THE EFFECT OF A MATERIAL'S HETEROGENEITY ON THE STRESS AND STRAIN DISTRIBUTION IN THE VICINITY OF A CRACK FRONT

VPLIV HETEROGENOSTI MATERIALA NA PORAZDELITEV NAPETOSTI IN DEFORMACIJE V BLIŽINI KONICE RAZPOKE

Dražan Kozak[1], Nenad Gubeljak[2], Jelena Vojvodič Tuma[3]

[1]University of Osijek, Mechanical Engineering Faculty, Trg I. Brlić-Mažuranić 2, 35000 Slavonski brod, Croatia
[2]University of Maribor, Faculty of Mechanical Engineering, Smetanova 17, 2000 Maribor, Slovenia
[3]Institute of Metals and Technology, Lepi pot 11, 1000 Ljubljana, Slovenia
[1]dkozak@sfsb.hr, [2]nenad.gubeljak@uni-mb.si, [3]jelena.tuma@imt.si

In this investigation a high-strength low-alloyed (HSLA) steel of the 700-MPa strength class was used as a base material. A butt-welded joint with X grooves was produced with an overmatched weld metal that had a yield strength 23 % greater than that of the base material. Three-point bending $B \times 2B$ test specimens (thickness $B = 36$ mm) were extracted from the welded joints. The straight crack front ($a_0 = 35,571$ mm) crosses different microstructures through the thickness of the specimen.

Both fracture-mechanics tests and a 3D finite-element analysis were performed. The CTOD parameter of the fracture toughness was measured and calculated numerically. The loading level at which stable crack growth occurred was also determined. The comparison of the experimental and numerical values of the CTOD (δ_5) displacements showed good agreement. The principal stress, σ_y, the Mises equivalent stress, σ_{eq}, and the plastic equivalent strain, $\varepsilon_{pl, eq}$, at the moment of crack initiation were studied for six equidistant layers from the surface to the mid-thickness of the specimen. The dependence of the crack-opening stress (denoted as σ_x in this paper) on the local fracture-toughness value was considered as the parameter which determines the direction of the crack-front propagation. The results show that the lower strength of the base metal contributes to the crack-path deviation in the mid-thickness of the specimen. Both the crack-path deviation and the higher toughness of the base metal increase the critical fracture toughness value of the welded joint.

Key words: strength overmatched welded joint, crack, stress and strain distribution, finite element analysis

V tej raziskavi je bilo kot osnovni material uporabljeno visokotrdno malolegirano jeklo (HSLA) s trdnostjo 700 MPa za čelni zvar z X-žlebovi je bil pripravljen in uporabljen deponirani material z mejo plastičnosti, ki je bila za 23 % večja kot pri osnovnem materialu. Tri-točkovni upogibni preizkušanci $B \times 2B$ (debelina $B = 36$ mm) so bili izrezani iz zvarjenega spoja. Čelo ravne razpoke ($a_0 = 35,571$ mm) seka skozi debelino preizkušanca različne mikrostrukture. Opravljeni so bili lomnomehanski preizkusi in analiza 3D končnih elementov. CTOD-parameter mehanike loma je bil izmerjen in numerično izračunan. Določen je bil tudi nivo obremenitve, pri katerem je nastala stabilna rast razpoke. Primerjava eksperimentalnih in numeričnih vrednosti za CTOD (δ_5)-premike je pokazala dobro ujemanje. Glavna napetost σ_y, ekvivalentna Mises-napetost σ_{eq} in ekvivalentna plastična deformacija ε_{ok-eq} so bile opredeljene za 6 med seboj enako oddaljenih plasti od površine do sredine preizkušanca. Odvisnost med napetostjo odprtja razpoke (označeno z σ_x v tem članku) in lokalno vrednostjo za žilavost loma je upoštevana kot parameter, ki določa smer propagacije čela razpoke. Rezultati kažejo, da manjša trdnost osnovnega materiala povzroči deviacijo poteka razpoke v sredini preizkušanca. Deviacija poti razpoke in večja žilavost osnovnega materiala povečata žilavost loma zvarnega spoja.

Ključne besede: trdnost spoja z večjo trdnostjo vara, razpoka, porazdelitev napetosti in deformacije, analiza končnih elementov

1 INTRODUCTION

The heterogeneity of the materials in a welded joint on the macroscopic level has been made possible by modern joining techniques such as laser welding and electron-beam welding [1]. Such inhomogeneity in the materials can also be intentional, for example, when using functionally graded materials [2]. If a component made from such dissimilar materials has defects, it should be assessed from the fracture-mechanics point of view. The knowledge of the stress distribution can be very useful for calculating the fracture-mechanics parameters as part of the SINTAP defect-assessment procedure [3]. It also helps to determine numerically the yield load solution [4]. To evaluate the fracture toughness and the mechanicsms of failure, the stress-strain field at cracks located in the joint must be understood [5]. An asymmetry in the distribution of the stresses in the vicinity of the crack tip could influence the crack-path deviation from its original direction. The usual failure criterion for a homogeneous material is that the crack grows in a direction perpendicular to the maximum principal stress. In a multiphase material, the fracture criterion based on the ratio of the crack opening stress to the material toughness distributed in front of the crack tip is proposed for determining the direction of the crack propagation of a mixed-mode fracture problem in [6].

Therefore, the stress-strain distribution near the crack front due to the increasing load is very important for the better understanding of the whole fracture process. Experimental methods applied to follow the strain fields (e.g., the object grating method) are very accurate, but
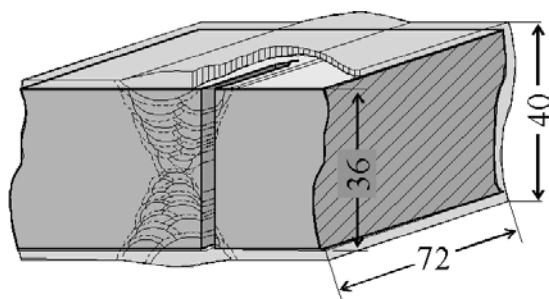
limited to the visible surface of the specimen [7]. As a result a finite-element analysis becomes very useful.

Although many factors influence the yielding in cracked welded components [8], the aim of this paper is to show how the yield strength of overmatched weld metal affects the stress and strains fields. To do this a $B \times 2B$ three-point bend specimen with an X-weld cracked through the thickness of the specimen was considered. Both 3D finite-element calculations and experiments were performed.
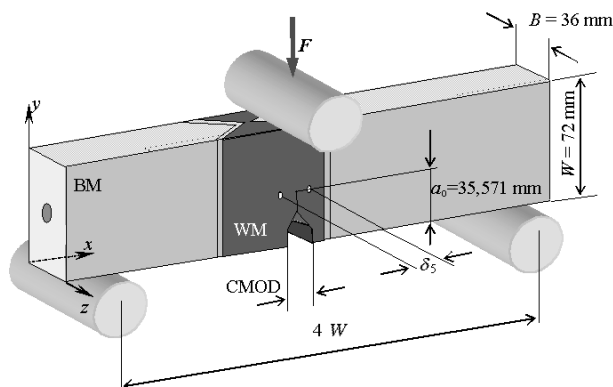
2 TESTING OF FRACTURE-TOUGHNESS SPECIMENS

$B \times 2B$ three-point-bend fracture-toughness speci-mens (thickness $B = 36$ mm) were extracted from the welded plate (**Figure 1**) and prepared for fracture-mechanics testing. HSLA steel with yield strength of 676 MPa was used as the base material (BM). The X-welded joint was produced using an overmatched weld metal (WM) with a yield strength of 833 MPa. In this case the yield-strength mismatch factor, defined as the ratio $M = R_{p0,2}^{WM}/R_{p0,2}^{BM}$, was equal to $M = 833/676 = 1.23$. The straight crack front passed over the overmatched weld metal near the surfaces, while the base metal of lower strength was located in the middle of the specimen (**Figure 2**).
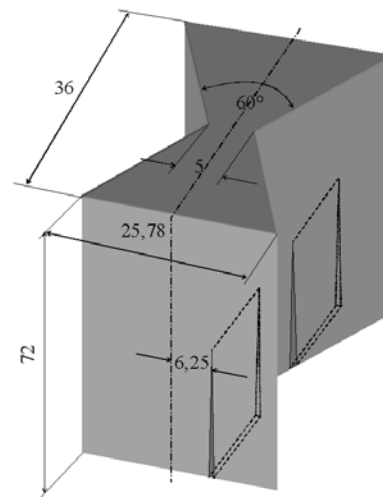
During the CTOD (δ_5) fracture-toughness testing unstable crack propagation occurred after some initial

Figure 1: Welded plate from which specimens were extracted
Slika 1: Zvarjena plošča, iz katere so bili izdelani preizkušanci

Figure 2: $B \times 2B$ fracture-toughness specimen
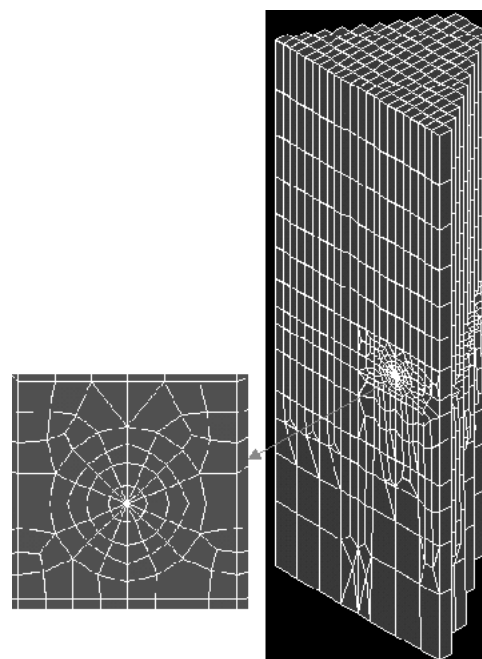**Slika 2:** $B \times 2B$-preizkušanec za žilavost loma

Figure 3: Geometry of the weld
Slika 3: Geometrija zvara

stable crack growth. Fractographic and metallographic analyses showed that the crack path started to deviate in the mid-thickness of the specimen, where the crack front passes from the heat-affected zone (HAZ) to the softer base metal. For this reason, the finite-element calculation was performed to provide an insight into the state of the stresses and strains at the moment of onset of the stable crack growth.

3 FINITE-ELEMENT ANALYSIS

The geometry of the weld with the specified location of the crack is depicted in **Figure 3**. The finite-element calculation was performed on a solid numerical model.

Figure 4: FE mesh of the weld part
Slika 4: FE-mreža zvarjenega dela

Taking into account the thickness symmetry of the specimen, only one half is modelled. A standard 20-node structural solid element from the ANSYS [9] library was used. Commercial programs specialised in modelling crack fronts, e.g., Zencrack or FEA Crack, were not applied. The free-meshing technique was applied, with a size of 100 μm for the first fan of elements (**Figure 4**). The nodes, a distance of 2.5 mm from both sides of the crack tip, should be foreseen so as to be able to calculate the CTOD (δ_5) parameter of the fracture toughness for each load up to the load at which stable crack growth occurs. The load is applied incrementally as the pressure on the two rows of mid-plane elements. The total numbers of elements and nodes were 5450 and 24384, respectively. Both materials in the joint were modelled as isotropic elastic-plastic with their own yield laws. Because of its minimal influence on the results, the modelling of the HAZ as a particular material in the joint was omitted.

4 RESULTS AND DISCUSSION

The opening displacements measured at the crack mouth (CMOD) are in very good agreement with those determined numerically. On the other hand, the finite-element results for the CTOD (δ_5) displacements are lower than the experimentally measured values (**Figure 5**). This proves that it is much more difficult to really simulate the local fracture behaviour of the material than the global behaviour. It is also evident that a crack-tip opening displacement calculated by the finite-element method deviates significantly as the loading is increased.

The stress σ_y caused by the force acting in the y-direction, the Mises equivalent stress, σ_{eq}, and the plastic equivalent strain, $\varepsilon_{pl, eq}$, at the moment of the crack initiation are presented for the six equidistant layers from the surface to the mid-thickness of the specimen (**Figure 6**). In addition, the variation of the plastic equivalent strain, $\varepsilon_{pl, eq}$, during the load increase is presented in **Figure 7**.
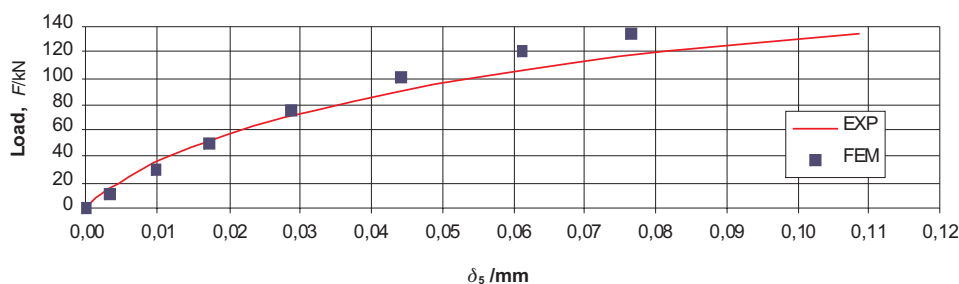
5 DISCUSSION AND CONCLUSIONS

The effect of the yield strength of the overmatched weld metal on the stress and strain distribution in the case of a $B \times 2B$ fracture-toughness specimen cracked in the middle was studied experimentally and numerically. The crack front passes over the different materials through the thickness of the specimen, which tends to complicate the finite-element analysis.

The numerical values of the global fracture-toughness parameters, such as the load-line displacement or the crack-mouth opening displacement are in very good agreement with the experiment up to the moment of the crack initiation. On the other hand, the finite-element results for the local toughness parameters, such as the CTOD (δ_5) displacement, are lower than the experimentally measured values.

The magnitude of the σ_y stress is significantly greater in the mid-thickness of the specimen than on the surface, which is the opposite of the effective stress, σ_{eff}. A characteristic asymmetry of the stress and strain field due to material's heterogeneity in the joint occurred in the vicinity of the crack front. It is evident from the effective stress distribution that higher values of the stresses are present in the weld material that has a higher yield strength, which is in accordance with the theory. The peak of the highest stress is shifted from the crack tip point, depending on the local material toughness parameter. In contrast to the effective stress distribution, the higher values of the equivalent plastic strain, $\varepsilon_{pl, eq}$, spread to the softer base metal with an increase in the loading.

The crack-opening stress (σ_x in this case) divided by the local fracture-toughness value can be considered as the parameter that determines the direction of the crack-front propagation. The results show that the presence of a low-strength base metal contributes to the crack path deviation in the mid-thickness of the specimen. Both the crack-path deviation and the higher toughness of base metal increase the critical fracture toughness value of the welded joint.

Figure 5: *F*-CTOD (δ_5) diagram
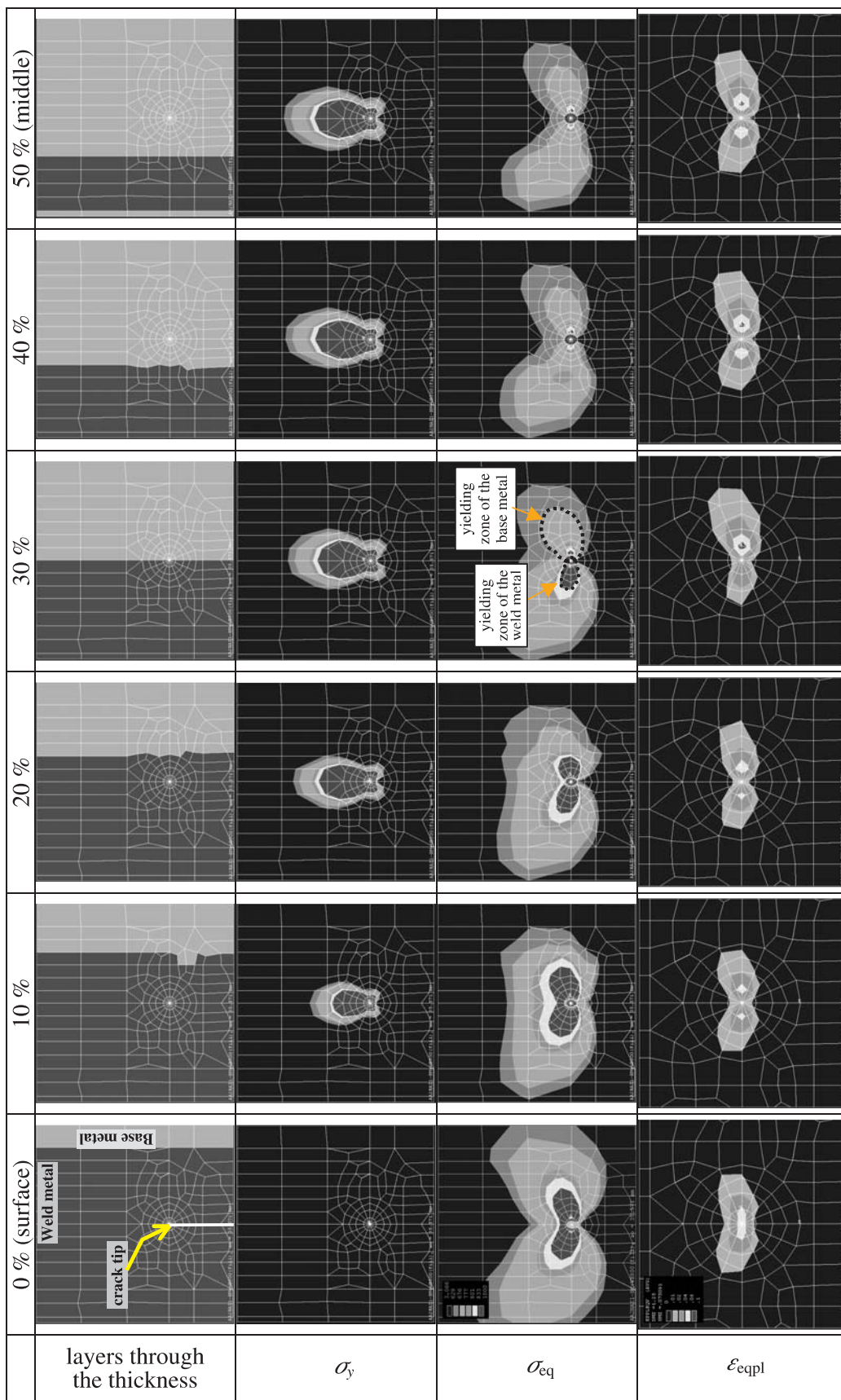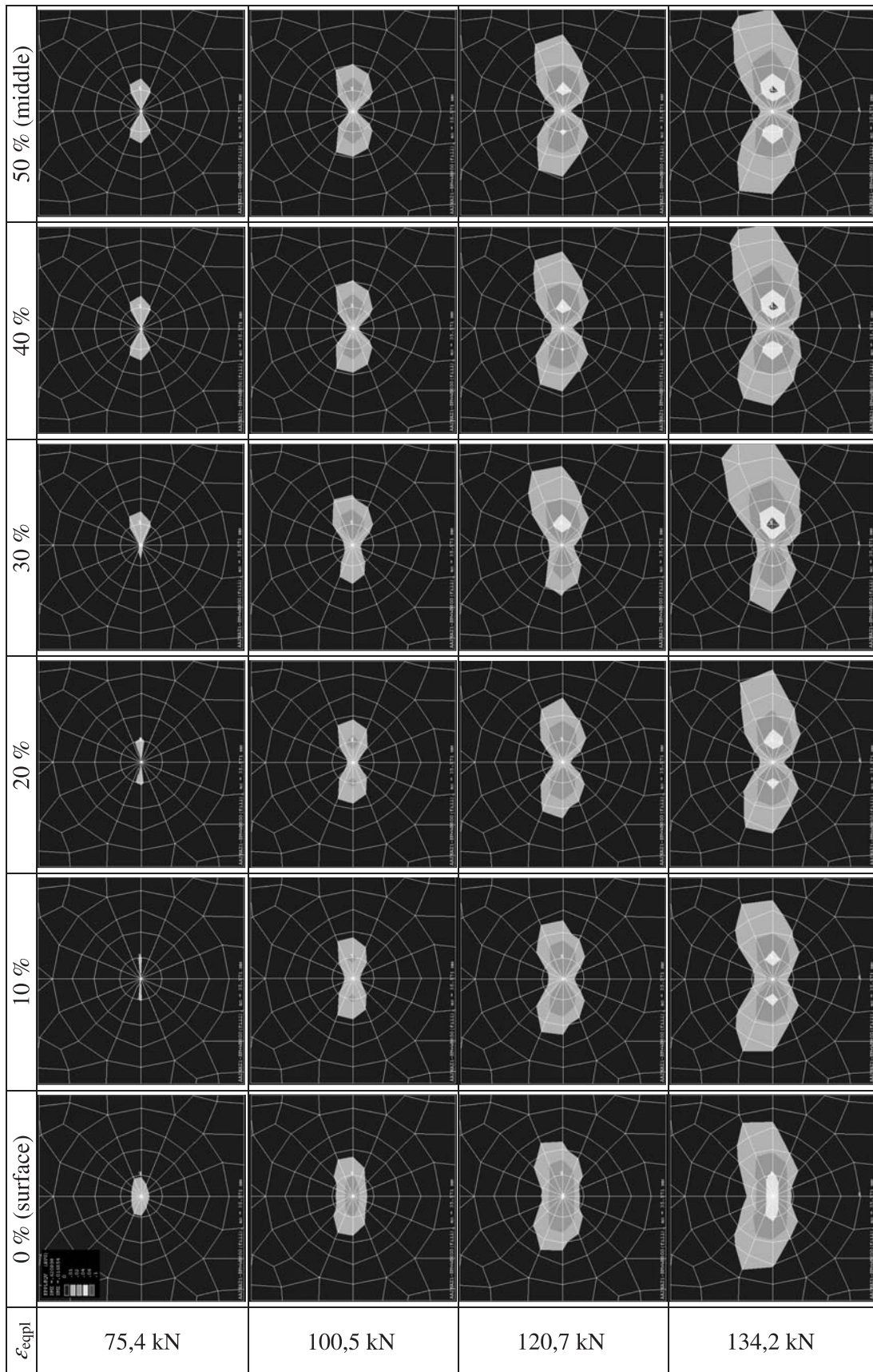**Slika 5:** F-CTOD (δ_5)-diagram

Figure 6: Stress and strain fields near the crack tip at the moment of crack initiation (F = 134.2 kN)
Slika 6: Polje napetosti in deformacije v bližini konice razpoke v trenutku začetka razpoke (F = 134,2 kN)

Figure 7: Spreading of the equivalent plastic strain fields in the vicinity of the crack front as the loading increases
Slika 7: Razširitev ekvivalentnega polja plastične deformacije v bližini vrha razpoke pri povečanju obremenitve

6 REFERENCES

[1] G. Çam, S. Erim, Ç. Yeni, M. Koçak, Determination of mechanical and fracture properties of laser beam welded steel joints, *Welding Research*, *Welding Research Supplement* (**1999**), 193–201

[2] W. Pompe, H. Worch, M. Epple, W. Friess, M. Gelinsky, P. Greil, K. Hempel, D. Scharnweber, K. Schulte, Functionally graded materials for biomedical applications, Materials Science and Engineering A, 362 (**2003**) 1–2, 40–60

[3] Y.-J. Kim, M. Koçak, R. Ainsworth, U. Zerbst, SINTAP defect assessment procedure for strength mismatched structures, *Engineering Fracture Mechanics*, 67 (**2000**), 529–546

[4] Y.-J. Kim, K.-H. Schwalbe, Compendium of yield load solutions for strength mis-matched DE(T), SE(B) and C(T) specimens, *Engineering Fracture Mechanics,* 68 (**2001**), 1137–1151

[5] F. Matejicek, N. Gubeljak, D. Kozak, M. Koçak, Stress-strain state at the vicinity of the crack tip in strength mis-match welded joint, *Proceedings of the 13th European Conference on Fracture on CD Rom*, San Sebastian, 2000, Paper reference 1U.6

[6] Y. Chen, J. D. Lee, M. S. Oskard, A. Eskandarian, Meshless analysis of crack propagation in multiphase material, Proceedings of the XI. International Conference on Fracture on CD Rom, Turin, 2005

[7] N. Gubeljak, D. Semenski, N. Drvar, J. Predan, D. Kozak, M. Oblak, Object grating method application in strain determination on CTOD tests, *Strain*, 42 (**2006**), 81–87

[8] D. Kozak, J. Vojvodič Tuma, N. Gubeljak, D. Semenski, Factors influencing the yielding constraint for cracked welded components, *Mater. Tehnol.*, 39 (**2005**), 29–36

[9] ANSYS 10.0 Release, User's manual, 2005