Available online at www.sciencedirect.com
ScienceDirect
Procedia Structural Integrity 2 (2016) 3280–3287
Structural Integrity Procedia
www.elsevier.com/locate/procedia

21st European Conference on Fracture, ECF21, 20-24 June 2016, Catania, Italy

Fatigue crack nucleation and propagation in aluminum alloy plates with cold expanded holes

P. Yasniy, S. Glado, V. Iasnii

Ternopil Ivan Pul'uj National Technical University, Ruska street, 56, Ternopil, 46001, Ukraine

---

Abstract

Analysis of the literature shows that in some cases existing technological methods of processing, including cold expansion, are the effective means to improve fatigue durability of structural elements with holes. The effect of cold expansion (1−3 %) on the stress state and fatigue durability of aluminum plates with functional holes under uniaxial cyclic loading was studied. The fatigue crack growth in the plates with a thickness t = 6 mm and width of 60 mm with a central hole diameter of 8 mm and 10 mm of aluminum alloy D16chT (2024-T3) was investigated. Fatigue test was carried out under constant amplitude loading at stress ratio $R = \sigma_{\min}/\sigma_{\max} = 0$ and room temperature. Here $\sigma_{\min}, \sigma_{\max}$ are the minimum and maximum stresses, respectively. The stress range was 147 MPa, loading frequency was 25 Hz. The mechanical properties of the alloy at room temperature were: yield strength $\sigma_Y = 300$ MPa, tensile strength $\sigma_U = 430$ MPa. For all tested specimens with cold expanded holes the cracks initiation from the edges of holes on the entrance faces mandrel and from middle part for plain hole. Using the finite element method, the distribution of local residual stresses in the vicinity of the expanded hole was calculated. For specimens with cold expanded holes the least compressive stresses were near the entrance face and the largest were in the middle of the hole and near the exit face. With the increase of the cold expansion hole, the difference in values of compressive residual stress along the plate thickness is reduced. The width zone of residual compressive stresses increase with the increase of cold expansion. The dependencies of the number of cycles to crack initiation in aluminum specimens on the local maximum stress and local stresses range in the vicinity of surface hole were obtained. Cold expansion degree of 1% increases the lifetime of the plates to the initiation of fatigue crack length of 0.25 mm in 1.5-3 times as compared with plane plates. A similar dependence is observed for cold expansion of 2%. With further increase of cold expansion degree up to 3% the lifetime to fatigue crack initiation is increased in 7−10 times as compared with plane plate. By using the finite element method, the distributions of local stress range, maximum and minimum local stress near the hole depending on the number of loading cycles and cold expansion were built. In the middle section of the specimen the local stress ratio in the second half-cycle of load decrease with increasing of distance from the edge of the hole and with the increase of cold expansion. The lowest value of local stress ratio was obtained at cold expansion degree of 3% and it is constant across thickness of plate.

Peer-review under responsibility of the Scientific Committee of ECF21.

Keywords: Alunimun alloy; cold expansion; mandrell; residual stress; fatigue crack.

Peer review under responsibility of the Scientific Committee of ECF21.
10.1016/j.prostr.2016.06.409

Nomenclature

i	cold expansion degree
R	stress ratio
$\sigma_{\min}$	minimum stress
$\sigma_{\max}$	maximum stress
σ_{app}	applied stress
σ_{res}	residual stress
σ_Y	yield strength
σ_U	tensile stress
N_f	fracture period
d_0	diameter of a hole before cold expansion
d_f	diameter of a hole after cold expansion
a	bore crack length
c_1	entrance surface crack length
c_2	exit surface crack length
$\Delta\sigma$	stress range

1. Introduction.

The problem of fatigue of materials and structures acquired special significance due to the rapid development of industries, such as aerospace, automotive and mechanical engineering. Requirements for the safe operation of structures are of particular importance for cyclic loading and high stresses.

In thin-wall construction elements, in particular aviation ones, fatigue cracks nucleates in stress concentration places. To increase endurance of such construction elements, various technological methods of hardening and creating compressive residual stress in concentration places are used. There are effective methods of plastic deformation, in particular cold expansion is a means of fatigue durability of structural elements with holes [Pasta (2007), Gopalakrishna et al. (2010), Yasniy and Glado (2014)].

Consecutive cold expansions reduce maximum tensile stress in 1.54…1.63 times in stringer with holes for petrol flowing comparatively with stringer with unstrained holes [Grebenikov et al. (2009)]. Constructive and technological parameters of cold expansion have been investigated and optimal angle of mandrel taper for improvement of geometry of forming hole and decrease of after cold expansion have been suggested [Voronko (2009)]. The influence of geometry of mandrel and degree of cold expansion on fatigue durability of plates in aluminum alloys 2024-T3 has been investigated [Gopalakrishna et al. (2010)]. It was revealed that the durability of plates is increased in 5.3 times after degree of cold expansion 5% comparatively with specimens without cold expansion.

It has been investigated [Larac et al. (2000)] that the fatigue crack growth rate in plates with cold expanded holes in aluminum alloys Al2024 and Al2650 was caused by higher stress opening of fatigue crack what is a result of compressive residual stresses. However, no information is provided about the influence of plastic deformation on relation of the stage of fatigue crack nucleation to general durability of construction elements with hardened holes of different diameters. Generally, most of investigations were done in the field of crack initiation or its propagation [Larac et al. (2000)]. The results of investigation of the influence of cold expansion and diameter of holes on stress distribution, fatigue crack nucleation and its growths under uniaxial loading of plates in D16chT aluminum alloy with central hole were described in this article.

---

* Corresponding author. Tel.: +38-0352-524-181; fax: +38-0352-254-983.
E-mail address: petroyasniy@gmail.com (P. Yasniy)

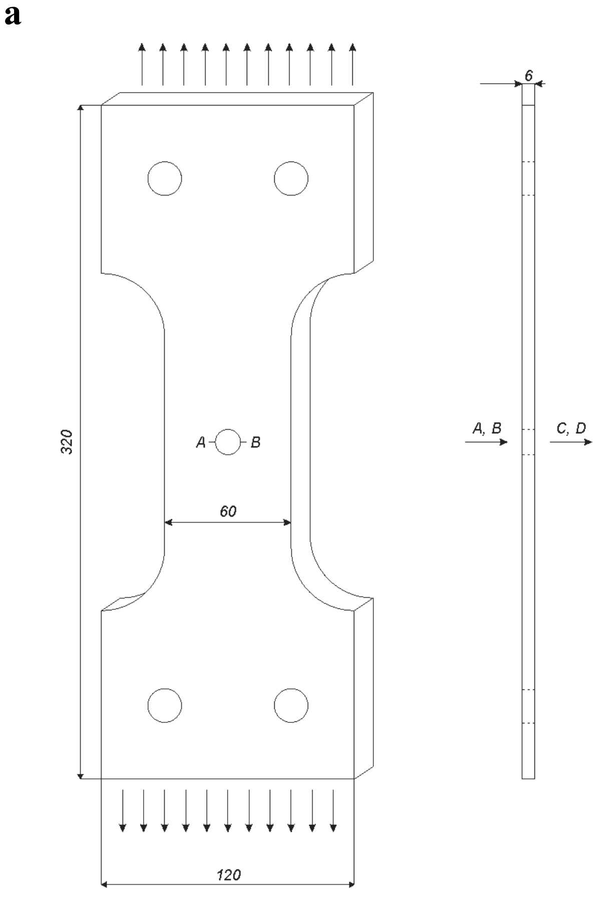
2. Experimental techniques.

Fatigue crack nucleation and growth in plates with 8 mm and 10 mm diameter central hole (Fig.1) in D16chT aluminum alloy of thickness $t = 6$ mm and width of 60 mm at stress ratio $R = \sigma_{\min} / \sigma_{\max} = 0$. Here $\sigma_{\min}, \sigma_{\max}$ are the minimum and maximum stresses, respectively. The stress range was $\Delta\sigma_{app} = 147$ MPa, load frequency – 25 Hz. Mechanical properties of alloy at room temperature: yield strength $\sigma_Y = 300$ MPa, tensile strength $\sigma_U = 430$ MPa. Crack initiation period was taken as number of load cycles when crack lengths on the surface was 0.25 mm ($N_{0.25}$), and the period of fatigue failure is regarded as the number of cycles for the crack reach a critical lengths (N_f). Fatigue crack initiation and growth were observed on the both surfaces of specimen by using of microscopes with accuracy 0.014 mm.

The plates with the diameter of hole 8 mm, 10 mm та 12 mm were subjected to cold expansion to create the compressive residual stresses using mandrels of the corresponding diameter [7]. The degree of cold expansion was calculated according to formula $i = \left| \left(d_f - d_0 \right) / d_0 \right| \cdot 100\%$, where d_0, d_f are diameter of a hole before and after cold expansion respectively.

Fatigue tested specimens with cold expanded holes have quarter-elliptic shape of crack. Initial fatigue crack usually nucleated from mandrel entrance face (A, B). When fatigue crack grew to the side of C, D, its sizes were characterized by parameters of length of surface cracks c_1 and c_2 (Fig. 1b) on entrance and exit faces, accordingly.

3. Results and discussion



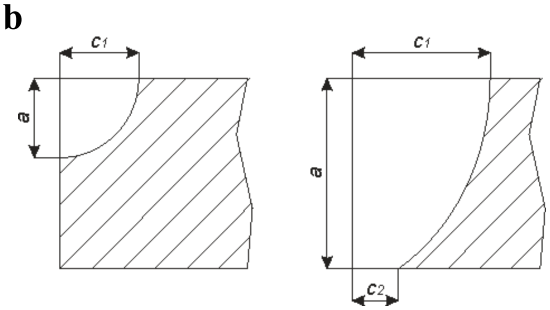


Fig. 1. Specimens for fatigue test: (a) dimension of specimen and direction of cold expansion (A and B – entrance face of mandrel, C and D – exit face of mandrel); (b) schematic crack extension (a – length of crack along thickness of specimen; c_1 – length of crack on entrance face of mandrel; c_2 – length of crack on exit face of mandrel)

Dependencies of surface fatigue cracks growth from 8 mm and 10 mm diameter holes to 5 mm length at cold expansion $i = 0\% \ldots 3\%$ were shown in Fig. 2. Maximum applied stress was $\sigma_{\max} = 0.49 \cdot \sigma_Y$. While cold expansion increases from 0% to 3%, curves of crack growth in plates with 8 mm diameter holes shift to the left. For cold expansion $i = 3\%$ crack growth stopped when it reached 0.43 mm for 8 mm diameter hole, and for 10 mm diameter (Fig. 2b) – fatigue crack at applied stress range $\Delta\sigma = 147$ MPa did not initiate.

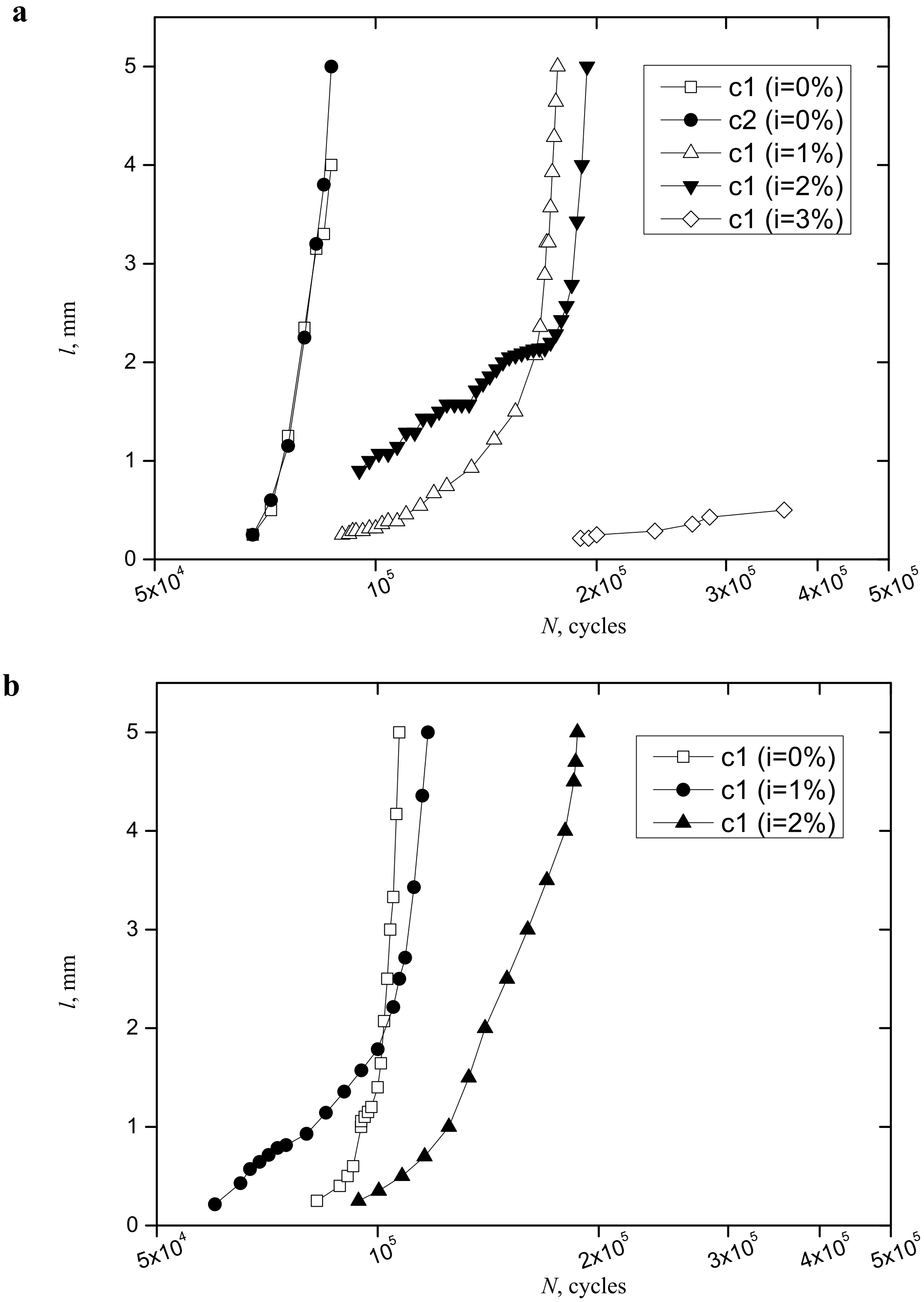


Fig. 2. Fatigue crack growth ($\Delta\sigma = 147$ MPa) in specimens with plain and cold expanded holes with diameter: (a) 8 mm; (b) 10 mm

For specimens of diameter 10 mm, fatigue crack was fixed on the surface at minimum number of loading cycles after cold expansion degree 1%. This was caused by the fact that in specimens without cold expansion hole, the crack nucleated and grew in the middle of a hole and then appeared on the side surfaces.

It is necessary to emphasize that in general, with increase of cold expansion degree the number of loading cycles to crack nucleation increase for specimens with 8 mm and 10 mm diameter holes.

The influence of cold expansion degree on the periods of initiation and propagation of fatigue cracks and total durability of plates with holes was investigated.

In Fig. 3a the dependencies of loading cycles for the crack initiation of a length of 0.25 mm and 0.5 mm on cold expansion degree has been shown. The total durability and periods of crack initiation of a length of 0.25 mm and 0.5 mm for plain and cold expanded holes are presented in Table 1 and in Fig. 3b.

Table 1. Periods of fatigue crack initiation and total durability for plate with plain and cold expanded holes at $\Delta\sigma = 147$ MPa

№	d_{final} , mm	*i*, %	$N_{0.25}$, cycles	$N_{0.5}$, cycles	N_f , cycles
1	8.03	0	37000	45000	94047
2	8.03	1.49	95000	113000	189907
3	8.02	2.37	72000	124000	189791
4	8.01	3.25	290000	–	$>10^6$
5	10.04	0	50000	55000	114223
6	10.02	1.1	58000	72000	126997
7	10.01	1.9	80000	122000	202925
8	10	3.2	370000	–	$>10^6$

Analyzing the results, we can make the conclusions that relative contribution of the crack initiation period into total durability at the given stress range $\Delta\sigma = 147$ MPa essentially depends on the cold expansion degree and meaning of criterion of "crack initiation". If we can take the 0.25 mm surface crack length as the criterion of crack initiation, then the relative period of fatigue crack initiation $N_{0,25}/N_f$ from 8 mm and 10 mm diameter holes decreases with increase of cold expansion from 0.29 to 0.5. There is an opposite character of the dependency of relative durability of plate with hole by criterion of crack initiation when as the criterion of crack nucleation was chosen the 0.5 mm surface crack length. With the increase of cold expansion degree for 8 mm and 10 mm diameter holes, $N_{0,5}/N_f$ increases from 0.48 for a plain hole till 0.65 for cold expansion degree 3%. It was caused by slowing of fatigue crack growth at the 3…5 mm distance from the surface of a hole as a result of compressive residual stress influence.

Stated above dependencies are among the determinative in choosing methodology and appropriate of diagnosis of defects in similar structural elements with stress concentrators.

For calculation of residual stress distribution near hole after cold expansion and also cyclic loading, the complex of nonlinear dynamics ANSYS Explicit Dynamics and model Steinberg Guinean Strength for description of true stress-strain curve of D16chT aluminum alloy [Steinberg et al. (1980)] were used. To determine residual stress near hole after different cold expansion degree with subsequent cyclic loading, the finite-element model of the plate quarter with central hole using element Solid 95 was built.

Stress state of a plate near cold expanded holes was analyzed according to residual stress after cold expansion σ_{res} ; maximum $\sigma_{yy\max}$ and minimum local stress $\sigma_{yy\min}$ at uniaxial cyclic loading; local stress range $\Delta\sigma_{yy}$.

The influence of the cold expansion on distribution of residual stress in D16chT aluminum alloy plate with holes of 8 mm and 10 mm diameter was described in the article [Yasnii et al. (2014)].

The distribution of local stress range $\Delta\sigma_{yy} = \sigma_{yy\max} - \sigma_{yy\min}$ and maximum and minimum stress near hole in the plane perpendicular to applied stress according to the number of loading cycles and cold expansion degree was obtained. Local stresses $\sigma_{yy\min}$ and $\sigma_{yy\max}$ were calculated taking into consideration residual stresses after cold expansion.

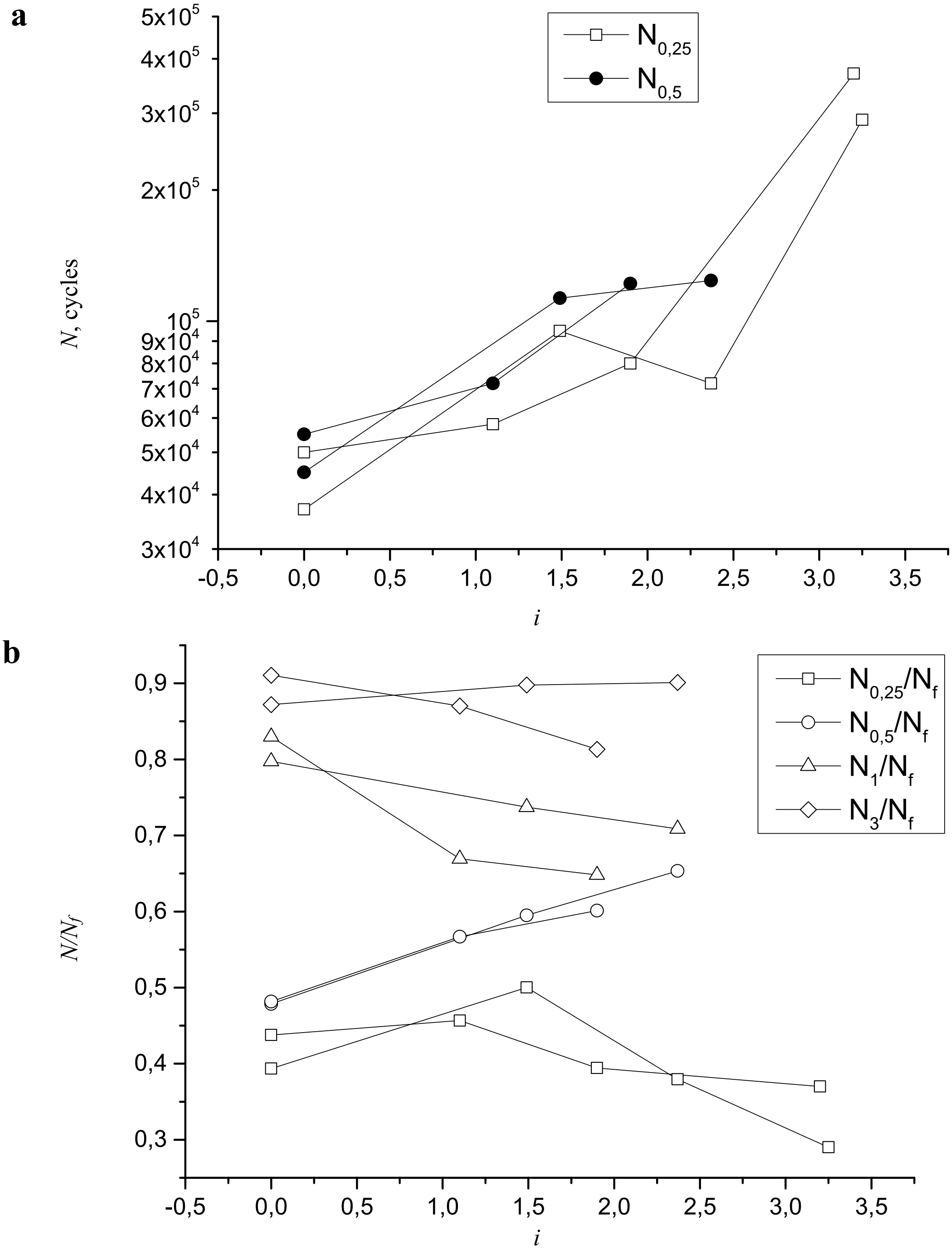


Fig. 3. Durability of aluminum plates ($\Delta\sigma = 147$ MPa): (a) fatigue crack initiation of a length of 0.25 mm, 0.5 mm; (b) relative period of fatigue crack initiation of a length of 0.25 mm, 0.5 mm, 1 mm and 3 mm

It was analyzed that local stresses $\sigma_{yy\min}$ and $\sigma_{yy\max}$ are already stabilized at the second half cycle of load. Therefore stress state was analyzed being limited only by the second half cycle of load.

In Fig. 4 the distribution of local stress range near the holes with diameter of 8 mm (Fig. 4a) and 10 mm (Fig. 4b) for the cold expansion 1%, 2%, 3% and without cold expansion for the second half cycle was shown. The distribution of local stress range on the surface of specimen from the entrance face has been calculated.

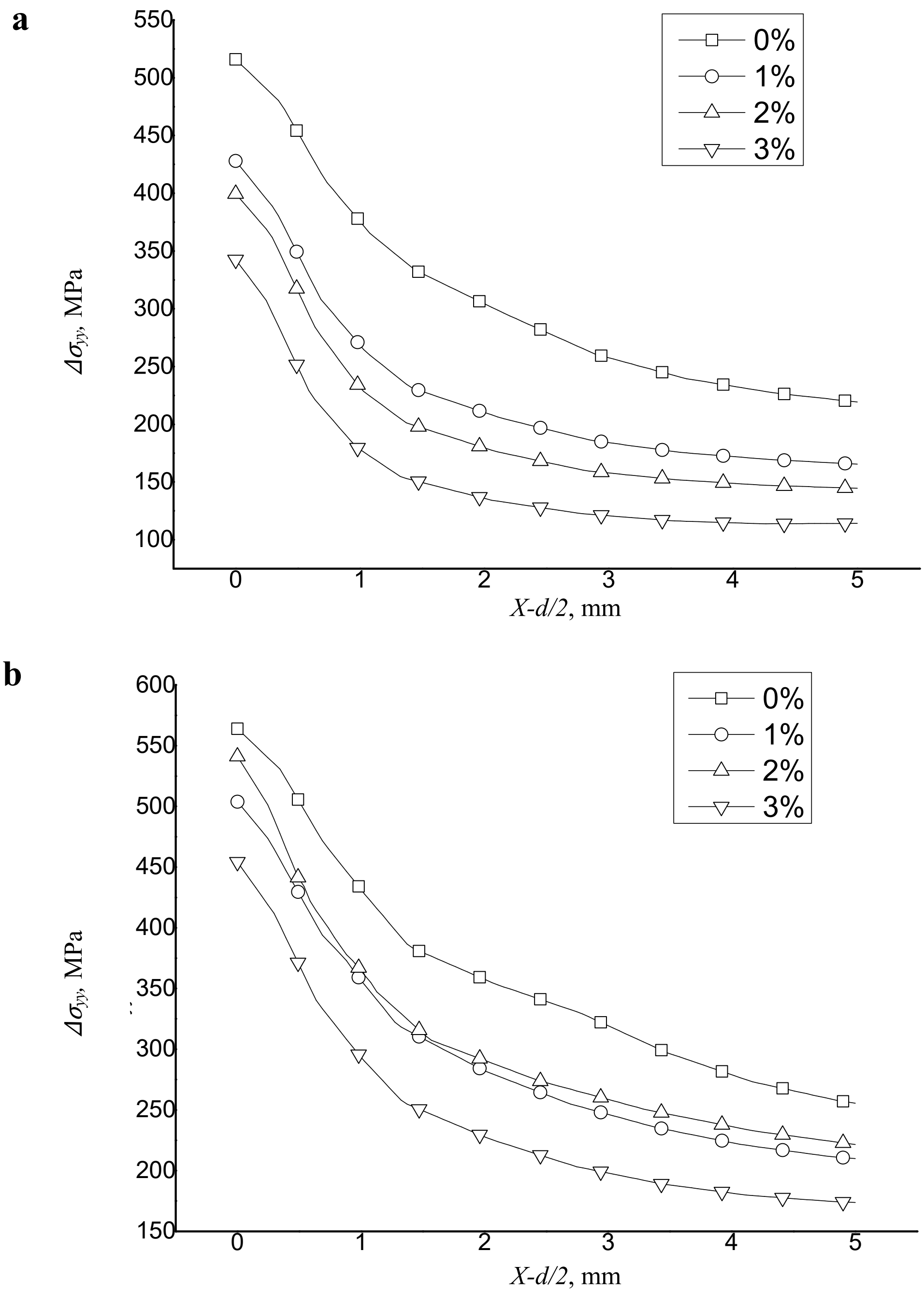


Fig. 4.Normal stress range distribution on the entrance face with plane and cold expanded holes at $\Delta\sigma = 147$ MPa with diameter: (a) 8 mm; (b) 10 mm

From the obtained results follows that the highest local stress range is in the middle part along the thickness of a hole without cold expansion. So crack nucleation and propagation in the middle part of specimen at uniaxial loading occurred during experimental investigations can be explained by this fact.

References

Pasta, S., 2007. Fatigue crack propagation from a cold-worked hole. Engineering Fracture Mechanics 74, 1525-1538.

Gopalakrishna, H. D., Narasimha Murthy, H. N., Krishna, M., 2010. Cold expansion of holes and resulting fatigue life enhancement and residual stresses in Al 2024 T3 alloy. Anexperimental study. Engng. Failure Analysis 17, 361–368.

Yasniy, P., Glado, S., 2014. Influence of cold expansion of holes on crack initiation and growth in aluminum alloy. Scientific Journal Of The Ternopil National Technical University 73, 7-17.

Grebenikov, A.G., Curve, G.A., Vasilevsky, E.T., Matvienko, V.A., Reznik, V.A., Gumennyy, A.M., Svetlichniy, S.P., Zmiev, I.P., 2009. Experimental study of the effect of sequential use cold expansion and compression on fatigue life stringers in the zone of holes for overflowing fuel. Public information and computer integrated technology 43, 54-64.

Voronko, V.V., 2009. High speed cold expansion of holes of aircraft structures. Public information and computer integrated technology 41, 213-226.

Lacarac, V., Smith, D.J., Pavier, M.J., Priest, M., 2000. Fatigue crack growth from plain and cold expanded holes in aluminium alloys. International Journal of Fatigue 22, 189-203.

Yasnii, P. V., Hlad'o, S. V., Skochylyas, V. V., Semenets', O. I., 2014. Formation of Residual Stresses in Plates with Functional Holes After Cold Expansion. Materials Science 50(6), 877-881.

Steinberg, D.J., Cochran, S.G., Guinan, M.W., 1980. A constitutive model for metals applicable at highstrain rate. Appl. Phys. 51(3), 1498-1504.