f	kraj ispitivanja	the end of testing

Vrednost J integrala u tački i, J_i, za poznatu vrednost širenja prsline Δa_i, može se odrediti na osnovu jed. (3) iz Preporuka ESIS P2 ili na osnovu jednačine date u tački A1.5.3 standarda ASTM 1737. Uzimanjem vrednosti J_i i Δa_i za različite tačke na dijagramu opterećenje P–ugib f, projektuje se kriva otpornosti J_R. Praktična primena predloženog pristupa otkriva da vrednosti konstanti C_1 i C_2, kao i projektovana kriva otpornosti, bitno zavise od izbora tačke P_1 na krivoj zavisnosti P–f, sl. 1, ali i od toga kako se definiše linija zatupljivanja. Zbog toga su uvedeni kriterijumi za izbor tačke P_1.

The J integral value in point i, J_i, for known value of crack extension Δa_i, can be determined based on Eq. (3) from ESIS P2 Recommendation or based on Equation given in clause A1.5.3. of ASTM 1737. Using values J_i and Δa_i for different points on the load P vs. deflection f diagram, the resistance curve J_R is designed. Practical use of the proposed approach reveals that the constants C_1 and C_2 and the designed resistance curve strongly depend on the selection of point P_1 on the dependence curve P–f, Fig. 1, but also on how the blunting line is defined. For that account the selection criteria for point P_1 are introduced.

EKSPERIMENT

Istraživanja za utvrđivanje kriterijuma za izbor tačke P_1 su izvedena sa čelicima, na sedam nivoa čvrstoće, u području od 700 do 1320 MPa. Jedan čelik (38CrNi3MoV-ESR) je ispitan na tri nivoa čvrstoće, prema temperaturi otpuštanja. Za druga četiri čelika je ispitan po jedan nivo čvrstoće. Podaci o čelicima su dati u tab. 1.

Tačka P_1 je izabrana poređenjem vrednosti širenja prsline, Δa_c, sračunate prema jed. (5) i vrednosti Δa_e, dobijene eksperimentalno iz popustljivosti epruvete. Minimalna razlika ove dve vrednosti širenja prsline je uzeta kao uslov za izbor tačke P_1. Linija zatupljivanja je definisana prema ESIS P2. Primeri J–Δa zavisnosti, dobijeni metodom popustljivosti i poređenjem sračunatih i eksperimentalnih vrednosti su dati za čelik 35CrNi2MoV ESR prema ESIS P2 (sl. 2) i za čelik SUMITEN, prema ASTM 1737 (sl. 3).

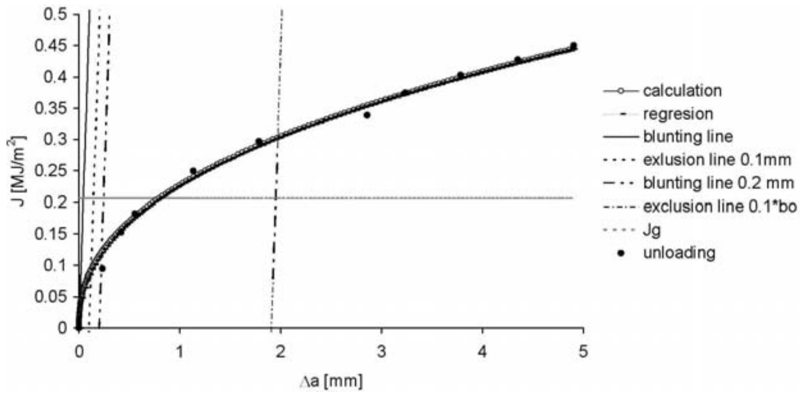
EXPERIMENT

Investigations for establishing criteria for point P_1 selection are performed with steels at seven strength levels, ranging from 700 to 1320 MPa. One steel (38CrNi3MoV-ESR) is tested at three strength levels, for different tempering temperatures. Only one strength level is tested for the other four steels. Data for steels are given in Table 1.

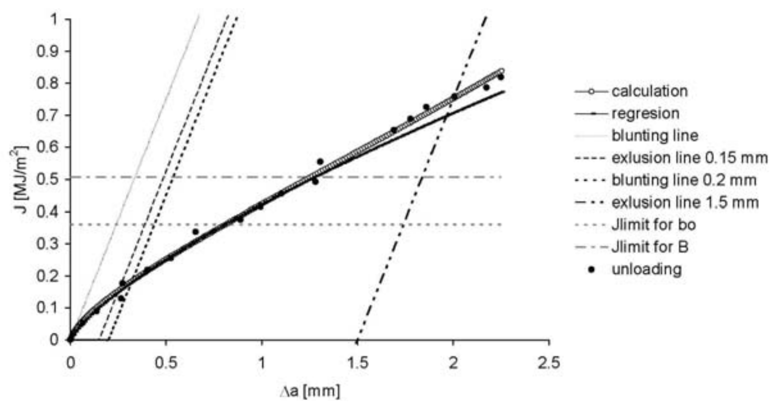
Selection of point P_1 is made by comparing crack extension value, Δa_c, calculated by Eq. (5), and Δa_e, experimentally obtained from specimen compliance. Minimal difference of these two values is used as the condition for point P_1 selection. Blunting line is defined by ESIS P2. Examples of J–Δa dependence, obtained by compliance method, and a comparison of calculated and experimental values are given for steel 35CrNi2MoV ESR according to ESIS P2 (Fig. 2), and for steel SUMITEN, according to ASTM 1737 (Fig. 3).

Tabela 1. Zatezne karakteristike i dimenzije epruveta ispitivanih čelika
Table 1. Tensile properties and specimen sizes for tested steels.

Čelik Steel	Temperatura otpuštanja Tempering temperature	Napon tečenja Yield strength	Zatezna čvrstoća Ultimate tensile strength	Debljina, širina i raspon SENB epruvete Thickness, width, and span of SENB specimen
	t_{tem}, °C	$R_{p0.2}$, MPa	R_m, MPa	B×W×S, mm
38CrNi3MoV-ESR	550	1320	1470	20×40×200
38CrNi3MoV-ESR	600	1235	1320	20×40×200
38CrNi3MoV-ESR	620	1130	1220	20×40×200
35CrNi2MoV-ESR	-	1130	1220	20×40×200
NAXTRA	-	600	650	19.2×38.4×185
NIONIKRAL	-	740	800	14.75×29.5×140
SUMITEN	-	810	860	14.8×29.8×140



Slika 2. Kriva otpornosti za čelik 35CrNiMoV ESR, dobijena prema ESIS P2 proceduri
Figure 2. Crack resistance curve for 35CrNiMoV ESR steel, obtained by ESIS P2 procedure.



Slika 3. Kriva otpornosti za čelik 3 NIONIKRAL 70, dobijena prema ASTM 1737 proceduri
Figure 3. Crack resistance curve for NIONIKRAL 70 steel, obtained by ASTM 1737 procedure.

REZULTATI DOBIJENI ISPITIVANJEM

Vrednosti konstanti C_1 i C_2 (ASTM 1737) i podaci za njihovo određivanje dati su u tab. 2, a za konstante A i D (ESIS P2) u tab. 3. Za neke vrednosti u tab. 2, kriterijum za krivu otpornosti nije ispunjen.

Koeficijent korelacije r je u tab. 2 dat od tačke P_M do P_ω, a u ASTM 1737 do širenja prsline 2,5 mm, za jednačinu

$$a_0 = a_{0q} + \frac{1}{2M} J + mJ^2 + nJ^3 \quad (6)$$

RESULTS OBTAINED FROM TESTS

Values of constants C_1 and C_2 (ASTM 1737) and data for their determination are given in Table 2, and of constants A and D (ESIS P2) in Table 3. For some values in Table 2, the criterion for the resistance curve is not satisfied.

Correlation coefficient r is in Table 2 given from point P_M to P_ω, in ASTM 1737 to crack extension 2.5 mm in

$$a_0 = a_{0q} + \frac{1}{2M} J + mJ^2 + nJ^3 \quad (6)$$

Tabela 2. Konstante C_1 i C_2 prema standardu ASTM 1737 i podaci potrebni za njihovo određivanje za $M = 2$
Table 2. Constants C_1 and C_2 according to ASTM 1737 standard and necessary data for their determination, for $M = 2$.

Čelik Steel	Temperatura otpuštanja / Tempering temperature	Kritični J integral za 0,2 mm liniju zatupljivanja / Critical J integral for 0.2 mm blunting line	Nagib J_R krive / Slope of J_R curve	Modul čupanja / Tearing modulus	Koeficijent korelacije / Correlation coefficient	Konstante / Constants	
	t_{tem}, °C	$J_{0.2BL}$, MJ/m^2	$(dJ/da)_{0.2BL}$	$T_{J0.2BL}$	r	C_1	C_2
38CrNi3MoV-ESR	550	0.0728	124.46	14.93	0.97084	0.1294	0.3864
38CrNi3MoV-ESR	600	0.0942	166.56	22.82	0.96537	0.1722	0.4188
38CrNi3MoV-ESR	620	0.1193	200.00	32.74	0.96167	0.2134	0.4205
35CrNi2MoV-ESR	-	0.1223	214.94	35.18	0.96257	0.2252	0.4430
NAXTRA	-	0.1226	256.15	148.71	0.73450	0.2606	0.6226
NIONIKRAL 70	-	0.1840	421.40	179.74	0.76604	0.4245	0.7389
SUMITEN	-	0.4389	726.44	231.41	0.71194	0.7919	0.7660

Tabela 3. Konstante A i D prema preporuci ESIS P2 i podaci potrebni za njihovo određivanje, za $M = 3{,}75$
Table 3. Constants A and D according to ESIS P2 recommendation and necessary data for their determination, for $M = 3.75$.

Čelik Steel	Temperatura otpuštanja / Tempering temperature	Kritični J integral za 0,2 mm liniju zatupljivanja / Critical J integral for 0.2 mm blunting line	Nagib J_R krive / Slope of J_R curve	Modul čupanja / Tearing modulus	Konstante / Constants	
	t_{tem}, °C	$J_{0.2BL}$, MJ/m^2	$(dJ/da)_{0.2BL}$	$T_{J0.2BL}$	C_1	C_2
38CrNi3MoV-ESR	550	0.0739	261.01	15.65	0.1322	0.3756
38CrNi3MoV-ESR	600	0.0946	349.27	23.93	0.1747	0.4027
38CrNi3MoV-ESR	620	0.1188	424.14	34.71	0.2162	0.4010
35CrNi2MoV-ESR	610	0.1213	454.58	37.20	0.2276	0.4218
NAXTRA	-	0.1082	525.23	152.46	0.2490	0.5877
NIONIKRAL 70	-	0.1511	834.88	178.05	0.3928	0.6831
SUMITEN	-	0.3030*	1480.56	235.81	0.7280	0.7065

*Ova vrednost $J_{0.2BL}$ nije važeća, jer je iza P_{max}. Vrednost $J_{0.2BL}$ je nešto pre P_{max} za čelike NAXTRA i NIONIKRAL 70.
*This value of $J_{0.2BL}$ is not valid, being beyond P_{max}. The value of $J_{0.2BL}$ is slightly before P_{max} for steels NAXTRA and NIONIKRAL 70.

Krive otpornosti, projektovane sa sračunatim koeficijentima C_1 i C_2 u tab. 2, su upoređene na sl. 4.

Kriterijum za izbor tačke P_1 je uspostavljen razmatranjem zavisnosti opterećenja, ugiba i energija za tačku P_1 i merodavnih vrednosti za tačku $P_{\max}$. Dobijena je zadovoljavajuća zavisnost za odnos ugib/opterećenje, kriva na sl. 5. Četiri grupisane tačke odnosa ugib/opterećenje minimalnih vrednosti (sl. 5) odgovaraju epruveti za koju su dobijene važeće krive otpornosti i kritične vrednosti J integrala, J_{Ic}, mere žilavosti loma. Sve druge tačke odgovaraju epruvetama za koje nije dobijena važeća kriva otpornosti.

ANALIZA RESULTATA

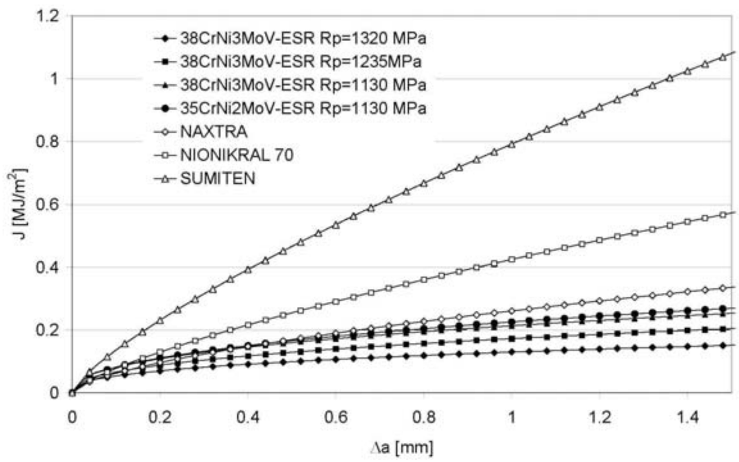
Vrednosti modula čupanja $T_{J0.2BL}$ od 14,93 do 231,41 prema ASTM 1737, i 15,65 do 235,81, prema ESIS P2, pokazuju da je ispitivano široko područje plastičnosti. Primenom metode dve tačke može se izabrati dovoljan broj tačaka u bilo kom rasponu, i tako ispuniti zahtevi ASTM 1737 i ESIS P2.

Resistance curves designed with calculated coefficients C_1 and C_2 from Table 2, are compared in Fig. 4.

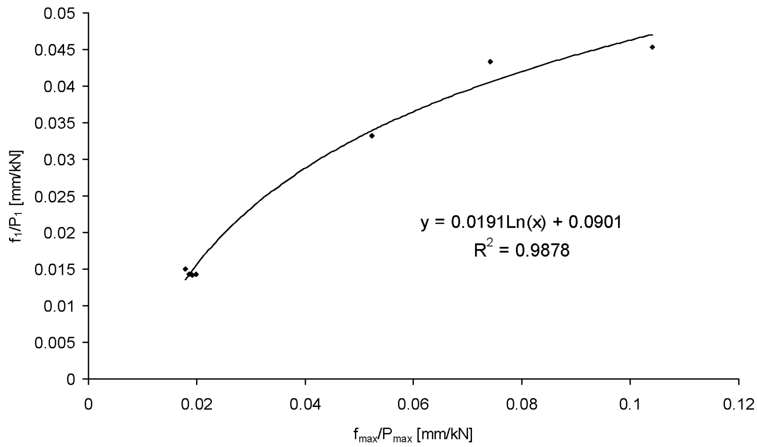
Criterion for point P_1 selection is established considering the relations of load, deflection, and energies for point P_1 and relevant values for point $P_{\max}$. Satisfactory relation is obtained for ratio deflection/load, curve in Fig. 5. Four grouped points of the deflection/load ratio (Fig. 5) of minimal values correspond to the specimen with valid resistance curve and value of critical J integral, J_{Ic}, a measure of fracture toughness. All other points correspond to specimens for which the valid resistance curve is not obtained.

ANALYSIS OF RESULTS

Values of tearing modulus TJ0.2BL from 14.93 to 231.41, according ASTM 1737, and 15.65 to 235.81, according to ESIS P2, show that wide plasticity range is tested. The two points method makes it possible to select a sufficient number of points in any span, satisfying ASTM 1737 and ESIS P2.



Slika 4. Krive otpornosti za različite čelike, sračunate prema standardu ASTM 1737
Figure 4. Resistance curves for different steels, calculated according to ASTM 1737 standard.



Slika 5. Zavisnost odnosa *f/P* za tačku P_1 (f_1/P_1) i tačku P_{max} (f_{max}/P_{max})
Figure 5. Dependence of *f/P* ratios for point P_1 (f_1/P_1) and point P_{max} (f_{max}/P_{max}).

To je značajna prednost u poređenju sa određivanjem širenja prsline Δa preko popustljivosti epruvete (sl. 2 i 3).

Poređenje sračunatih krivih na sl. 4 pokazuje da metoda dve tačke daje bolju selektivnost u opisu ponašanja materijala. Ovi eksperimenti nisu dali dovoljno podataka za ocenu tačnosti i reproduktivnosti metode.

Rezultati dati u tab. 2 i 3 pokazuju veliku razliku u pogledu ispunjenja kriterijuma važenja za J_R krivu kada se primenjuju ASTM 1737 i ESIS P2. Važeća J_R kriva je dobijena za čelik 38CrNi3MoV-ESR u sva tri stanja termičke obrade i za čelik 35CrNi2MoV-ESR sa oba razmatrana dokumenta. Važeće J_R krive su dobijene i za epruvete od čelika NAXTRA i NIONIKRAL 70 prema ESIS P2, ali ne i prema ASTM 1737. Važeća J_R kriva nije dobijena sa epruvetama od čelika SUMITEN prema ASTM 1737, ni prema ESIS P2. Rezultati prikazani u tab. 2 i 3 su dobijeni na osnovu istih vrednosti opterećenja *P*, ugiba *f* i širenja prsline Δa. To je dokaz da je velika razlika u pogledu zadovoljenja kriterijuma za važenje J_R krive, prema ASTM 1737 i ESIS P2, posledica propisanih metodologija. Iskustva stečena u ovom istraživanju pokazuju da je potrebno kombinovati preporuke za važenje ispitivanja J_R krive prema ASTM 1737 i preporuke za ograničenje J_R krive do vrednosti nagiba krive $\omega = 10$, što je dato u ESIS P2.

This is a significant advantage compared to determining crack extension Δa by specimen compliance (Figs. 2 and 3).

The comparison of calculated curves in Fig. 4 shows that two points method allows better selectivity in material behaviour description. Experiments did not give sufficient data to evaluate accuracy and resettability of the method.

Results given in Tables 2 and 3 show great difference regarding the satisfaction of validity criteria for J_R curve, by applying ASTM 1737 and ESIS P2. Valid J_R curve is obtained for 38CrNi3MoV-ESR steel in all three states of heat treatment and for the 35CrNi2MoV-ESR steel, by both considered documents. Valid J_R curves are also obtained with specimens of NAXTRA and NIONIKRAL 70 steels, according to ESIS P2, but not according to ASTM 1737. Valid J_R curve is not obtained with SUMITEN steel specimens neither by ASTM 1737, nor by ESIS P2. Results given in Tables 2 and 3 are obtained for the same values of load *P*, deflection *f* and crack extension Δa. This is proof that the great difference in satisfaction criteria of J_R curve validity, according to ASTM 1737 and ESIS P2, is a consequence of prescribed methodologies. Experience in the investigation show as necessary to combine recommendations of validity tests of J_R curve from ASTM 1737 and J_R curve limitation to the value of curve slope $\omega = 10$, as given in ESIS P2.

Iz izvedene analize se vidi da se kriterijum zadovoljenja izbora tačke P_1 može definisati iz veze $f_1/P_1 - f_{max}/P_{max}$. Grupisanje tačaka za epruvete koje daju važeće krive otpornosti pokazuje da kriterijum izbora tačke P_1 treba da bude izdvojen. U ovom slučaju to nije urađeno zbog nedovoljnog broja tačaka. Takođe treba imati u vidu da su analizirani čelici martenzitne ili martenzitno-beinitne strukture. Ovakve strukture karakteriše mali koeficijent deformacijskog ojačavanja u odnosu na feritno-perlitne strukture, što može da utiče na primenljivost predloženih kriterijuma.

Sličnost oblika zavisnosti opterećenje P–ugib f i opterećenje P–otvaranje prsline COD za SENB epruvetu omogućava da se primeni predloženi pristup za definisanje CTOD–Δa krive i poređenje vrednosti širenja prsline Δa.

Interesantan problem je poređenje širenja prsline u tački P_1 i odgovarajuće vrednosti zone razvlačenja u toku zatupljivanja, Δa_{szw}, To nije bilo moguće u ovom istraživanju jer vrednost Δa_{szw} nije merena na ispitivanim epruvetama.

ZAKLJUČAK

Izvedeno istraživanje je pokazalo da je moguće uspostaviti kriterijum izbora tačke P_1 na krivoj zavisnosti opterećenje–ugib. Međutim, u tom pogledu su potrebna dalja istraživanja.

Za sledeća istraživanja mogu da se koriste postojeći rezultati za krive otpornosti. Istraživanja treba proširiti na razmatranje primenljivosti jed. (6) za određivanje širenja prsline.

Da bi se dobio bolji uvid, potrebna su istraživanja sa čelicima većeg koeficijenta ojačavanja nego što je to slučaj kod ovde ispitanih martenzitnih i martenzitno-beinitnih čelika, sa drugim oblicima epruveta i na mogućnost određivanja širenja prsline Δa sa krivih P–COD.

Za određivanje krive otpornosti preporučuje se kombinovanje zahteva ASTM 1737 standarda i ESIS P2 preporuka, kakve se dobijaju proverom važenja J_R krive i ograničenja u nagibu krive ω.

Takođe se preporučuje da se analizira uticaj položaja tačke P_f na tačku nestabilnosti epruvete P_{nssp}.

Performed analysis has shown that satisfactory criterion of point P_1 selection can be defined from the relation f_1/P_1 vs. f_{max}/P_{max}. Grouping of points for specimens giving valid resistance curve indicates that the selection criteria for point P_1 should be separated. In this case it is not done due to insufficient number of points. Also, one should have in mind that analysed steels are of martensitic or martensitic-bainitic structure. These structures are characterized by lower strain hardening coefficient compared to ferrite-pearlite structure which can affect the applicability of proposed criterion.

Similarity in relations load P vs. deflection f and load P vs. crack opening displacement COD for SENB specimen allows to apply proposed approach to define CTOD vs. Δa curve and to compare crack extension values Δa.

An interesting problem is to compare crack extension in P_1 and corresponding value of stretch zone during blunting, Δa_{szw}. This was not possible in the investigation because Δa_{szw} value had not been measured for tested specimens.

CONCLUSIONS

Performed investigations have shown that it is possible to establish the criterion for the selection of point P_1 on the relationship curve load vs. deflection. However, further investigations in that sense are necessary.

Further investigations can adopt the existing results for resistance curves. Investigations should be extended to considerations of the applicability of Eq. (6) for determining crack extension.

In order to get more insight, research is necessary with steels of higher strain hardening coefficient than the applied here martensitic and martensitic-bainitic steels, to other specimen types and to the possibility of determining crack extension Δa from P vs. COD curves.

In determining resistance curves it is recommended to combine requirements from ASTM 1737 standard and ESIS P2 recommendation, such as obtained by validity checking of J_R curve and limitation in curve slope ω.

It is also recommended to analyse the effect of point P_f position on specimen instability point P_{nssp}.

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