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INFLUENCE OF GEOMETRICAL SHAPE OF SPECIMEN IN FATIGUE LIFE CHARACTERIZATION ON WELDED JOINT IN TITANIUM ALLOY

UTICAJ GEOMETRIJSKOG OBLIKA EPRUVETE U KARAKTERIZACIJI VEKA ZAMARANJA ZAVARENOG SPOJA LEGURE TITANA

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Keywords
- fatigue life
- crack initiation
- welded joints

Abstract

From literature we can find many theories on description of behaviour of different kind of materials. But just a few of them take into account an exact correlation between theoretical and experimental applications. In many instances the behaviour of these materials could be represented in function of some characteristics as density, Young modulus and Poisson ratio. One material with good characteristics of these listed above, that has been subjected to examination in this study, could be represented by titanium alloy and in particular titanium alloy grade 5. This material is suitable for the majority of applications in aeronautical, aerospace and naval industries and biomedical area. To be used in the field mentioned above, often titanium must be incorporated in different structures that can be fabricated by welding process assembly. This new component could be more sensitive to crack initiation near the welded area due to the influence of the welding process. In this paper we try to elucidate some problems related to the fatigue life resistance of components, simulating the activity during the real life of an assembly. The results have been confirmed by fractography analysis of broken surfaces, with Scanning Electron Microscopy (SEM) and an optical microscope, and have been correlated through numerical analysis.

Ključne reči
- vek zamaranja
- inicijacija prsline
- zavareni spojevi

Izvod

U literaturi se mogu naći mnoge teorije koje opisuju ponašanje različitih vrsta materijala. Međutim, samo neke od njih uzimaju u obzir preciznu vezu teorijske i eksperimentalne primene. U mnogim slučajevima, ponašanje ovih materijala se može predstaviti funkciji nekih karakteristika, na pr. gustina, modul elastičnosti, Poasonov koeficijent. Jedan materijal sa dobrim gore spomenutim karakteristikama, koji je podvrgnut ispitivanju u ovom radu, može biti legura titana, odnosno, legura titana klase 5. Ovaj materijal je pogodan za većinu primena u vazduhoplovnoj i kosmičkoj industriji, brodogradnji i u oblasti biomedicine. Da bi imao primenu u spomenutim oblastima, često se titan uvodi u različite konstrukcije koje se proizvode-spajaju zavarivanjem. Ovakva komponenta može postati osetljiva na inicijaciju prsline u okolini zavarenog spoja usled procesa zavarivanja. U ovom radu pokušavamo da rasvetlimo neke probleme vezane za otpornost komponenata prema zamaranju (vek zamaranja), simulacijom rada tokom realnog veka datog sklopa. Rezultati su potvrđeni fraktografskom analizom polomljenih površina, sa skening elektronskom mikroskopijom (SEM) i optičkim mikroskopom, a zatim su međusobno korelisani numeričkom analizom.

INTRODUCTION

Material inhomogeneities are, in general, defects in the translational invariance of material properties. In a specimen, different material regions can be seen, with rapid changes of microstructure and properties, which may be more or less smooth or even abrupt /1/. Obviously it is virtually impossible to manufacture particles with perfectly smooth geometries /2/.

The presence of micro defects in materials due to certain variation of temperature or a void merge during the process of fabrication is inevitable. The study of the physical process about the behaviour of the material can be dedicated to the nucleation phase of a crack or void, described with the inequality ($a < a_m$) /3/, where a_m is the smallest crack length detectable by current technology, which is about 0.1 μm. Heterogeneities in the order of a few micrometers are present in stainless steel as sulphide inclusions with the size of 10 μm, /4/. In effect, damage tolerance analysis which describes fatigue crack growth should be one connection to solve the fatigue nucleation stage.

In a theoretical vision, defects correspond to mathematical singularities in a continuous description that can be easily detected in the elastic field. An important subject of contemporary theoretical and applied mechanics is the fracture. The most relevant notions developed by engineers in that context are those of driving force acting on the tip of a crack and of energy-release rate.

OVERVIEW OF THE STATE OF THE ART

Description of fatigue initiation life in different medium, represented by solid mechanics and fluid mechanics fields, is yet open for all research society. Moreover, the technical society until today have provided particular descriptions in literature, lemmas and corollaries in goal to explain that topic. In the following few lines, we will point to some of the most important issues.

Definition of Fatigue Life Initiation

In literature, fatigue initiation life of solid materials is assumed to be represented by the phase of crack initiation activity. In this way, for the description of this phase of crack initiation, different definitions have been proposed. In the absence of a standard agreement, it is admitted to define the fatigue life initiation by a threshold crack length. The definition of the micro-crack initiation length is supposed to be quite equal to 0.1 mm for the majority of steels. This dimension is generally easy to detect and corresponds to a defect comparable to the steel grain size average. Fatigue initiation life is a consequence of cyclic slip in slip bands which implies cyclic plastic deformation as the result of moving dislocations. This microplasticity can occur more easily in the grains at the material surface. Accordingly, the initiation fatigue life is supposed to be completed when micro-crack growth is no longer depending on the free surface conditions.

Fatigue Life Without Initiation

Some authors, like Murakami /5/, considered that each material contains a defect as a crack. Where the size is characterized by the root square of the 'area' parameter ('area' of the defect projected on the plane perpendicular to the direction of the maximum principal stress) and defined that crack initiation stage is negligible ($N_i \approx 0$). Fatigue life is therefore assumed to be controlled by the crack propagation law.

Fatigue Initiation Parameter

In any case, fatigue resistance to initiation could be represented by a power relationship of the form $P_i = f(N_i b)$ where P_i is an initiation parameter and b is the exponent of Basquin's type. Several approaches have been used to define the initiation parameter P_i: effective stress, notch stress intensity factor, damage parameter issued from SWT parameter /6/, energy parameter.

It is acceptable to use the stress range as a parameter to express fatigue resistance to initiation. In this case it is necessary to take into account that fatigue generally initiates from the stress concentration area which induce the stress gradient at the notch tip. Stress distribution at the notch tip is assumed to derive from Irwin's elastic stress distribution at the crack tip by Creager and Paris /7/. To avoid stress singularity at the notch tip, the Irwin stress distribution at the notch tip is shifted by introduction of a new origin located at distance $\rho/2$ to the previous one. The stress distribution is governed by the (crack) stress intensity factor K and represented by:

$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left[1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right] + \frac{K_I}{\sqrt{2\pi r}}\frac{\rho}{2r}\frac{\theta}{2} \quad (1)$$

where r and θ are polar coordinates and ρ is the notch radius.

This method assumes that the effective stress is the maximum stress located at the notch tip which is given by:

$$\sigma_{\max} = \sigma_{yy}(x=\rho/2,\ \theta=0) = \frac{2K}{\sqrt{\pi\rho}} \quad (2)$$

Barsom and McNicol /8/, Jack and Price /9/, Clark /10/ and Truchon /11/ have used the parameter $\Delta K/\sqrt{\rho}$ to express fatigue resistance on notched specimens.

This fatigue resistance can be expressed by the concept of effective stress range /12/ $\Delta\sigma_{ef}$ which represents the average stress over the fatigue process volume often reduced to the average stress over the effective distance X_{ef} due to the assumption that this volume is cylindrical.

$$\Delta\sigma_{ef} = \frac{1}{X_{ef}} \int_0^{X_{ef}} \Delta\sigma_{yy}(r)dr \quad (3)$$

Lukas et al. /13/ approximated this stress by an equivalent stress in the proximity of a notch tip, prolonged with fictitious microcracks by the following relationship:

$$\Delta\sigma_{eq.Lukas} = \frac{k_i \Delta\sigma_g}{\sqrt{1+4.5\,a_0/\rho}} \quad (4)$$

k_t is the elastic stress concentration factor, σ_g is the applied gross stress range. The fictitious microcrack length used by Lukas et al /14/ is here assumed equal to a_0:

$$a_0 = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\sigma_D}\right)^2 \quad (5)$$

where σ_D is the fatigue limit and ΔK_{th} the fatigue threshold.

Due to stress concentration, cyclic plasticity occurs generally at the notch tip and elasto-plastic stress distribution is generally more complex than the elastic one, and it can be obtained by Finite Element computing. By applying the effective stress range definition given in Eq.(3), Capelle et al. /15/ have presented the fatigue resistance to initiation for an X52 pipe steel.

The stress distribution at the notch tip at a distance greater than the effective distance, can be described by the so-called Notch Stress Intensity Factor (NSIF). Lazzarin et al. /16/, use the elastic NSIF K^* as parameter for fatigue initiation. Boukharouba et al. /17/ have compared fatigue initiation criteria with a criterion based on the elasto-plastic notch stress intensity factor K_ρ on welded specimens made of low strength steel. The weld toe was considered as a notch with a notch angle of 135°. The NSIF has then the unit MPa×m$^\alpha$, where α is the power dependence of the stress distribution ($\alpha = 0.385$).

Smith et al. /18/ have shown experimentally that the result of Eq.(6) is constant, whatever the stress ratio is:

$$\sqrt{\sigma_{\max} E \varepsilon_a} = C = \text{SWT} \quad (6)$$

where $\sigma_{\max}$ is the maximum stress, E is Young's modulus, and ε_a is the strain amplitude. This result is called the SWT parameter and it is generally used to convert low cycle fatigue resistance at zero stress ratio to low cycle fatigue resistance at any stress ratio. Lazzarin et al. /16/ have derived a so-called damage parameter D from the SWT parameter and expressed it as a stress (MPa*units); They have presented that for thin plates notched by symmetric lateral U-, V- shaped notches with notch root radii ranging from 0.1 to 10 mm and made of steel. All the results merge in an unique curve, independently of the notch radius.

Fatigue crack initiation of engineering components exhibiting significantly small sized imperfections “short flaws” is expressed as:

$$\Delta\sigma_{th} = \frac{\Delta K_0}{F\sqrt{\pi a_c}} \tag{7}$$

where F is a geometrical factor.

This fatigue initiation stress range for both a short and a long crack is expressed by the Kitagawa and Takahashi diagram /19/, where the crack growth threshold is plotted against the crack size. Using the empirical law relationship (5) we can write:

$$\Delta\sigma_{th} = \frac{\Delta K_0}{F\sqrt{\pi(a_c + a_0)}} \tag{8}$$

Another formula is presented by Jelaska and Podrug /20/ in cumulative HCF/LCF loading:

$$N_i = \frac{N_{gr}\sigma_0^{m_i}}{\left(\dfrac{2\sigma_U\sigma_a}{\sigma_U + \sigma_a - \sigma_m}\right)^{m_i} + \dfrac{\sigma_m^{m_i}}{n_{HCF}}} \tag{9}$$

where m_i, σ_U, σ_a, σ_m, σ_0, N_{gr}, n_{HCF} are material constant, ultimate strength, stress amplitude, maximum stress, endurance limit, sufficiently long fatigue life, number of HCF cycles.

MATERIALS AND WELDED BUTT JOINTS

In the last period, materials as titanium and titanium alloys, are finding widespread applications due to their good characteristics. Consequently, they show a good balance of mechanical and chemical properties and, hence, cover many areas of application in diverse industries. The most widely used titanium alloy is Ti-6Al-4V (α–β alloys). These alloys contain larger amounts of beta stabilizers (4 to 6%) /21/. Compared with steel, titanium or titanium alloys have low density and show a similar fatigue resistance and present a very attractive strength weight ratio.

The most influential microstructural parameter of the mechanical properties of titanium alloys can be influenced by either α alloys (hexagonal crystal structure) or β alloys (body centred cubic structure) and α–β alloys. Properties of α–β alloys (titanium grade 5) can be controlled through heat treatments /22, 23/. Chemical compositions of tested materials are reported in Tables 1 and 2.

Table 1. Chemical composition of titanium alloy grade 5.
Tabela 1. Hemijski sastav legure titana klase 5

Titanium grade 5	C	Al	V	Fe	H	N	O
ASTM B265	<0.08	5.5-0.75	3.5-4.5	<0.30	<0.015	<0.03	<0.25

Table 2. Mechanical properties of titanium alloy grade 5.
Tabela 2. Mehaničke osobine legure titana klase 5

Titanium grade 5	Modulus of elasticity E (MPa)	Ultimate tensile strength R (MPa)	Yield tensile strength R_{02} (MPa)
ASTM B265	1.138	956.4	760

The alloy is recommended mainly for designing disks, blades, spacer rings, engine body and other aircraft-engine components operating at temperatures up to 400-450°C /24/. In the case where these materials are integrated in structures mentioned above, different procedures for joining are used. One possibility is to use mechanical joining by welding process as a butt welded joint. Cited by Casavola et al. /22/, specimens obtained by process of welding and more precisely “butt welded joint” show sensitivity to fatigue life initiation at conjunction of weld cord and parent material. Of course, in this region, which corresponds to the heat affected zone (hosting microstructural changes) the stress/strain field is usually amplified with respect to the nominal stress values because of the effects of local geometry of the seam, localized plasticization and secondary bending produced by misalignments.

In the other hand, one great problem is represented by the slags which are formed and deposited, during the welding process, in proximity of the weld cord. Due to the difficult task to eliminate these entities caused by solidification, the life of the butt welded joint could decrease. For example use of metal removal in steels and low alloyed steels, can cause the untempered martensitic structure to form, which is brittle and causes significant shortening of fatigue life. In this case the welding processes must be improved, redefining welding time and speed, /25/.

Figure 1 shows the approximate profiles recognized by a tactile device, acquired namely by a Coordinate Measuring Machine (CMM) for the right and reverse sides of the butt welded specimen.

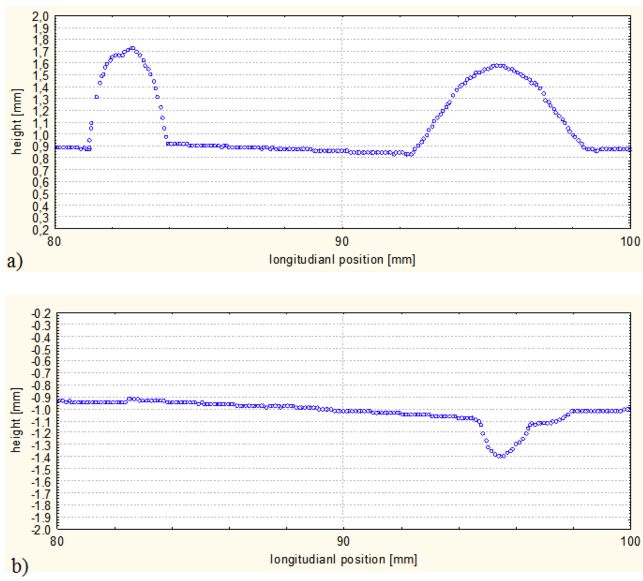


Figure 1. Butt welded joint specimen: right (upper) (a) and reverse (lower) (b) side seam profile.
Slika 1. Epruveta sučeonog zavarenog spoja: desna (gornja) (a) i suprotna (donja) (b) strana profila šava

RESULTS AND DISCUSSION

After fatigue tests, on specimens of butt welded joint of titanium alloy, a summary of macrographs about details of the microstructure has been illustrated. Thus such macrography characterizes areas where initiation of crack occurs. In this way are taken samples all over the material surface, both from the welding area connection and also from the area where the slag irregularities are deposited. With an optical microscope we show the arrangement of grains, where we can see the distribution of lamellar grains. In Fig. 2 we can see the distribution of microcracks between grains which occur concerning intergranular crack initiation.

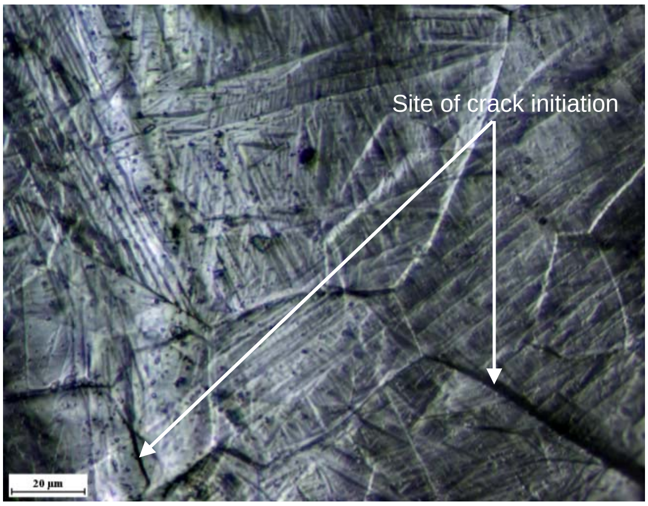
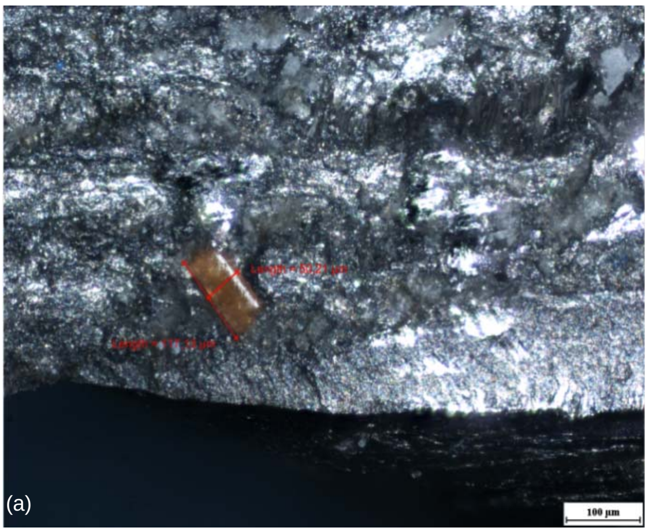


Figure 2. Microcrack initiation in intergranular mode, titanium alloy Ti-6Al-4V (α-β).
Slika 2. Inicijacija interkristalne mikroprsline, legura titana Ti-6Al-4V (α-β)

On the other hand, in the adjacent area of slag we found some inclusions which can trigger the process of fatigue. Difference in colour between material layer under the slag and titanium alloy displayed in Figure 3a, leads to the idea that, in this area a chemical process could occurred in a different way that also influences the fatigue behaviour. At the interface of these layers in Figure 3b, the distribution of line of fatigue is evident.



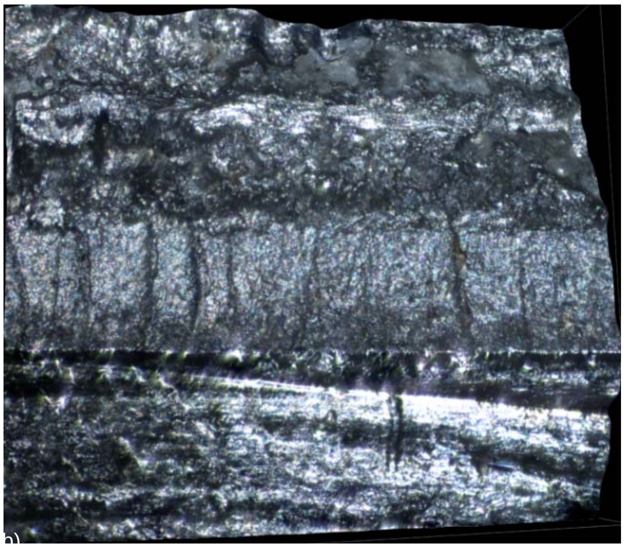


Figure 3. Site of fatigue initiation characterized through a) inclusion on the slag area, b) line of fatigue crack initiation.
Slika 3. Oblast inicijacije zamora karakteristično po a) uključku u zoni troske, b) liniji inicijacije zamorne prsline

Under some influences of temperature variations, correlated with the fatigue damage test effect involved, the critical strain in ductile mode fracture is locally shown. As this critical strain exceeds, shear bands and small voids are formed. These voids are known as strain induced porosity (SIP). An example of strain induced porosity in Ti-6Al-4V is shown in Fig. 4. Once this porosity is created in the forging billet, it is not always healed during subsequent forging operations. Consequently, it can be carried over into a finished component as a defect that can act as an early fatigue crack initiation site, /25/.

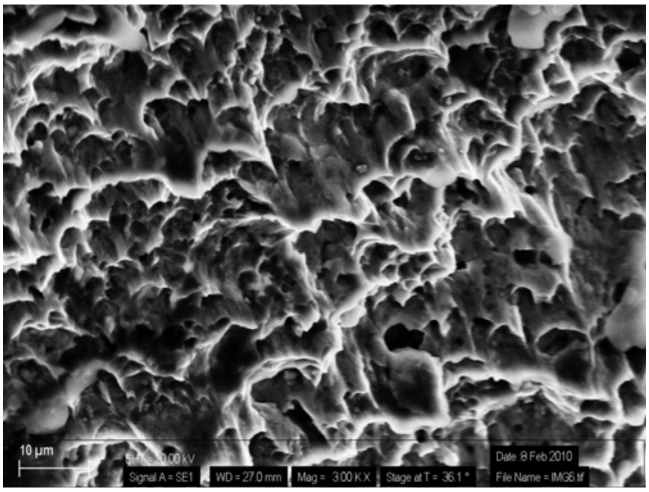


Figure 4. Representation of face of crack initiation life.
Slika 4. Izgled lica inicijalne prsline

In order to correlate the experimental results, we apply the numerical analysis model. Models with Extended Finite Element Method (XFEM) have been realised and the analysis has been executed through Abaqus software. The numerical model considered had the same shape of the butt welded joint acquired by the Coordinate Measuring Machines. For fatigue tests a value of charge loading of 24.5 kN has been imposed. According to experimental results, the model has incorporated one irregularity. This irregularity is exemplified through one crack of about 0.1 mm in the weld cord area. The shape of the specimen is represented in Fig. 5a. Although, this crack may produce implications, expecting an increase of stress in the welded cord area, an obvious increase in stress in the slag area, has been registered. These trends of stress distribution are shown in Fig. 5b. This complex behaviour can be explained by the appearance of inclusions under the slag area as displayed in Fig. 6.

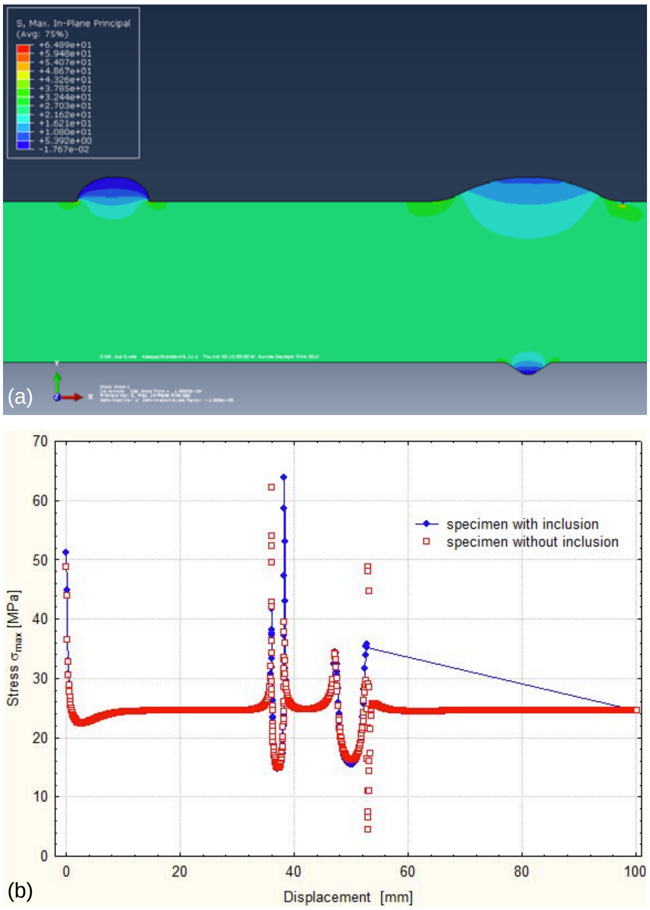


Figure 5. a) Shape of specimen analysed with crack in weld area, b) distribution of maximal stress versus displacement in the sample with and without inclusion.
Slika 5. a) Oblik analizirane epruvete sa prslinom u zoni šava, b) raspodela maksimalnog napona sa pomeranjem u epruveti sa i bez uključka

CONCLUSION

Experimental determination and numerical analysis of the fatigue life initiation are illustrated in this paper. Thus, factors which could influence the behaviour of the butt welded joint specimen are determined. Some specific parameters which could be mentioned are: distribution of boundary grains in the material which show lamellar form and an early phase in microcrack intergranular behaviour, varieties of some inclusion unexpected in the base material, difference in the temperature in the bonding area represented through the interface slag and parent material. The same could be cited about the factors regarding the growing in size of voids, which involve the strain behaviour and initiation life.

On the other hand, by XFEM is presented the distribution of stress along the shape of the butt welded joint and the behaviour of one irregularity in the body of the material alloy, through which we can deduce that the true life initiation of fatigue, in the titanium alloy, is represented by a complex of parameters from the shape of the material to the manufacturing process.

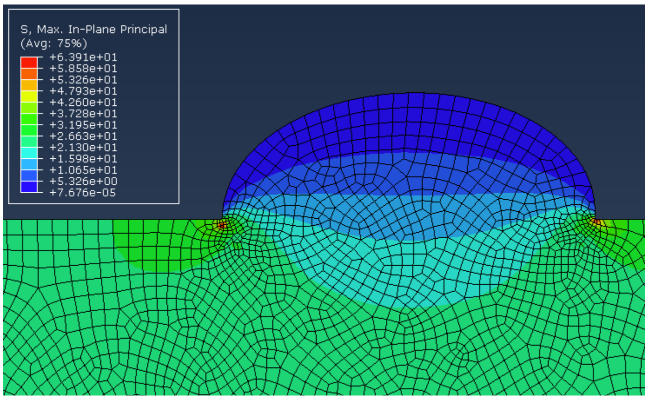


Figure 6. Model of butt welded joint with inclusion in the slag area.
Slika 6. Model sučeonog zavarenog spoja sa uključkom u troski

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European Structural Integrity Society (ESIS)
ESIS TC1 Spring Meeting 2013
Workshop on “Crack Closure Effects in Fatigue Crack Propagation”

The workshop aims at providing a basis for knowledge exchange between scientists and field experts dealing with predictive methods for assessing fatigue crack growth in metallic structural components. In particular, the following aspects are suggested to be discussed:

- Plasticity induced crack closure: experimental techniques and numerical prediction,
- Other crack closure mechanisms, such as oxide-induced, roughness-induced, etc.,
- Crack closure effect on short and long crack propagation,
- Crack closure effect in different regions of the da/dN-DK curve, including the threshold regime,
- Crack closure models for variable amplitude loading, load reversal, etc.,
- Geometry or constraint dependent crack closure,
- Interdependency between the crack closure effect and other phenomena,
- Transferability of crack closure models from specimens to components.

The workshop should highlight both the progress in fatigue crack closure evaluation and deficiencies of currently existing techniques, specify practical needs, and promote an open discussion as to the feasibility of crack closure modelling for cracked components. Therefore, it is intended to provide ample time for discussion and thus to limit the number of presentations to about 15.

The meeting is planned to be held on June 6–7, 2013 (two full days). It will take place at
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