Multi-purpose fatigue sensor. Part 1. Uniaxial and multiaxial fatigue

M.V. Karuskevich, S.R. Ignatovich, T.P. Maslak
National Aviation University, Kiev, 03680, Ukraine

A. Menou
International Academy of Civil Aviation, Casablanca, Morocco

P.O. Maruschak
Ternopil National Ivan Pul'uj Technical University, Ternopil, 46001, Ukraine
Maruschak.tu.edu@gmail.com

S.V. Panin
Institute of Strength Physics and Materials Sciences SB RAS, Tomsk, 634055, Russia
National Research Tomsk Polytechnic University, Tomsk, 634050, Russia

F. Berto
University of Padova, Vicenza, 36100, Italy

ABSTRACT. The paper describes the key principles and results of preliminary experiments aimed at the development of new technique for the fatigue life prediction under conditions of biaxial cyclic tension. The foundations of the method were developed early by the numerous tests with monitoring the process of surface deformation relief formation, which is proved to be an indicator of accumulated fatigue damage under uniaxial fatigue. The employed phenomenon was early applied for the development of a family of uniaxial loading fatigue sensors. The formation of strain induced relief has been recently taken into consideration as a part of damage accumulation criteria under biaxial fatigue as well. The home-made testing machine has been designed to implement combined bending and torsion loading that simulates loads experienced by an aircraft wing skin. The experimental evidences on formation and evolution of the deformation relief revealed under conditions of combined loading, supports the proposed concept of biaxial fatigue sensor.

KEYWORDS. Defects; Fatigue sensors; Damage; Aviation.

Citation: Karuskevich, M.V., Ignatovich, S.R., Maslak, T.P., Menou, A., Maruschak, P.O., Panin, S.V., Berto, F., Multi-purpose fatigue sensor. Part 1. Uniaxial and multiaxial fatigue, Frattura ed Integrità Strutturale, 38 (2016) 198-204.

Received: 15.05.2016
Accepted: 20.06.2016
Published: 01.10.2016

INTRODUCTION

Being first emerged in aviation, Structural Health Monitoring (SHM) systems recently have been spread into the different areas of mechanical engineering applications. Among the highly responsible components of SHM systems, the fatigue sensor should be considered as a key one. The history of research and developments of metal-based fatigue sensors started together with awareness of the fatigue problem importance. Unfortunately, it should be stated that the practical application of metal fatigue sensors remains to be pretty limited even in the spheres were sensors are of high demand. The low level of industrial applications, to our mind is related to the poor scientific basis of many proposed approaches and designs in this area. To an even greater degree this problem is of crucial importance for multiaxial fatigue monitoring.

The multiaxial loading is the mostly spread mode for many engineering structures. The complexity of phenomena to develop there has led to numerous theories, models, experimental studies, etc. [1-5]. The papers [6-10] present some recent reviews and approaches for multiaxial fatigue and fracture problems. Being general ones for multiaxial fatigue analysis, these criteria might be classified into three groups, being based on fatigue damage parameter used, i.e. stress, strain and strain energy density criteria [11]. Each one was described mainly by the critical plane orientation. Critical plane concept usually applies different loading parameters within the critical plane whose orientation is determined by i) only shear loading parameters; ii) only normal loading parameters or sometimes iii) mixed loading parameters [12]. The variety of loading conditions gives rise to the development of new concepts, providing rather accurate prediction of the fatigue life. In some cases the unique properties of particular materials might favour a possibility for the prediction their service life. These approaches demand for the obtaining new experimental data. Experimental studies of multiaxial fatigue are based on testing specimens of rather complicated shape. The most commonly used specimens have the pipe shapes (similar to ones used in bulge test) as well as cross-shaped (cruciform) ones. In so doing, metal specimens were tested.

The available experimental data related to the multiaxial loading of aircraft structure are somehow unavailable. For example, the report on biaxial tests of aircraft component might be found in [10]. The data presented in the paper are the part of investigations aimed at development of the creation for accumulated fatigue damage assessment for structures subjected to multiaxial fatigue.

The monitoring of the process was performed with the use of computer aided optical technique based on observation of surface deformation relief of aircraft components made of cladded aluminium alloys [13-15]. Since the strain-induced relief results from localized plastic deformation this approach might be referred to as the strain criteria. Recently it has been suggested that the deformation relief might be as well taken into consideration within a criterion of the biaxial fatigue damage.

LOADS TO ACT ONTO AIRCRAFT IN FLIGHT AND ON THE GROUND

Aircraft structure is considered as a typical one being subjected to biaxial loading since it experiences the spectrum of loads in air and on the ground. Among them are: wind gusts, loads from airdrome unevenness, buffeting motor vibration, acoustic vibration, loads at maneuvers, pressurization, etc. The complexity of analytical and experimental estimation of aircraft components fatigue life is determined by the complexity of their loading patterns, i.e. by irregular (random) character of the loads sequence, multiaxial stress state, etc.

The fuselage skin is subjected to the simultaneous action of loadings coming from pressurization, bending and torsion. In the case of airwings the stresses caused by the combined action of bending and torsion are considered as dominant ones. These loads give rise to normal and tangent stresses to act in the bearing components (Fig. 1). In doing so, normal stresses are caused by the bending of the wing, while tangent ones result from the shear force and torque moment. The assessment of the accumulated fatigue damage can be performed analytically as well as by instrumental inspection. Both approaches need further improvement especially under multiaxial fatigue.

DEFORMATION RELIEF FORMATION UNDER UNIAXIAL FATIGUE

The aircraft skin is usually made of cladded aluminium (alclad) alloys (2024T3, 7075T6, etc.). The detailed description of the deformation relief nature, its evolution and methods for the analysis can be found in [13-15].

Let us point out some key aspects of the nondestructive methods aimed at the analysis of the strain-induced relief. The 2D–optical images of the latter were registered on aluminum alloy specimens under fatigue tests. In order to protect them against corrosion, sheets of aircraft alloys are often coated with a layer of pure aluminum (for instance, 2024T3) or with a layer of Al doped with 1.0 % of Zn (for instance, 7075T6). The depth of cladded layer is varied from 4 to 7 % of the total sheet thickness. Aluminum and some of its alloys which are used for the cladding must be persistent slip bands type materials.

Deformation relief is formed and develops on the surface of the aluminium cladded layer under cyclic loading. The relief consists of persistent slip bands, extrusions, intrusions, etc. The intensity of the relief formation is the function of the stress level, distribution of the stress near the stress concentrator and the number of cycles.

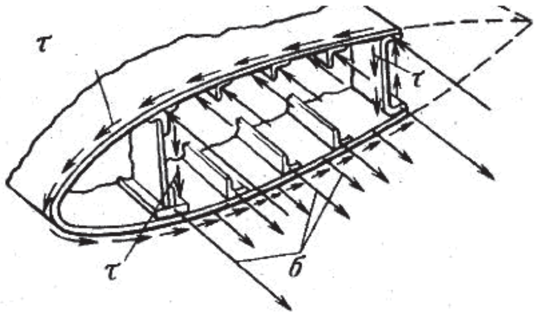


Figure 1: Stresses in the wing components.

In order to induce stress localization with further fracture flat specimens with a central hole were tested under cyclic loading. Tests were performed under wide spectrum of loads. The procedure of accumulated fatigue damage estimation used in the study included the analysis of digital optical images of the deformation relief registered with the use of a light microscope. The deformation relief was numerically estimated with the use of damage parameter *D*. It is calculated as the ratio of the surface area covered with extrusion/intrusion structures over the total area under analysis (observation). Usually the round shape region with the size of 0.3 mm located near the stress concentrator was analyzed. The characteristic dependence of the parameter *D* was a function of number of loading cycles. Corresponding images of the strain-induced relief under fatigue tests are shown in Fig. 2. It should be noticed that besides the damage parameter *D*, the fractal dimension of the deformation relief clasters were successfully employed for the analysis.

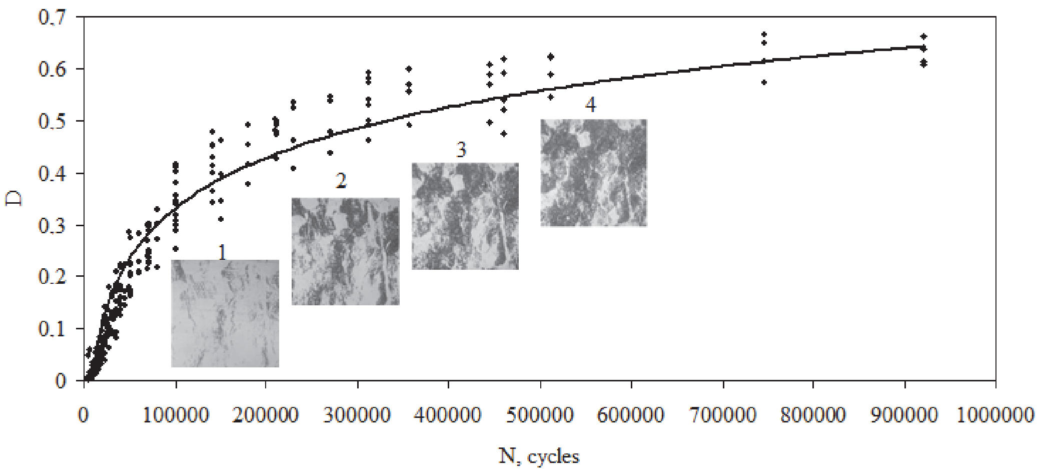


Figure 2: Evolution of the deformation relief under fatigue testing.

DEFORMATION RELIEF EXPECTED UNDER BIAXIAL FATIGUE

It is known that morphology of the deformation relief is determined by the dislocation processes to develop in surface layer. In single crystals one might distinguish preferential gliding (slip) planes. Within them the preferential crystallographic directions of dislocation motion might be pointed out (slip directions). The set of slip planes and

directions constitutes slip systems. In doing so, dislocations move towards particular directions of planes as the response to shear stresses applied along them.
For aluminium, which belongs to the metals with FCC (face centered cubic) lattice the dislocation movement occurs mainly within planes {111} along the direction [110]. The strain hardening, as well as process of plastic deformation in general, depends on the number of actuated slip systems. These, in turn, depend on the level of the resolved shear stress. From this, the number of actuated slip systems depends on the normal stress σy as well as crystallographic orientations. For example, at the loading axis orientation of [011] the total number of equally loaded octahedral slip planes is equal to 2, while for the [001] orientation they make 4.
The development of plastic deformation and fatigue processes in polycrystalline metals is more complicated phenomenon. The deformation pattern of a grain there depend on many characteristics, for examples, the size, shape and crystallographic orientation of the grain, the presence of impurities, etc. The straining in neighbouring grains in polycrystalline metals must be compatible in order to maintain continuity and cohesiveness.
Von Mises [16] first showed that a minimum number of active independent slip systems for strain compatibility are equal to five. Taylor then suggested [17] that among them only those become active which is require by the least work. Because of multiple slip system actuations, polycrystals do not exhibit a stage of easy glide. Under the biaxial fatigue, apparently, the additional component of loading, shear or tension/compression increases the number of actuated slip systems or at least alters the order of their involvement.

EXPERIMENTAL SIMULATION OF THE WING SKIN BEHAVIOR UNDER BIAXIAL LOADING

Since the amount of available experimental testing data is very limited it calls for obtaining new original experimental results. Commercial biaxial testing systems are complex, expensive, and hence relatively scarce. For this reason the special homemade machine has been designed. It makes possible to investigate some regularities of the fatigue accumulation process. The scheme of the combined "bending-torsion" machine is presented in Fig. 3.

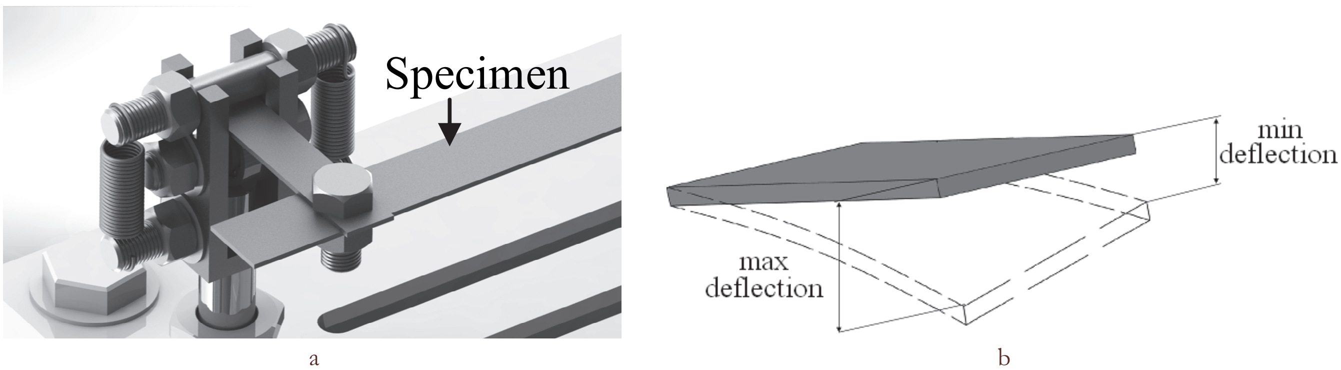


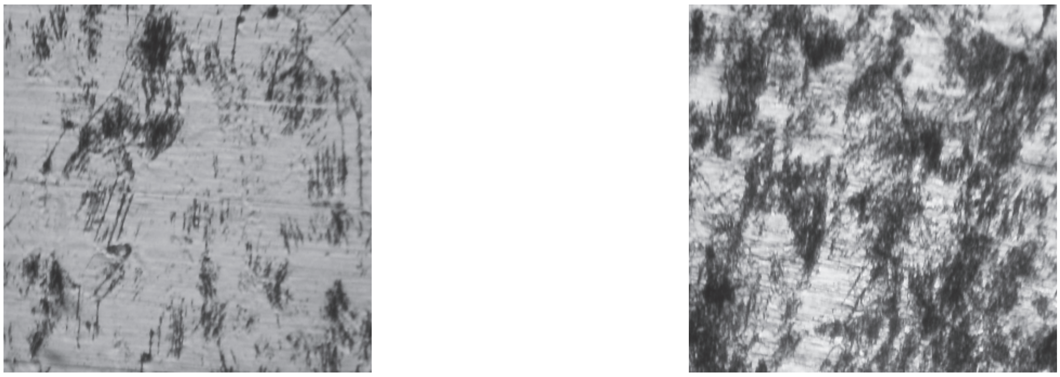
Figure 3: The scheme of the loading: a- specimen end fixed in the loading mechanism; b - scheme of combined deformation of the specimen.

The simplified design of machine does not provide full spectrum of combinations on torsion and bending components. Nevertheless, available regimes allow simulating the stress-strain state in the wing skin components. Specimens were made of Al clad alloy D16AT (2024T3) widely used in Ukrainian aviation industry, covered by the layer of pure aluminium. Dimensions of the rectangular plata shape specimen with 1 mm diameter central hole (as a stress concentrator where the surface relief was observed) made 140 × 10 × 1.0 mm. Normal stresses from the bending moment are determined at the gauge length of the specimen being a function of its deflection. Shear stresses are determined by the torque moment, which depends on the displacement of the torsion lever and bending stiffness of the specimen.

Comparison of the surface deformation relief formed under uniaxial and biaxial loading

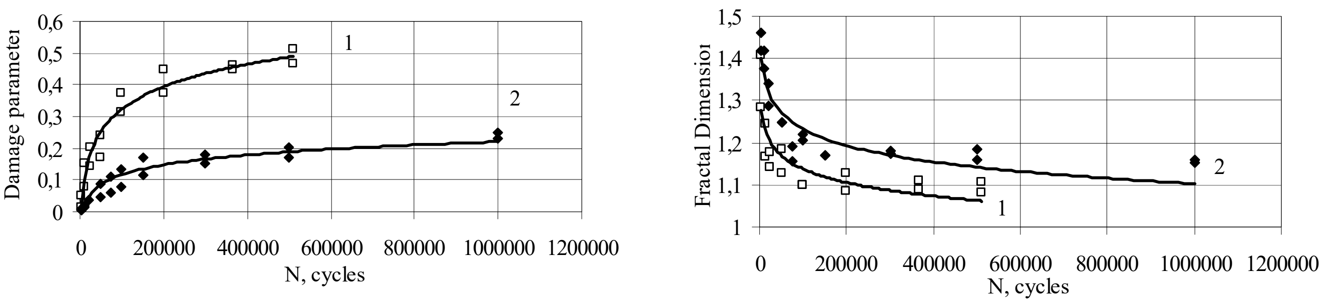
The deformation relief monitoring was conducted at the points located to the left and to the right from the stress concentrator. The stresses were determined with the use of the common formulas of the strength of materials. In doing so, the stress in the inspected cross section under the bending was equal to σ_{max} = 107.8 MPa. Under the combined

loading the tension stress made σ_{max} = 108 MPa while the shear stress component in the inspected area was equal to τ = 85 MPa.
Let us compare the pattern of strain induced relief to form under the combined loading with one being developed under applying of the normal stresses. Fig. 4 shows typical optical images of the deformation relief being formed under the uniaxial and biaxial loadings.



a b

Figure 4: Deformation relief formed under bending (a) and under biaxial loading (b); N=500 000 cycles.



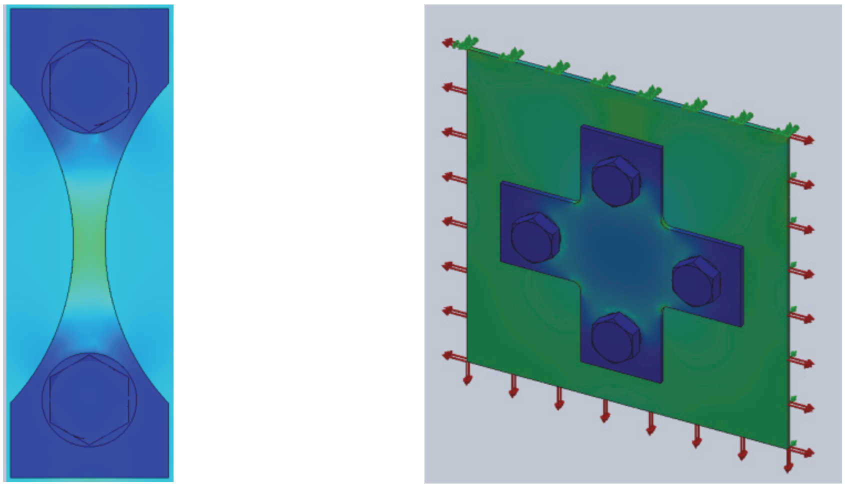
a b

Figure 5: The evolution of the deformation relief, estimated through calculation of damage parameter D (a) and fractal dimention D_p/s (b): 1-uniaxial loading; 2-biaxial loading.

All photos were taken at the magnification of ×300. The number of cycles prior to failure of the specimen under bending made 1 450 000 cycles. The specimen subjected to the combined biaxial loading has failured after applying of 512 000 cycles.
Fig. 5 shows the diagram that characterizes evolution of the deformation relief theough the damage parameter D as well as fractal dimention Dp/s. Procedures of their calculations were described in [6]. It was experimentally revealed that under uniaxial tests the ultimate value of the parameter D does not exceed the range 0,2 - 0,25. At the same time under combined biaxial loading it can reach significantly higher values. In doing so, in the current test the ultimate value of D was equal to 0,5. The substantial difference was found in the variation of value of the fractal dimension Dp/s.
The main reason for the increase of the ultimate intensity of the strain induced relief formation is activating of additional slip systems due to the action of torsion and associated shear stresses [18]. Monotonic character of the deformation relief evolution calls for the possibility to monitor fatigue damage by the couple of the parameters employed at evaluating the deformation relief both under uniaxial and biaxial loadings.

Prospects of the developoment multiaxial fatigue criteria based on deformation relief parameters

It is known, that currently used multiaxial fatigue criteria are aimed at the "reduction" of the complex multiaxial loading to an equivalent uniaxial one. Experimental results presented in the paper as well as studies previously carried out on the strain-induced relief formation have proved the possibility to monitor damage by calculating the parameters of deformation relief, Fig. 6.



a b

Figure 6: Sensors for fatigue monitoring: a) uniaxial fatigue; b) biaxial fatigue.

It is expected that the detailed testing towards these directions will make possible to develop new multiaxial fatigue criteria, being based on the concept of equivalent deformation relief. In concern of practical applications both techniques are of importance: i) direct diagnostic of persistent slip bands; ii) application of fatigue sensors. The latter might be based on the principles proposed for the uniaxial loading, except the design of the sensor shown at the scheme (Fig. 6,b).
Another important problem there is optimization of the sensitivity in concern of real loading conditions. In this sense the geometry of the gauge (sensor) is to be changed. The FE method looks very promising for solving this problem as well.

CONCLUSION

Aircraft structure is very susceptible to the action of fluctuating loading. Many components of modern planes are subjected to the multiaxial fatigue. The presented experimental results are aimed at proving the possibility to monitor accumulated biaxial fatigue by the parameters of the surface strain induced relief.
It might be implemented through the direct inspection of some airplane components or by application of fatigue sensors. Both approaches rely on the phenomenon of formation and evolution of the deformation relief, i.e. conglomerates of persistent slip bands, extrusions and intrusions, etc. Further research activity will be directed towards the establishing the relationships between the deformation relief intensity under the uniaxial and multiaxial loading in order to develop the concept of equivalent damage by criteria of equivalent surface relief.
Basic relationships of relief parameters evolution during the cyclic uniaxial and multiaxial loading have been established.

REFERENCES

[1] Pan, W.-F., Hung, C.-Y., Chen, L.-L., Fatigue life estimation under multiaxial loadings, Int. J. of Fatigue, 21 (1999) 3-10. DOI:10.1016/S0142-1123(98)00050-4.
[2] Carpinteri, A., Spagnoli, A., Multiaxial high-cycle fatigue criterion for hard metals. Int. J. of Fatigue 23 (2001) 135-145. DOI:10.1016/S0142-1123(00)00075-X.
[3] Papadopoulos, I.V., Long life fatigue under multiaxial loading. Int. J. of Fatigue 23 (2001) 839-849. DOI:10.1016/S0142-1123(01)00059-7.
[4] Jiang, Y., A fatigue criterion for general multiaxial loading, Fatigue Fract. Eng. Mater. Struct., 23 (2000) 19-32. DOI: 10.1046/j.1460-2695.2000.00247.x.
[5] Wang, Y.-Y., Yao, W.-X., Evaluation and comparison of several multiaxial fatigue criteria Int. J. of Fatigue, 26 (2004) 17-25. DOI:10.1016/S0142-1123(03)00110-5.
[6] Karolczuk, A., Macha, E., A review of critical plane orientations in multiaxial criteria of metallic materials, Int. J. of Fracture, 134 (2005) 267-304. DOI:10.1007/s10704-005-1088-2.

[7] Susmel, L., Estimating fatigue lifetime of steel weldments locally damaged by variable amplitude multiaxial stress fields, Int. J. of Fatigue, 32 (2010) 1057-1080. DOI:10.1016/j.ijfatigue.2009.12.004.
[8] Ince, A., Glinka, G., Innovative computational modeling of multiaxial fatigue analysis for notched components, Int. J. of Fatigue, 82 (2016) 134-145. DOI:10.1016/j.ijfatigue.2015.03.019.
[9] Ince, A., A novel technique for multiaxial fatigue modelling of ground vehicle notched components, Int. J. of Vehicle Design, 67 (2015) 294-313. DOI:10.1504/IJVD.2015.069486.
[10] Uniaxial and Biaxial Tests on Riveted Fuselage Lap Joint Specimens, U.S. Department of Transportation Federal Aviation Administration, DOT/FAA/AR-98/33, Final Report, October 1998.
[11] Berto, F., Lazzarin, P., Fatigue strength of structural components under multi-axial loading in terms of local energy density averaged on a control volume, Int. J. of Fatigue, 33 (2011) 1055-1065. DOI:10.1016/j.ijfatigue.2010.11.019.
[12] Glinka, G., Shen, G., Plumtree, A., A multiaxial fatigue strain energy density parameter related to the critical fracture plane, Fatigue & Fracture of Engineering Materials & Structures, 18 (1995), 37-46. DOI:10.1111/j.1460-2695.1995.tb00140.x.
[13] Zasimchuk, E.E., Radchenco, A.I., Karuskevich, M.V., Single-crystals as an indicator of fatigue damage, Fatigue & Fracture of Engineering Materials & Structures, 15 (1992), 1281-1283. DOI:10.1111/j.1460-2695.1992.tb01263.x
[14] Karuskevich, M., Karuskevich, O., Maslak, T., Schepak, S., Extrusion/intrusion structures as quantitative indicators of accumulated fatigue damage, International Journal of Fatigue, 39 (2012) 116–121. DOI:10.1016/j.ijfatigue.2011.02.007.
[15] Petrasek, M., Ignatovich, S., Karuskevich, M., Maslak, T., Surface of metal as an indicator of fatigue damage, Adv. in Military Tech., 8 (2013) 83-91.
[16] Von Mises, R., Mechanik der plastischen formanderung von kristallen, Z. Angew. Math. Mech., 8 (1928) 161-185.
[17] Taylor, G.I., Plastic strain in metals, J. Inst. Met., 62 (1938) 307-324.
[18] Gliha, V., Vuherer, T., Maruschak, P., Yasniy, O., Bishchak, R., Parameters affecting the fatigue strength of welds, Proc. of Int. conference "In-Service Damage of Materials, its Diagnostics and Prediction", TSTU, (2009) 154-162.