The paper was presented at the Eleventh Meeting
“New Trends in Fatigue and Fracture” (NT2F11)
Polignano a Mare, Italy, 3–6 July, 2011

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NUMERICAL SIMULATION IN COATED MATERIALS: MODEL OF CRACK PROPAGATION BI-MATERIAL

NUMERIČKA SIMULACIJA MATERIJALA SA PREVLAKOM: MODEL RASTA PRSLINE BI-MATERIJALA

Originalni naučni rad / Original scientific paper
UDK /UDC: 539.42:519.87
Rad primljen / Paper received: 21.01.2012.

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Keywords
- stress intensity factors
- intermetallic layer
- crack propagation
- bi-material

Ključne reči
- faktori intenziteta napona
- intermetalni sloj
- rast prsline
- bi-materijal

Abstract

From the simple device to complex assembly, protection against corrosion is the most important treatment. As well as known, this treatment could be done in different varieties in the function of available resources and depending on economic price. Most of the time, protection is made with the use of one material, that holds the highest anti-corrosion characteristics, through a form of a thin film layer.

Among various materials, zinc may be considered as one. Zinc could be applied under the thin layer during the hot dip galvanized steel process. During this procedure of steel coating, some cracks are initiated in the intermetallic layer δ and spread in the layered surface of the zinc coating. For the simulation of this process we use the finite element method (FEM). The realization of modelling is done in the bi-material steel-zinc model, using the computer software application Abaqus 6.10.1.

Izvod

Od jednostavnog uređaja pa do kompleksnog sklopa, najvažnija obrada je zaštita od korozije. Koliko je poznato, ova obrada se može izvesti na različite načine, u funkciji postojećih resursa i u zavisnosti od ekonomskih uslova cene. U dužem vremenskom intervalu, zaštita se izvodi primenom jednog materijala, koji ima najbolje antikorozivne karakteristike, u obliku tankog sloja filma.

Cink se smatra jednim od materijala za ovu primenu. Cink se može primeniti kao tanak sloj tokom procesa tople galvanizacije čelika uranjanjem. Tokom ovog postupka prevlačenja čelika, neke prsline se iniciraju u intermetalnom sloju δ i šire se u površini zaštitnog sloja prevlake cinka. Primenili smo metodu konačnih elemenata (FME) za simulaciju ovog procesa. Realizacija je izvedena na modelu od bi-materijala čelik-cink, primenom softverske aplikacije Abaqus 6.10.1.

INTRODUCTION

One important issue is the behaviour of bi-materials. Almost in every medium we can find one type of bi-materials. Whether it is the human body or other media located in our environment, these bi-materials may consist of coupled layers containing filler elements or without. As a model, we take into consideration from the environment, for our study, the steel-zinc bi-material. This is formed by two principal layers of steel and zinc. During the joining process called hot dip galvanised steel, the zinc undergoes several changes in the chemical composition and also in the mechanical structure represented by cracks, as we can see in Fig. 1.

Generally, the behaviour of these materials could change due to the fatigue process and atmospheric attack represented by rust. Influence of one discontinuity in the material during the treatment process expressed by the presence of one crack or more may be evident during life service in coated materials.

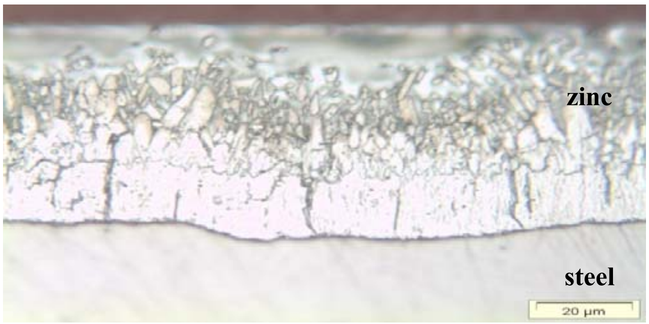


Figure 1. Structure of steel-zinc bi-material after bath at 460°C.
Slika 1. Struktura bi-materijala čelik-cink, posle obrade na 460°C

In literature, different theories are used for describing the behaviour in bonded material systems. Recently, in study of failure mechanics of adhesive joints, Krishnan /1/ used the fringe pattern concentration method. As a analytical model, he took into consideration the definite stress intensity factor in mode I to illustrate the behaviour of bi-material layer. The model is expressed by the formula:

$$K_I = \mathrm{Re}\left\{Ka^{i\varepsilon}\right\} \tag{1}$$

where K is the stress intensity factor for a bi-material specimen noted:

$$K = YT\sqrt{a}\,a^{-i\varepsilon}e^{i\psi} \tag{2}$$

where $T = P(3S/W^2)$ and Y and ψ are calibrating factors that depend on a/W, B/W, and on Dundur's parameters. a, B and W represent the length of a possible crack, specimen thickness and length, in respect. And ε is a function of Dundur's parameters, β, and is given by:

$$\varepsilon = \frac{1}{2\pi}\ln\left\{\frac{1-\beta}{1+\beta}\right\} \tag{3}$$

where β, Dundur's material parameter is expressed as:

$$\beta = \frac{\mu_1(1-2\nu_2)-\mu_2(1-2\nu_1)}{\mu_1(1-2\nu_2)+\mu_2(1-2\nu_1)} \tag{4}$$

where (1 and 2 denote the material), ν and μ are, respectively, the shear modulus and the Poisson's ratio.

MATERIAL AND EXPERIMENTAL PROCEDURES

According to manufacturing management, the designer engineer needs to reflect at the cost of the final product every time. When designing a whole, he needs to consider both the product quality and economic cost. In this context one material, as steel, could be optimal in the industrial engineering application and used in the environment as in the automotive industry, aeronautical design, etc. Unfortunately, this metal may have problems after some time of service at contact with the environment. In this way the treatment mentioned earlier, could be one solution against degradation.

The materials used in our research are two steel alloys: HE360DR and S420MC. Their characteristics are presented in Table 1.

Table 1. Mechanical and chemical characteristics of materials.
Tabela 1. Mehaničke i hemijske osobine materijala

Mechanical properties

Material	S420MC (brut)	HE360DR (brut)	S420MC (galvanized)	HE360DR (galvanized)
Yield tensile strength, (MPa)	366	460	450	514
Ultimate tensile strength, (MPa)	466	574	455	539

Chemical analysis (wt. %)

Material	C	Mn	P	S	Al	Nb	V	Ti
S420MC	≤0.12	≤0.16	≤0.025	≤0.50	≤0.015	≤0.090	≤0.20	≤0.15
HE360DR	0.11	1.40	0.030	0.025	0.015-0.08	0.100	0.100	0.100

In the laboratory, these coated materials are subjected to tensile testing in order to see their behaviour during the fatigue condition. From the results obtained and mentioned in his article, Pruncu /2/ has certified that the layer of zinc deposited over the alloy steel is uniformly distributed, and has a value around 50–80 μm.

SIMULATION PROCEDURE

In this paper, only the analytical and numerical simulation for the understanding of effects of cracks born during the hot dip galvanizing process is considered. To do this, we consider a zinc layer about 80 μm, applied over the entire steel surface. In conformity with mode I, the solution mentioned in literature, cracks found in the zinc layer propagate perpendicularly to the direction of the applied loading. The value of the applied load used is 500 MPa and the length of cracks before propagation are about 30 μm. On the other hand, we recognise that the crack contains two fronts A and B. Assuming that the crack front B is static, meaning that it does not propagate, and that the crack front A spreads.

Analytical model

Our analytical model in this paper is based on the numerical solution of singular integral equations, applied by Cook /3/ and used by Pruncu /2/ in his paper, by applying the following expressions:

$$\begin{cases} K_I(A) = \dfrac{2\mu_1}{(1+k_1)}\sqrt{a_0}\,g(-1) \\ K_I(B) = \dfrac{2\mu_1}{(1+k_1)}\sqrt{a_0}\,g(1) \end{cases} \tag{5}$$

where: a_0 – semi crack length; μ_1, μ_2 – shear modulus for materials 1 and 2; c – distance from crack centre at the interface plane; r, θ polar coordinates; $k = 3 - 4\nu$ for plane strain, and $k = (3 - \nu)/(1 + \nu)$ for plane stress; ν – Poisson's ratio, g – applied loading.

NUMERICAL RESULTS AND DISCUSSION

We compute this model by finite element method (FEM) using ABAQUS software, taking into consideration the two models:

Case (a) one crack in the bi-material

Figure 2 shows the presence of one crack in the zinc layer, which during the tensile test, grows and then stops close to the proximity of the zinc/steel interface. In the worst case, this crack causes opening of the contact area between the zinc and steel, called "debonding area", as we can see from Fig. 2c and d.

The fracture behaviour is described by using Normalised Stress Intensity Factors (NSIF), K. Results acquired show the behaviour of the crack tip in fronts A and B which are shown in Fig. 3. Hence we comprehend that the value of the SIF increases with the crack length to the value of about 0.050 mm, and then we observe a stabilization and even a diminishing of the SIF value. It appears that if the contact area is the "debonding area", the SIF value shows a sharp increase.

Due to assumptions that the initial crack has had the same stress in both fronts A, and respectively B, the two-dimensional finite element meshes are almost symmetric near these entities (crack front), which involves almost the same value of stress distribution during simulation. The shape of the stress-strain curve as a function of crack length is presented in Fig. 4, that shows an increase of intensity with the increase in crack length in front of crack tip A.

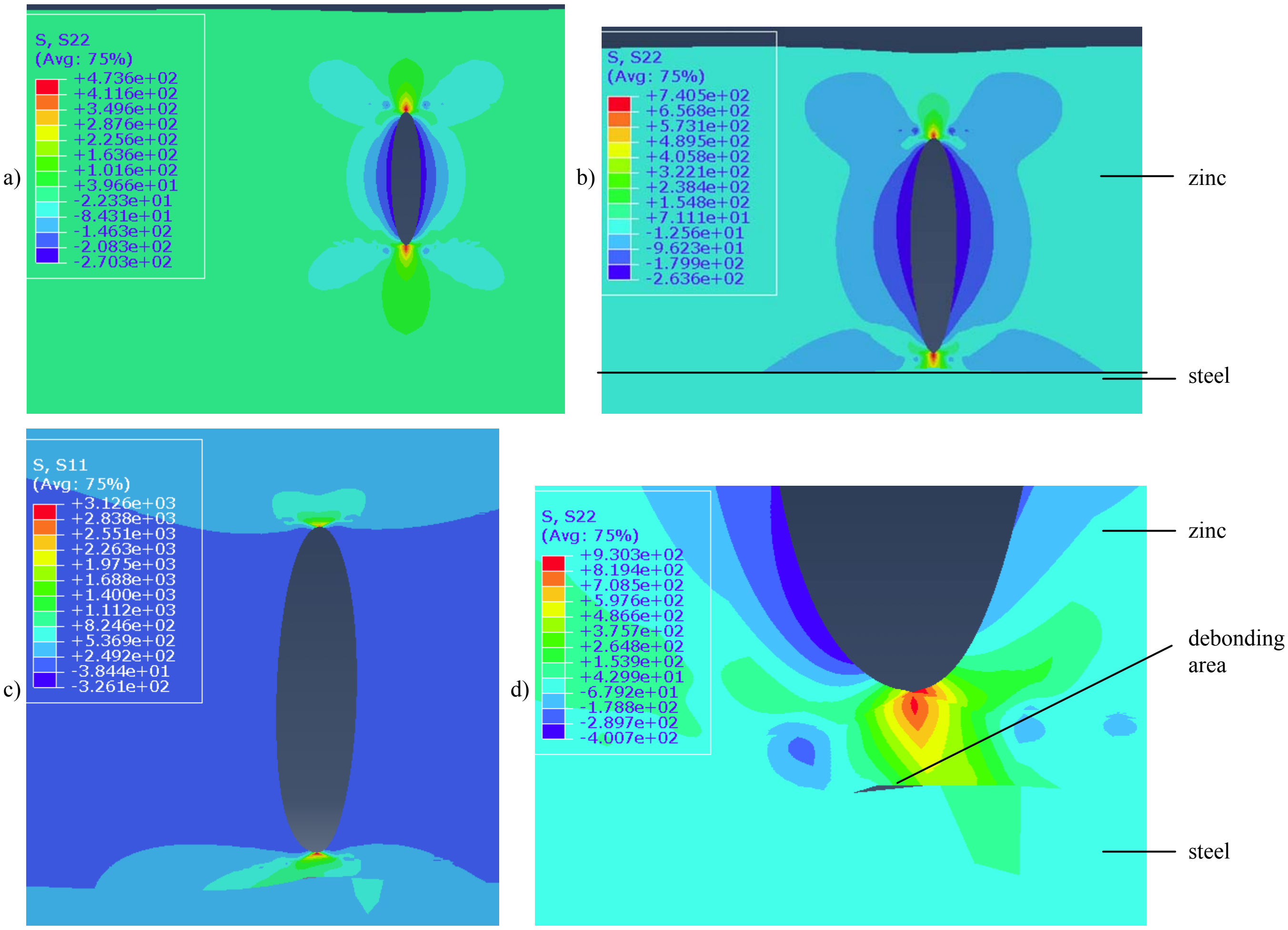


Figure 2. Representation of FEM model with one crack after 500 MPa loading: a) for one crack of length 0.030 mm; b) the crack after propagation of 0.57 mm in length; c) and d) when the crack creates the deflection between the steel and zinc.
Slika 2. Prikaz FEM modela sa jednom prslinom posle opterećenja 500 MPa: a) za jednu prslinu dužine 0.030 mm; b) prslina posle rasta od 0.57 mm; c) i d) prslina se formira između čelika i cinka

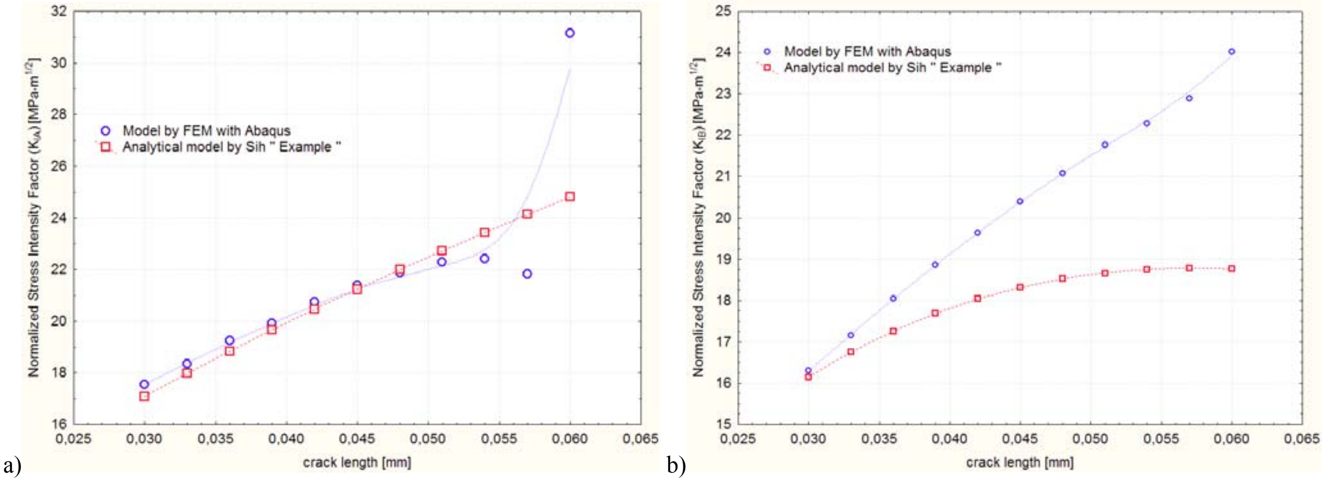


Figure 3. Single crack in bi-material: a) behaviour of crack tip in front A, during propagation, and b) behaviour in crack front B.
Slika 3. Jedna prslina u bimaterijalu: a) ponašanje vrha prsline u frontu A, tokom rasta, i b) ponašanje na frontu B prsline

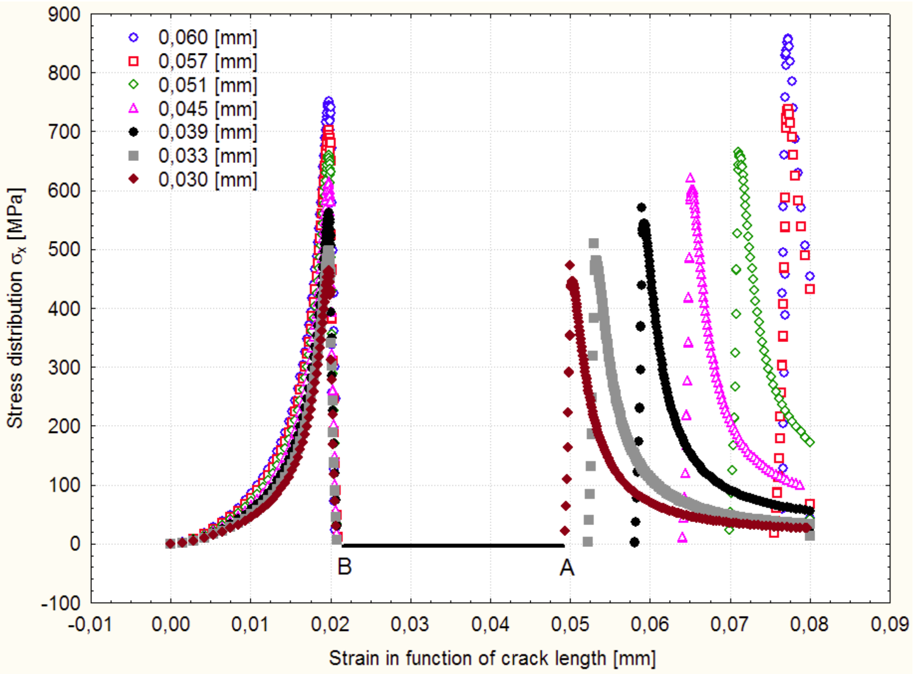


Figure 4. Stress-strain curve for distribution of crack tip in front A and in front B of crack, for different crack lengths.
Slika 4. Kriva raspodele napon-deformacija na vrhu prsline u frontu A i u frontu B prsline, za različite dužine prsline

Case b) two or more cracks

In the second case we set the model with more than one crack as “multiple cracks”. We made this decision in the purpose of detecting, should the situation change due to possible increase of SIF values due to the cumulative action of cracks. Related work is presented by Song /4/, according to which the interfacial crack will propagate if the principal stress at the crack tip exceeds a critical value.

We consider that the three cracks have the same length before propagation and the same shape of mesh. After the simulation, the results are presented in Fig. 5, where the “debonding area” is more evident.

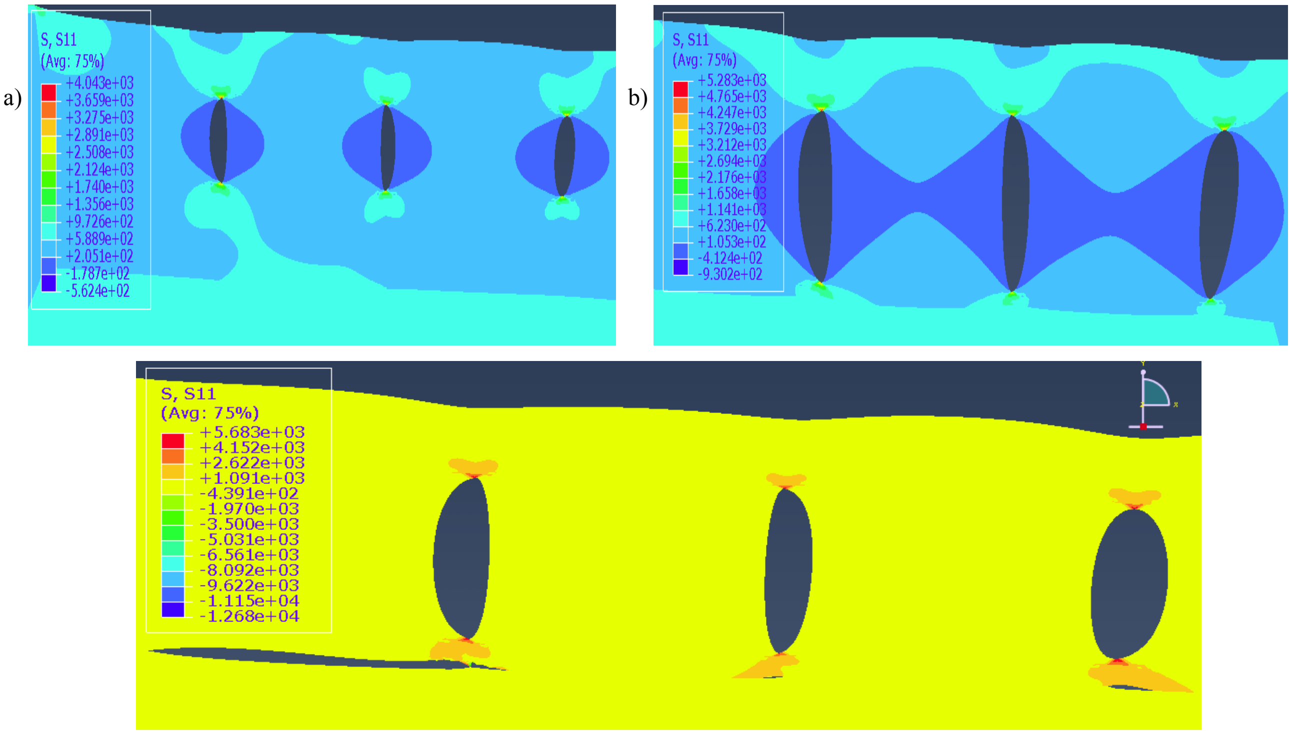
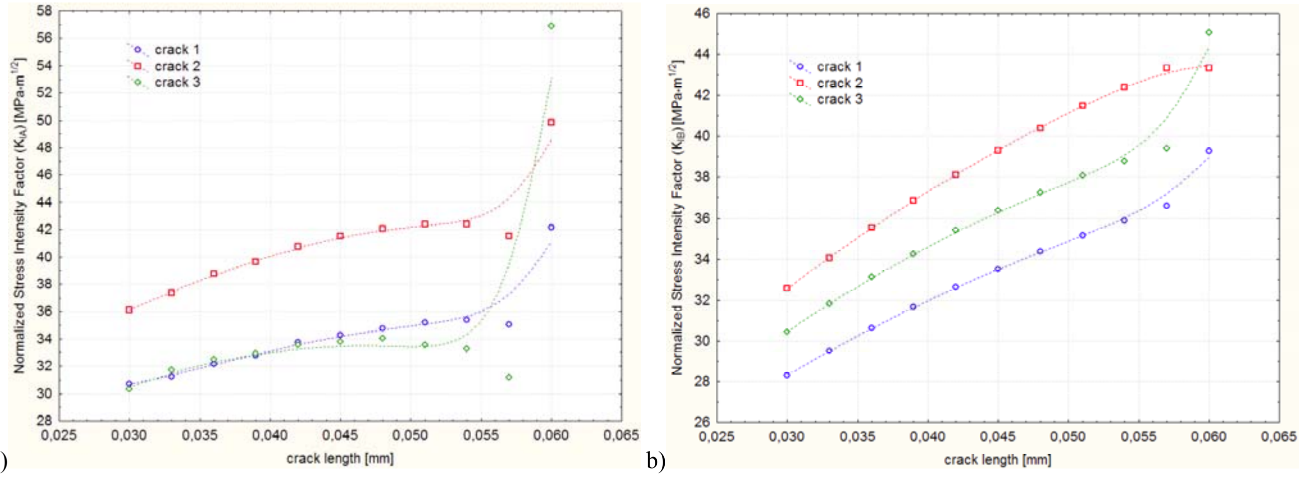


Figure 5. Representation of FEM model with three cracks after 500 MPa loading: a) for crack length 0.030 mm; b) the crack after propagation with 0.57 mm length; c) when the crack forms the deflection between the steel and zinc.
Slika 5. Prikaz FEM modela sa tri prsline posle 500 MPa opterećenja: a) za prslinu dužine 0.030 mm; b) prslina posle rasta, dužine 0.57 mm; c) kada se prslina formira između čelika i cinka



a) b)

Figure 6. Behaviour of three cracks in bi-material: a) crack tip in front A, during propagation, and b) in front of crack B.
Slika 6. Ponašanje tri prsline u bimaterijalu: a) vrh prsline u frontu A, tokom rasta i b) u frontu B prsline

To conclude the results obtained from the model with one crack, Fig. 6 shows the shape of the curve modelled in the bi-material with more than one crack, more precisely with three cracks. The shape is almost the same as for the single crack, but the difference is represented by the increased SIF value due to the cumulative strength of the three cracks. But this increase does not exceed a critical value of mode I fracture toughness for these alloys, e.g. a SIF value for the steel cited by Ashby, Ref. /5/, is about 80-170 MPa·m$^{0.5}$.

CONCLUSION

In this report, two models are used for calculating the SIF in the bonding area of the bi-material body. One model considers a single crack and the other has multiple cracks. The results show that the discontinuity born the during hot-dip galvanized steel process propagates during the fatigue process. It has a tendency of arresting near the steel-zinc interface at about 0.003 mm. In this case it is good to apply it on a damage model that includes the safety factor condition.

In the case when these methods are used to detect the damage behaviour of bi-materials we propose the application of one non-destructive testing method for evaluating this behaviour.

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