CODEN STJSAO ISSN 0562-1887
ZX470/1512 UDK 539.422:699.14.018.27:620.178.74

Dynamic Fracture Mechanics Assessments by Simultaneous Magnetic Emission and Potential Drop Techniques

Zoran RADAKOVIĆ

Mašinski fakultet, Univerziteta u Beogradu
(Faculty of Mechanical Engineering,
Belgrade University),
Kraljice Marije 16, 11120 Beograd,
Republic of Serbia

zradakovic@mas.bg.ac.rs

Preliminary notes

Modern structural integrity assessment procedures incorporate fracture mechanical concepts most of which rely on dynamic fracture mechanics parameter determination from experiments. In the case of dynamic loading conditions, various experimental methods have evolved for determining the loading parameters and load-displacement behaviour. Ductile structural steel has many applications and its properties are interesting for designing experiments that simulate ductile, brittle and mixed fracture behaviour. In this study are presented the results of fracture mechanics investigations of a ductile ferromagnetic low-alloy high strength steel, performed under dynamic loading conditions.

Standard Charpy specimens are tested by simultaneous coupled magnetic emission (ME) and potential drop (PD) techniques for determining critical crack initiation properties and resistance curve determination of a ductile steel behaviour. Equivalent brittle, ductile, and mixed mode fracture behaviour may be simulated by choice of test temperature and impact velocity. Analysis of integrated ME and PD signal data, employed in deriving critical J integral, has been successful in interpreting unstable or stable crack initiation and propagation. Experimental results are discussed with respect to the characteristics and the physical interpretations of both of the independent experimental techniques. Some specific experimental difficulties in the reliable assessment of dynamic crack initiation parameters are outlined.

Keywords
Crack initiation
Ductility
Dynamic fracture mechanics
Impact testing
Magnetic emission
Potential drop

Ključne riječi
Dinamička mehanika loma
Duktilonost
Inicijacija pukotine
Ispitivanje udarom
Magnetna emisija
Pad potencijala

Procjene u dinamičkoj mehanici loma tehnikama magnetne emisije i potencijalnog pada

Prethodno priopćenje

Moderni postupci procjene strukturne cjelovitosti inkorporiraju koncepte mehanike loma od kojih se većina oslanja na određivanje dinamičkih parametara mehanike loma iz eksperimenata. U uvjetima dinamičkog opterećenja, razne eksperimentalne metode su evoluirale za određivanje parametara opterećenja i ponašanja opterećenje-pomak. Duktilni strukturni čelik ima mnogo aplikacija i njegova svojstva su interesantna za projektiranje eksperimenata koji simuliraju duktilan, krhak i mješovit oblik ponašanja loma. U ovom radu su predstavljeni rezultati istraživanja mehanike loma duktilnog feromagnetičnog niskolegiranog čelika visoke čvrstoće, u uvjetima dinamičkog opterećenja.

Standardni Charpy uzorci su ispitani istovremenim odzivom signala od tehnika magnetne emisije (ME) i pada potencijala (PD), za utvrđivanje kritičnih svojstava inicijacije pukotine i krivulje otpornosti kod ponašanja duktilnog čelika. Ekvivalentno krhko, duktilno, ili mješovito ponašanje loma je moguće simulirati pravilnim izborom temperature ispitivanja i brzine udara. Analiza integriranog ME i PD signala, upotrijebljenih za iznalaženje kritičnog J integrala, je bila uspješna u interpretaciji nestabilne ili stabilne inicijacije pukotine i njenog širenja. Rasprava o dobivenim eksperimentalnim rezultatima odnosi se na karakteristike i fizička tumačenja ove dvije nezavisne eksperimentalne tehnike. Izdvojene su izvjesne poteškoće kod eksperimenata u pouzdanoj procjeni dinamičkih parametara inicijacije pukotine.

Primljeno (Received): 2010-01-26
Prihvaćeno (Accepted): 2011-04-25

Symbols/Oznake

A, C, D	- fitting expression constants - konstante funkcije fitovanja
a	- crack length, mm - duljina pukotine
a_o	- specimen pre-crack length, mm - početna duljina pukotine
Δa	- crack extension, mm - prirast duljine pukotine
B	- specimen thickness, mm - debljina epruvete
c	- factor in blunting line expression - faktor u izrazu za crtu otupljenja
DC	- direct current - istosmjerna struja
ΔE	- (electric) potential drop, mV - (električni) pad potencijala
E	- modulus of elasticity, MPa - modul elastičnosti
F	- force, N - sila
F_m	- maximal load force, N - maksimalna silai
$HSLA$	- high strength low-alloyed (steel) - nisko-legirani čelik povećane čvrstoće
J	- J-integral, kJ/m^2 - J integral
$J_{0.2d}$	- critical dynamic J-integral value related to 0.2 mm stable crack extension, kJ/m^2 - kritični dinamički J integral koji se odnosi na 0.2 mm stabilnog prirasta pukotine
J_{Id}	- critical dynamic J-integral, kJ/m^2 - kritični dinamički J integral
J_d	- dynamic J-integral, kJ/m^2 - dinamički J integral
J_{el}	- elastic component of J-integral, kJ/m^2 - elastična komponenta J integrala
J_{pl}	- plastic component of J-integral, kJ/m^2 - plastična komponenta J integrala
K_{cd}	- critical dynamic stress intensity factor, kN·m$^{-3/2}$ - kritični dinamički koeficijent intenzivnosti naprezanja
L	- support span length, mm - raspon oslonaca
ME	- magnetic emission, mV - magnetna emisija
MF	- integrated magnetic emission, mV·s - integrirana magnetna emisija
v	- Poisson's ration - Poissonov koeficijent
PD	- potential drop, mV - pad potencijala
R	- correlation coefficient - koeficijent korelacije
t	- time, ms - vrijeme
U_{pl}	- absorbed plastic deformation energy, kJ - apsorbirana energija plastične deformacije
W	- specimen width, mm - širina epruvete

1. Introduction

High strength low alloyed (HSLA) steels exhibit ductile properties, even with a moderately increased strength level. A ferrite-pearlite microalloyed steel tested here contains Nb and Ti and is control-rolled and accelerated cooled. With a yield stress of 411 MPa, it is very ductile at lower temperatures with a wide brittle-to-ductile transition range.

Critical dynamic loading in a structure may lead to various types of fracture, depending on the temperature. Instrumented impact testing of HSLA steel behaviour is done by applying dynamic loads at room temperature with the idea to design the experiment as such so that two independent techniques (ME and PD) may be applied simultaneously, confirming each others' results. The impact rate can be varied, but only to enable for the resistance curve determination (as in the "low-blow" method). Standard three-point bending specimens are fatigue pre-cracked, within the range of $a / W = 0.50 \pm 0.05$, where a–crack length, and W–is specimen width.

The instrumentation includes combined magnetic emission (ME) technique and potential drop (PD) technique. The ME technique has been used on ferromagnetic materials to determine crack initiation and propagation and was applied for instrumented impact testing of certain types of steels, [1].

The potential drop method (PD) is applied for recording the change in electrical resistance during the impact loading of the specimen, and is measured by the DC or AC – potential drop in the electric potential (ΔE) in front of the crack tip, [2]. Results were obtained by applying this technique on a single specimen with a method for evaluating the dynamic R-curve on instrumented Charpy pendulum with HSLA steels, [3]. Stable crack initiation in this case is also depicted from local minimum (or maximum, depending on the polarity) of the potential drop value. Both of these techniques had been used before and a major issue had been the uncertainty of interpreting local extreme values for ductile fracture, [4].

Ductile or mixed ductile/cleavage fracture, mostly at lower impact energies, is usually characterised by an ME signal with a high uncertainty in distinguishing crack initiation. Owing to its physical meaning, the integrated magnetic emission signal (MF) can be used to depict crack propagating events by analysing its change in slope. It is actually this signal that will practically coincide with the resulting potential drop signal. On the other hand, when stable crack growth is initialized it can be depicted from the local minimum (or maximum) of the potential drop signal and may not give clear local extreme values when conditions of fracture should change (ductile to brittle). A much better understanding of both signals is analysed in PD–time and MF-time diagrams. The change of slope was also analysed in these diagrams to evaluate critical crack behaviour, [4].

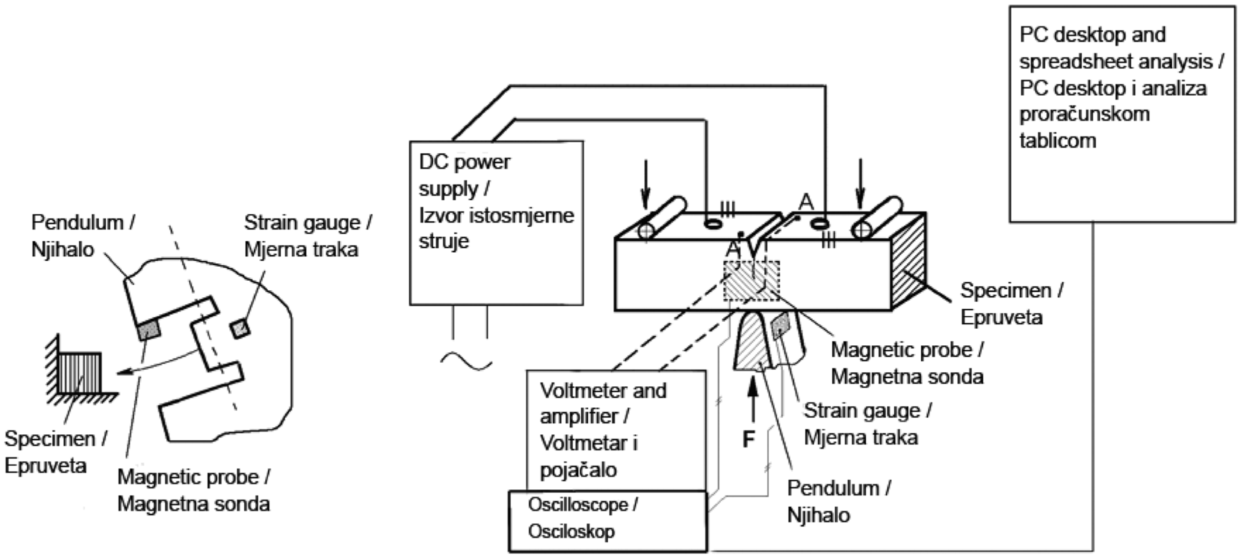

Figure 1. The impact specimen instrumentation and wiring scheme, [4].

Slika 1. Instrumentacija udarne epruvete i shema povezivanja, [4].

2. Experiment

Tests are performed at room temperature. The PD method cannot produce reliable results for low temperatures, below the nil-ductile point. Thus, ductile material behaviour for this steel is guaranteed at room temperature. The V-notched Charpy specimens are cut from 12 mm plates perpendicular to direction of roll, and pre-cracked by high frequency fatigue.

The scheme in Figure 1 shows the arrangement of devices used, and the connections to the test specimen. Thin connection wires, of steel, Ni, or Ni-Cr, for the PD signal output are resistance-spot-welded to the specimen at locations in the vicinity of notch opening (locations “A”, see Figure 1).

Higher values of the electric current are required so that the output PD signals can be recorded. In that sense massive Cu wires are used for connecting the DC power source to specimens, where the connection is achieved by bolts (position III on Figure 1). On the other hand, very high values of electric current may produce electrically induced heat in the material, thus creating temperature gradients in the specimen, giving rise to temperature induced stress levels. Locally induced, this heat can affect pronounced ductility behaviour by additional softening of the material, predominantly within the fracture-processing zone ahead of the crack tip, since the electric currents tend to close the circuit, passing through the crack ligament. Since all of the tested specimens are prepared exactly according to the scheme, the change of specimen stiffness due from the wiring and bolting is disregarded. A power source input DC electric current of 50 A is selected as nominal for producing readable output PD data, that was expected to be no higher than just a few milivolts.

In order to acquire ME data, changes in the external magnetic field ahead of the propagating crack are recorded by a magnetic emission probe, Figure 1. The TEKTRONIX TDS 420A data acquisition equipment is connected to a DC amplifier and voltage supply. The HP transient recorder with an interior circuit amplifier is tied to a channel on the oscilloscope. Magnetic and electric potential drop signals are recorded in real time sampling intervals of 2, 4, 10 and 40 μs. Spreadsheet procedures are then used for evaluating the absorbed energy (U) and the critical dynamic J-integral.

Fracture resistance is determined by J-integral standard testing procedure requiring multiple specimens. Although the potential drop method has been applied independently with much success on single specimen for quasi-static loading conditions, [5], it has yet to be applied in the case of dynamic impact loading conditions.

Inertial effects concerning the dynamic loading of the Charpy specimen were discussed in [6]. Some research included even high strain rate (explosion, blast penetration) response in structures [7], where the effects of shock waves on the strain rate and induced damage were classified and explained.

Linear elastic–plastic behaviour with a considerable plastic deformation and stable crack growth preceding the unstable crack growth, allows the *J* integral value for unstable crack initiation to represent the material fracture resistance characteristic. The ASTM Standard E 813-89 (1996) and later standards allow this parameter to be evaluated from the load–displacement curve as

$$J_{\mathrm{Id}} = J_{\mathrm{el}} + J_{\mathrm{pl}} \tag{1}$$

where J_{el} and J_{pl} are the elastic and plastic component of *J*, in respect, and are evaluated from

$$J_{\mathrm{el}} = \frac{K_{\mathrm{cd}}^2\left(1-v^2\right)}{E} \text{ (for plane strain)} \tag{2}$$

and

$$J_{\mathrm{pl}} = \frac{2U_{\mathrm{pl}}}{B\left(W-a_o\right)}, \tag{3}$$

where: U_{pl}–plastic work, evaluated from the surface area under the load–displacement curve, up to the onset of unstable fracture, or to the unloading point. K_{cd} is the critical dynamic stress intensity factor at unstable crack initiation, due to critical load, and is evaluated according to the ASTM Standard. Specimen width is designated as *W*; a_{o} is the specimen pre-crack length; *B* is the specimen thickness; *E* and *v* are the elasticity modulus and Poisson's ratio, in respect.

The load–displacement curve and the displacement–time function are determined as explained in [8].

At stable crack growth, or when crack development is mostly stable, material behaviour can be characterised by the critical *J* integral value at the onset of ductile crack initiation, usually interpreted in two different ways: by critical *J* integral at initiation of crack growth; or from the *J* integral value at stable crack extension, $\Delta a = 0.2$ mm, derived by the dynamic resistance curve, or R-curve method (ASTM Standard E 813-89).

3. Results and discussion

By implementing the introduced procedures, the material resistance curve is calculated with a series of 7-8 specimens. A resulting regression curve is given in the diagram J_d–Δa, shown in Figure 2. The regression curve is calculated by applying the procedure described in [9, 10], according to which the fitting expression is given in the general form as

$$y = A + C\Delta a^{\mathrm{D}}, \tag{4}$$

where: *y*–depicts the corresponding value for *J*; Δa–crack extension; and *A*, *C*, and *D* are constants that need to be calculated.

By introducing and substituting a variable $x = \Delta a^{\mathrm{D}}$ in Eq. (4), the constants *A* and *C* are determined from linear regression. Subsequently, the constant *D* is determined such that the maximal correlation coefficient ($R = 0.975$) is achieved.

The diagram in Figure 2 shows that the material resistance curve, determined from 7 points, between offset lines at 0.15 mm and 1.5 mm, that are parallel to the blunting line, can be expressed as $J = 1105 \cdot \Delta a^{0.596}$. The blunting line is plotted according to [11], as

$$J = 2\frac{F_{\mathrm{m}}L}{cB(W-a_o)^2}\Delta a = s_1\Delta a, \tag{5}$$

where: F_{m} [N]–maximal load force; *c*–factor ($c = 1.46$ for the plane strain condition); *L*–support span length ($L = 40$ mm).

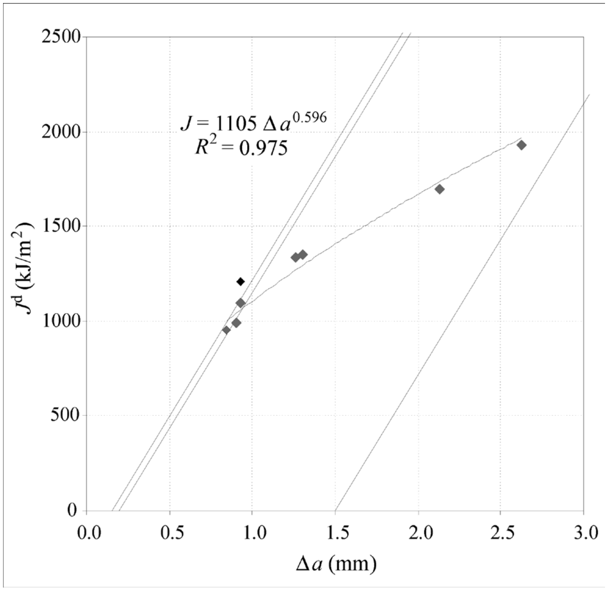

Figure 2. Dynamic *R*–curve for the specimen series. ($T = 20$°C; $J_{0,2\mathrm{d}} = 1069$ kJ/m^2, for offset line at $\Delta a = 0.2$ mm)

Slika 2. Dinamička *R*–krivulja otpornosti za seriju epruveta. ($T = 20$°C; $J_{0,2\mathrm{d}} = 1069$ kJ/m^2, za ofset liniju $\Delta a = 0{,}2$ mm)

The critical *J* integral value is determined from the intersection of regression *R*–curve and an offset line, parallel to the blunting line at $\Delta a = 0.2$ mm. The average slope of the blunting line, for all 8 specimens, equals $s_1 = 1433$ N/mm^2, and the critical dynamic *J* integral value is calculated for the regression function and offset line intersection at $\Delta a = 0.2$ mm, and equals $J_{0.2\mathrm{d}} = 1069$ kJ/m^2.

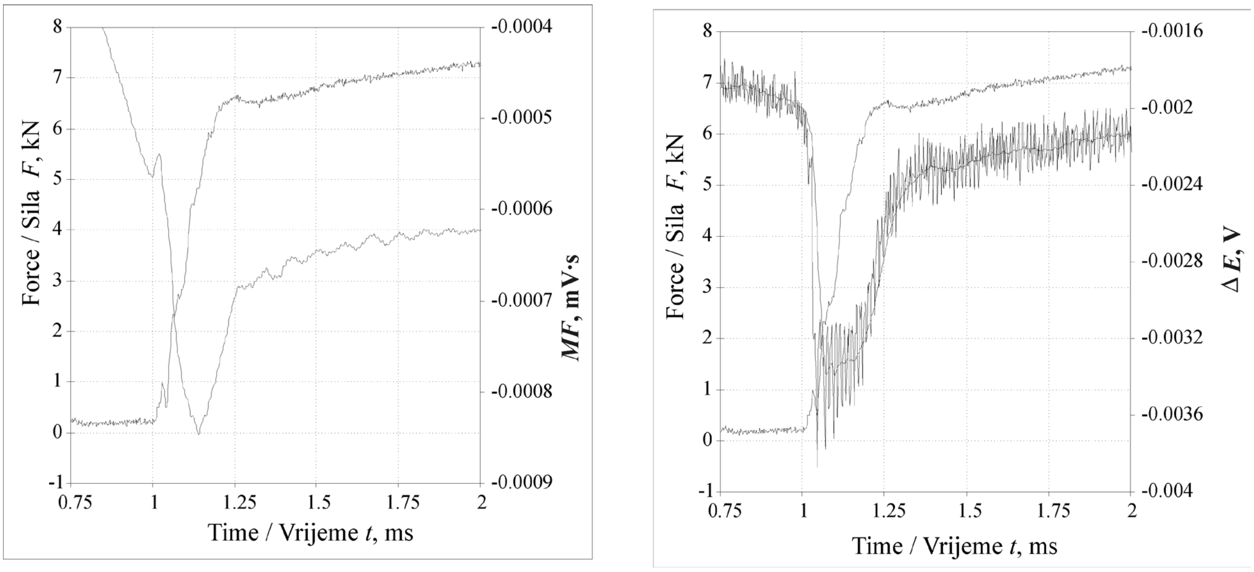

Figure 3. A comparison of diagrams of the integrated magnetic emission (MF) (left) and potential drop (ΔE) signals.

Slika 3. Usporedba dijagrama signala integrirane magnetne emisije (MF) (lijevo) i pada potencijala (ΔE).

A good example of almost coinciding diagrams: force vs. time; integrated magnetic emission (MF) vs. time; and potential drop (ΔE) vs. time, is given in the following Figure 3.

Similar results have been achieved for other test samples, [12]. These results had confirmed the assumption that the independent measuring techniques continue to function independently in a coupled scheme, where the integrated magnetic emission and potential drop signals are acquired simultaneously.

The tested specimen of pre-crack length $a_o = 4.23$ mm (Figure 3) was subjected to an impact energy of 20 J. The time to stable crack initiation is estimated to be at little over 1.25 ms, from the integrated magnetic emission signal change of slope. At this instant a small noticeable drop in the force is noticeable. A comparison of these diagrams shows that the PD signal is accompanied by a background noise that is attributed to poor insulation between specimen and the anvil. Placement of insulation between the specimen and anvil has resulted in a much better signal quality. Apart from this, the similarity in the character of both signals is evident.

4. Conclusions

The paper presented the results of researching ductile material behaviour of the HSLA steel in dynamic loading conditions.

Experiments were designed so that standard Charpy specimens were tested by simultaneously acquiring the magnetic emission and potential drop signal data. Determination of critical crack initiation properties and resistance curve calculation of a ductile steel behaviour is made possible by analysing both signals. The integrated ME and PD were employed in deriving the critical dynamic J integral, and the interpretation of the stable crack initiation and propagation was successful.

As expected, the physical interpretation of the integrated ME coincides with that of the PD signal. Both of the independent experimental techniques proved to be reliable when applied simultaneously. Thus, uncertainties may be lessened when implementing both techniques instead of one.

The well known advances of the PD technique enable the evaluation of the dynamic resistance curve by using a single specimen, provided a calibration curve is already made. Apparently, the attention in this paper was focused on the analysis of the acquired diagrams, so to estimate the crack initiation events, and hence, multiple specimens were used to determine the dynamic resistance curve. However, special attention was not paid in analysing the shape of the potential drop signal, but often its maximal and minimal values, as opposed to the integrated magnetic emission signal. Some specific experimental difficulties in the reliable assessment of dynamic crack initiation parameters are also outlined.

Matching of the recorded diagrams (F–time–MF and F–time–ΔE) has proved to be satisfying. The possibility of the simultaneous application of these techniques has also been proved and the assessment of dynamic fracture mechanics parameters is made with less uncertainty.

Recently, newer methods have evolved with an effort to simplify the crack resistance curve design, [13]. The J_R is described by a polynomial function with two coefficients instead of three, used in this example (see Eq.

(4)). Coefficients are determined from two pairs of values of the J integral and crack extension Δa. The procedure also relies on the acquired experimental results of one of these parameters. The procedure is further simplified by accepting the second pair of values belonging to the blunting line, with a requirement for additional criteria, that need to be established. Apparently, resistance curve determination should combine requirements from the ASTM 1737 standard and the ESIS P2 recommendation.

Some applied experimental procedures for impact testing of high strength steel weld ductility and toughness have shown to be selective, [14, 15, 16]. As stated in [14], the Charpy impact test results are compatible i.e. with explosion bulge test results. Although experiments in this case were performed independently and separately, according to the applicable standards, they had also produced complementary results.

REFERENCES

[1] LENKEY, Gy. B.; WINKLER, S. R.: *On the Applicability of the Magnetic Emission Technique for the Determination of Ductile Crack Initiation in Impact Tests*, Fatigue and Fracture of Engineering Materials and Structures, Vol 20, No 2: 143-150, 1997.

[2] MACGILLIVRAY, H. J.; TURNER, C. E.: *A Comparison of Dynamic R-Curve Methods*, Fourth International Conference on the Mechanical Properties of Materials at High Rates of Strain, Oxford.

[3] GRABULOV, V.; MACGILLIVRAY, H. J.; TOMIĆ, D.; JOVANIĆ, P.: *Evaluation of Static and Dynamic R Curve Using DC Potential Drop Single Specimen Method*, ECF9-Reliability and structural integrity of advanced materials (Ed. S. Sedmak, A. Sedmak and D. Ružić), EMAS, Warley West Midlands: 315-320, 1992.

[4] RADAKOVIĆ, Z.; SEDMAK, A.; LENKEY, Gy.B.; GRABULOV, V.: *Determination of Ductile Crack Initiation by Magnetic Emission and Potential Drop Techniques Using Pre-cracked Charpy Specimens*, From Charpy to Present Impact Testing, Eds. D. Francois & A. Pineau, ESIS Publication 30, Elsevier, Amsterdam: 71-78, 2002.

[5] GRABULOV, V.: *Određivanje parametara krive otpornosti primenom potenciometrijske metode za merenje rasta prsline*, doktorska disertacija (engl.: Evaluation of Resistance Curve Parameters Using Potential Drop Method for Crack Growth Measurement, Ph.D. Thesis), Tehnološko-metalurški fakultet Univerziteta u Beogradu, Beograd, 1995.

[6] RINTAMAA, R.: *Single Specimen Fracture Toughness Determination Procedure Using Instrumented Impact Test*, Ph.D. Thesis, Helsinki University of Technology, Espoo, 1993.

[7] MOMČILOVIĆ, D.; DELIĆ, B.; GRABULOV, V.: *Ponašanje metala pri udarnom opterećenju* (engl.: Behaviour of Metals at Impact Loading), Integritet i vek konstrukcija, 1 (2001), 1, 23-28.

[8] RADAKOVIĆ, Z.: *Magnetic Emission Technique in Assessing Dynamic Fracture Mechanics Parameters of Ductile Steel*, FME Transactions, 33 (2005), 1: 1-9.

[9] SCHWALBE, K. H.; NEALE, B. K.; HEERENS, J.: *The GKSS test procedure for determining the fracture behaviour of materials: EFAM GTP 94*, GKSS 94/E/60, GKSS-Forschungszentrum Geesthacht GmbH, 1994.

[10] NEALE, B. K.: *On the best fit curve through crack growth fracture resistance data*, Fatigue and Fracture of Engineering Materials and Structures 16 (1993), 4: 465-472.

[11] SCHINDLER, H. J.: *Approximative Bestimmung Dynamischer J_c–Werte und J-R-Kurven mit Schlagbiegeversuchen*, Tagungsband der 24. Vortrags-Veranstaltung des DVM-Arbeitskreises Bruch-vorgänge, Aachen: 119-129, 1992.

[12] RADAKOVIĆ, Z.: *Eksperimentalno određivanje dinamičkih parametara mehanike loma primenom tehnike magnetne emisije*, doktorska disertacija (engl.: Experimental Determination of Dynamic Fracture Mechanics Parameters by Applying the Magnetic Emission Technique, Ph.D. Thesis), Mašinski fakultet Univerziteta u Beogradu, Beograd, 2004.

[13] BLAČIĆ, I.; GRABULOV, V.: *Determination of J Resistance Curve by Two Points Method*, Structural Integrity and Life, 8 (2008), 3: 165-170.

[14] GRABULOV, V.; BLAČIĆ, I.; RADOVIĆ, A.; SEDMAK, S.: *Toughness and Ductility of High Strength Steels Welded Joints*, Structural Integrity and Life, 8 (2008), 3: 181-190.

[15] GUBELJAK, N.; PREDAN, J.; KOZAK, D.; TUMA, J.; KOVAČIĆ, B.; KONJATIĆ, P.; SERTIĆ, J.: *An Estimation of Sufficient Impact Toughness for the Material of a Turbine Shaft*, Strojarstvo 51 (2009), 4: 263-271.

[16] ŠARKOČEVIĆ, Ž.; ARSIĆ, M.; MEDJO, B.; KOZAK, D.; RAKIN, M.; BURZIĆ, Z., SEDMAK, A.: *Damage Level Estimate of API J55 Steel for Welded Seam Casing Pipes*, Strojarstvo 51 (2009), 4: 303-311.