Periodica Polytechnica
Mechanical Engineering

Crack Closure Detection Using Photometrical Analysis

59(3), pp. 114-119, 2015
DOI: 10.3311/PPme.7893
Creative Commons Attribution

Alexey Savkin[1], Artem Andronik[1*], Ravishankar Abhilash[2]

RESEARCH ARTICLE

Received 07 January 2015; accepted after revision 15 April 2015

Abstract

Three tests using photometrical analysis were completed for crack closure estimation and covered at present paper. Constant and variable amplitude loading cases are both analyzed. Inadequacy of contemporary crack closure estimation models to explain results of the simple tests is shown. Hysteresis loops are given occurring due to various material reactions on tension and compression and specifying displacement of material close to crack tip.

Keywords

Photometrical analysis, energetical approach, crack closure, hysteresis loop, variable amplitude loading

[1] Strength of Materials Department, Automobile Faculty,
Volgograd State Technical University,
400005 Volgograd, Lenina st. 28, Russia

[2] Department of Software Applications,
BiSS-ITW, 41A, 1st Cross, AECS Layout, RMV II stage, Bangalore, India

[*] Corresponding author, e-mail: tank_leclerc@mail.ru

1 Introduction

In the early 1970 Elber observed [1] that when the remotely applied load is tensile the surfaces of fatigue cracks contact each other and do not open until other, more sufficient tensile load. Thereafter the researcher developed crack closure theory in an attempt to describe this phenomenon. He assumed that even at partial crack closure the crack growth is absolutely impossible (Fig. 1). Today crack closure models are in use for fatigue durability prediction under variable amplitude loading along with plasticity models near crack tip and statistical models.

Durability estimation under variable amplitude loading considers load interaction, and, specifically, such effects as crack tip blunting, inducing of residual stresses near crack tip and crack closure effect. Definition of the first of two effects is a well-run procedure while quantification of closure is a still debatable topic. Clear method for crack closure estimation under constant amplitude loading is not applicable for variable amplitude loading and every new loading history becomes a problem for researcher in the first instance [2]. Some scientists see advance in creating of complex and, in some degree, "speculative" crack closure models based on finite-elemental analysis [3]. Such models usually interpret unexpected result of experimental durability as consequence of unconsidered crack closure alteration, though it leads to crack closure overestimation to the point when result cannot be reasonably explained. In view of such approach to modelling it seems necessary to complete more experimental investigations on crack closure. At present work an experimental approach for crack closure estimation using photometrical approach is undertaken. This method proposes to compare results from crack opening displacement transducer (COD) and data image correlation (DIC) via software based on photographic images and current loading on specimen.

2 Procedure of results processing and abbreviations

Point set $\{P_i; t_i; \Delta l_i\}$, where P_i is load value and Δl_i is vertical displacement averaged by area at time moment t_i, is a usual desirable test result using photometrical technique. Relationship between P_i and Δl_i is almost directly proportional and approximation by least square technique (LST) in linear formulation is necessary to define that relationship. If $x_i=\Delta l_i$ and $y_i=P_i$, then $y=kx+b$ in linear view and sought factor may be found by formula:

$$k=\frac{n\cdot\sum_{i=1}^{n}x_iy_i-\sum_{i=1}^{n}x_i\sum_{i=1}^{n}y_i}{n\cdot\sum_{i=1}^{n}x_i^2-\left(\sum_{i=1}^{n}x_i\right)^2}, \quad (1)$$

where n – number of points.

Let us denote the relationship Δl_i-$(P_i$-$b)/k$ as Δh_i. In this case point set $\{\Delta h_i;\ P_i\}$ becomes interesting because it allows crack closure estimation. Comparison of DIC and COD results looks rational. Let us denote the vertical displacement of material close to crack tip defined using COD as Δc_i. Then denote the relationship Δc_i-$(P_i$-$b)/k$ as Δm_i. All these values will be used in crack closure estimation below.

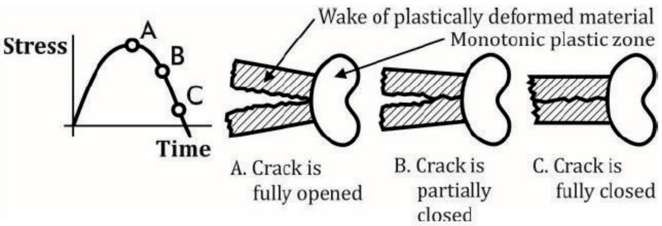

Fig. 1 Crack closure phenomenon

3 Experiments

3.1 Constant amplitude loading

It was decided to complete constant amplitude loading of C(T) specimens with 5 mm thickness made of aluminum alloy 2024-T3 (Fig. 2a). Thickness of specimen is less than standard and it allows decreasing of specimen region which undergoes plane strain state. Tests are performed on servohydraulic test machine BiSS Nano 5 kN [4] in the laboratory BiSS Labs (Bangalore, India). Loading and crack size estimations are completed using commercial software BiSS TestBuilder.

Side face of the specimen is inked by instant spray paint Crayons for pattern image creation for DIC. The DIC in-house software is developed in BiSS-ITW and it is used for strain calculation based on displacement of probe dots. Analyzed region is spaced Δa_s=0.25 mm apart from visible crack tip at maximal load P_{max} and the region is a square area of side a_e=0.25 mm (Fig. 2b).

After precracking (P_{max}=2 kN, R=0.1) till initial crack size a_0=17 mm the specimen undergoes constant amplitude loading with load frequency F=10^{-2} Hz (Fig. 2c), represented by three same cycles (P_{max}=4.5 kN, R=0), following each other. During the test side face of the specimen is snapshot by high-speed camera Nikon FASTNEC TS3. Shooting frequency is F_{DAQ}=0.25 Hz.

Plots P-Δh are obtained as test result (Fig. 2d) and they have hysteresis loop shape. The loops are smooth and well perceptible, thus approximation is not required. The regions of loops corresponding to load ascending and descending are almost parallel. The regions of loops close to P_{max} where deviation from parallelism is typical may be described via model of material memory proposed by Massing and the regions of loops close to P_{min} – by crack closure phenomenon: those are exclusions [3]. In such a manner, it may be concluded that in current test the closure (opening) load level is not higher than P_{op}=1.5 kN ($P_{op}/P_{max}\leq$0.33) and it does not correspond to Elber formula [1], or Shijve formula [5], or even Newman formula [6], the expressions are presented below correspondingly:

$$\frac{P_{op}}{P_{\max}}=0.5+0.1R+0.4R^2, \quad (2)$$

$$\frac{P_{op}}{P_{\max}}=0.45+0.22R+0.21R^2+0.12R^3, \quad (3)$$

$$\begin{cases}\dfrac{P_{op}}{P_{\max}}=\begin{bmatrix}R\geq 0\Rightarrow \max(R, A_0+A_1R+A_2R^2+A_3R^3);\\ -2\leq R<0\Rightarrow A_0+A_1R;\end{bmatrix}\\ A_0=\left(0.825-0.34\alpha+0.05\alpha^2\right)\left(\cos\left(\dfrac{\pi\cdot S_{\max}}{2\sigma_y}\right)\right)^{\frac{1}{\alpha}};\\ A_1=\left(0.415-0.071\alpha\right)\dfrac{S_{\max}}{\sigma_y};\\ A_2=1-A_0-A_1-A_3;\\ A_3=2A_0+A_1-1;\end{cases} \quad (4)$$

where

S_{max} – maximal cyclic stress;

σ_y – yield limit;

α – factor of plane stress / strain state.

Here and below by closure load level is meant a first moment of discernible partial crack closure (Fig. 1).

It must be noted that Newman formula is in use in Forman-Mettu crack growth model which is embedded in NASGRO application and frequently used in aerospace field. Results of the current test leave validity of the model in doubt.

However received plots P-Δh are similar to those which were obtained earlier by Sunder using laser interferometry (Fig. 2e). Besides the relationship P_{op}/P_{max} = 0.3…0.4 was found in his test with overloads and it corresponds to the results of current work. Photometry method is cheaper than laser interferometry. Basing on loops shape it may be concluded that given procedure has good repeatability for constant amplitude loading.

3.2 Variable amplitude loading in tension

After constant amplitude loading test it was decided to complete variable amplitude loading in tension according to the procedure given above. After precracking (P_{max}=2 kN, R=0.1) till

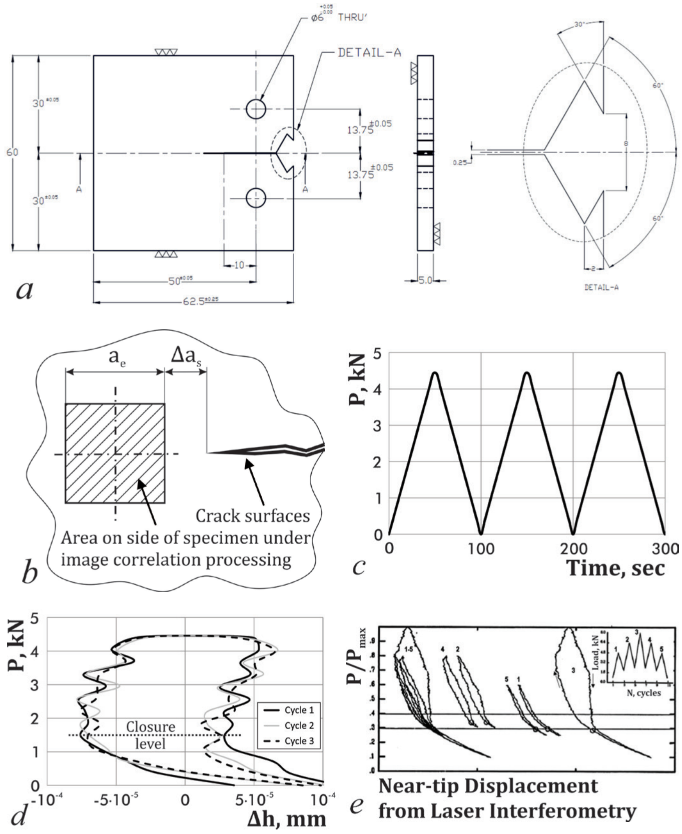

Fig. 2 a - geometry of C(T) specimen; b - specimen area under data image correlation analysis; c – constant amplitude loading; d - displacement close to crack tip by DIC; e - displacement close to crack tip by laser interferometry obtained by Sunder

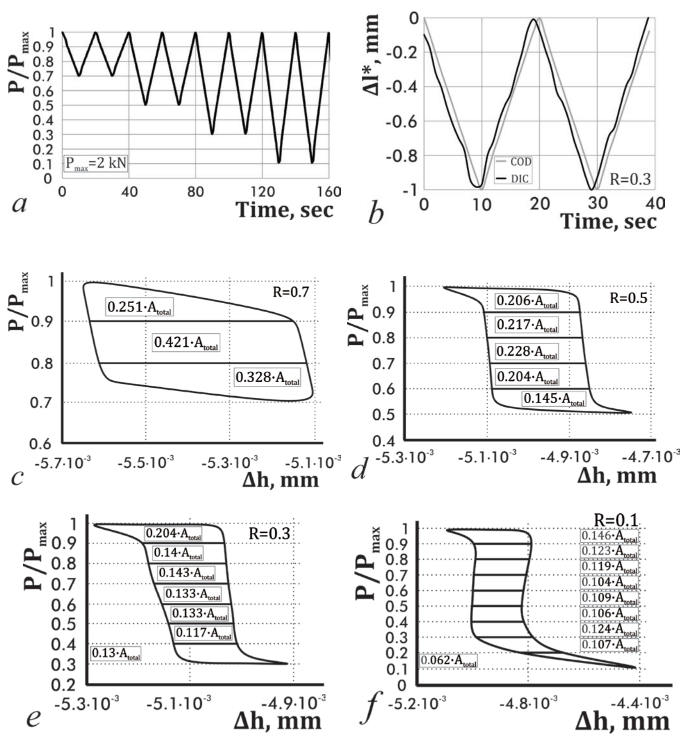

Fig. 3 a - variable amplitude loading in tension; b - comparison of displacements close to crack tip by COD and DIC; c – f – hysteresis loops describing displacement close crack tip as reaction on variable amplitude loading in tension.

initial crack size a_0=20 mm the specimen undergoes variable amplitude loading with load frequency $F=5\cdot10^{-2}$ Hz (Fig. 3a), represented by four pairs of cycles (P_{max}=2 kN, R_1=0.7, R_2=0.5, R_3=0.3, R_4=0.1), following each other. Camera and COD were both used in the test. Shooting frequency and COD recording frequency were F_{DAQ}=10 Hz. Analyzed region is spaced Δa_s=0.5 mm apart from visible crack tip at maximal load P_{max} and the region is a square area of side a_e=0.25 mm (Fig. 2b).

Comparison of averaged vertical displacements Δh obtained using COD and DIC and given on Fig. 3c. Similarity of these results is apparent. High data recording frequency leads to necessity of LST results approximation. Plots P/P_{max}-Δh are given on Fig. 3c-f. These plots have shape of hysteresis loops and exposed together on Fig. 4a. Parallelism of the regions of loops corresponding to load ascending and descending was confirmed. Also parallelism is detected for the loops regions close to maximal P_{max} and minimal load values P_{min}. Then loops are split using criterion of the equal $\Delta P/P_{max}$=0.1. It was found that areas of generated segments are almost the same and it implies absence of crack closure. Exclusions are lower segments, especially in R=0.1 cycle (Fig. 3f). Besides regions of loops close to P_{max} and close to P_{min} are not parallel each other in R=0.1 cycle. Moreover parallelism of the regions of loops corresponding to load ascending and descending is typical for

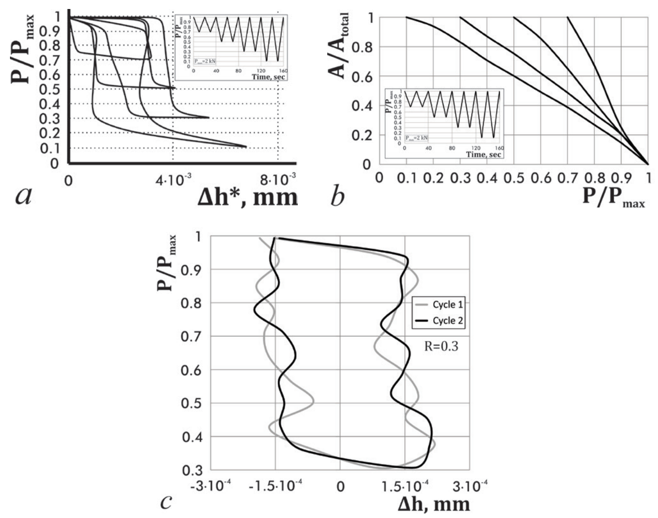

Fig. 4 a - combined plot of hysteresis loops describing displacement close crack tip as reaction on variable amplitude loading; b - almost linear relationship between area of hysteresis loop and relative loading in various cycle ratio; c - displacement close crack tip by DIC in R=0.3 cycle (without approximation).

cycles with various cycle ratio: all those regions have almost the same slope of the loop curve, except R=0.1 cycle; one can note that loop for R=0.1 cycle is more curved than others.

All these features give a suspicion that crack closure was in R=0.1 cycle, but it was absent in other cycles (even in R=0.3 cycle). Plot A/A_{total} - P/P_{max} is shown on fig. 4b, where A_{total} – total area of the loop, A – current area of the loop at P/P_{max}, P – current load. It was assumed that A=0 at P_{max}, but

$A=A_{total}$ at P_{min} for every cycle. Detailed comparison allowed establishing of clear proportional relationship between A/A_{total} and P/P_{max} showed absence of crack closure.

Thus, we postulate that in the current test crack closure took a place only somewhat at P_{op}/P_{max}=0.1…0.3. Decrease of crack closure comparing to constant amplitude loading conditioned by sequence effect, and precisely: cycles following each other and induce residual tensile stresses which even in absence of crack closure and potential squeezing and yielding of new generated fracture surfaces. Contemporary models for crack closure estimation under variable amplitude loading conditions (including Forman-Mettu model) are not able to explain the test results.

Plot P/P_{max}–Δh is presented on Fig. 4c for the cycle R=0.3 and its dots had no approximation by LST. Though instrumental noise is there, it can be concluded that the procedure given above has good repeatability for variable amplitude loading too. Plot P/P_{max}–Δm seems to be interesting; however comparison of such plots for the next variable amplitude test with tensile and compressive overloads is more promising. In the current test this plot has shape of the straight line with one slope value for all the cycles and therefore it is dropped.

The test was repeated after precracking (P_{max}=2 kN, R=0.1) till initial crack size a_0=23 mm. The only difference of the test procedure was in the fact that shooting of the specimen side face completed using webcam with autofocusing function and it was glued directly to the test specimen. Webcam is cheaper than high-speed camera, but its result contain more sufficient instrumental errors. Permanent connection using the glue implies shooting possibility only at one crack size therefore fixture allowing movement of camera along specimen width is more advanced. Results of using webcam are not given in this paper, but they are similar to the high-speed camera results thus such test setup has right to exist.

3.3 Variable amplitude loading in tension and compression

Then it was decided to perform variable amplitude loading according to the proposed procedure in tension and compression. After precracking (P_{max}=2 kN, R=0.1) till initial crack size a_0=27 mm the specimen undergoes variable amplitude loading with load frequency $F=2\cdot10^{-2}$ Hz (Fig. 5a). Camera and COD were both used in the test. Shooting frequency and COD recording frequency are F_{DAQ}=10 Hz. Analyzed region is spaced Δa_s=0.5 mm apart from visible crack tip at maximal load P_{max} and the region is a square area of side a_e=0.5 mm (Fig. 2b).

The most interesting subject here is behaviour of material in compressive overloads. Pair of the cycles were introduced between such overloads R=0.1 to minimize effect of residual tensile stress induced by previous pair of compressive overloads. High frequency data record leads to necessity of approximation via LST. However it should be recognized that the results are similar to those received by Sunder using laser interferometry (Fig. 2e). Plot of vertical displacement close to crack tip obtained using DIC for R=-2.5 cycle and it is presented on Fig. 5b.

In distinct from previous tests, the plots P/P_{max}–Δm are very interesting. Draw attention to the plot for the first R=0.1 cycle (Fig. 5c). Plot shape is usually a straight line and it exposes crack closure absence. However this plot shape is not typical for negative R. For example, P/P_{max}–Δm plot for the first R=-2.5 cycle has shape of straight line in top part and loop shape in bottom. That means crack closure is absent in R=-2.5 cycle in top part, but it is there in bottom part. Beginning of partial crack closure should not be associated with appearance of visible hysteresis loop, but with maximal load which correlates to change of curve slope. Therefore, $P/P_{max}\leq0$ for the cycle R=-2.5 and it is possible phenomenon for modern fracture mechanics, but it is usually not considered in design practice due to occurrence rarity. One can see that above-mentioned crack closure models have scatter with the test results.

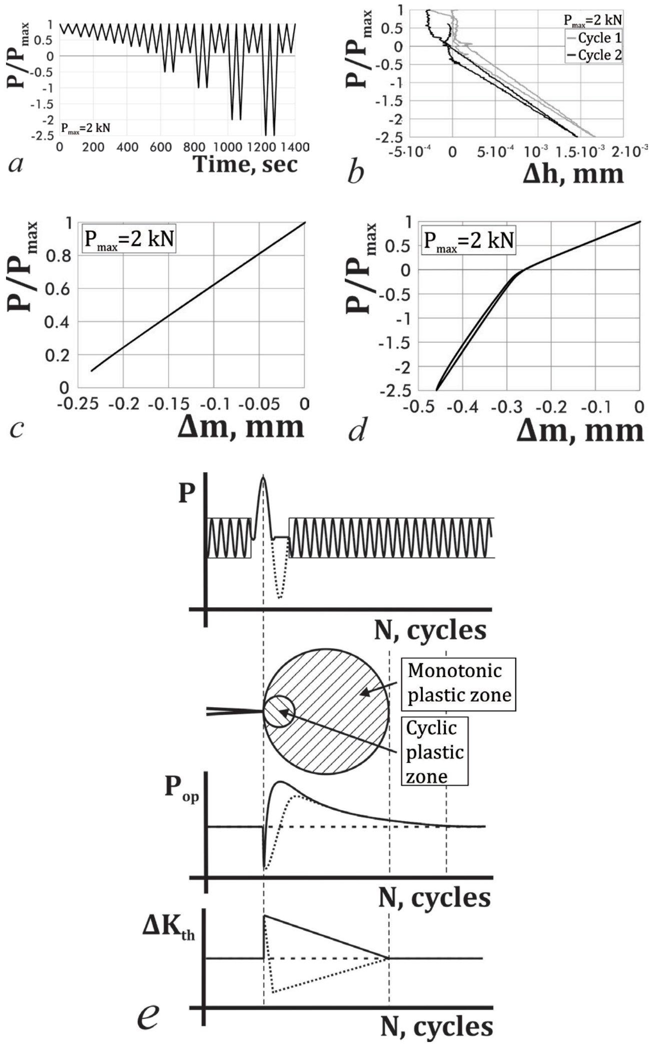

Fig. 5 a - variable amplitude loading with compressive overloads; b - comparison of displacements close to crack tip by DIC in R=-2.5 cycle (without approximation); c - difference of displacements close to crack tip by DIC and COD in R=0.1 has shape of straight line; d - difference of displacements close to crack tip by DIC and COD in R=-2.5 has hybrid shape of straight line and loop; e - variable character of crack closure alteration and threshold SIF range in cases of single tensile overload and combination of tensile and compressive overloads

4 Discussion

Current work poses a challenge to the contemporary models for crack growth rate estimation based on crack closure phenomenon to explain results of the simple tests. Is seems that excessive theorization and mathematization of crack closure brings loss of reality sense to many researchers nowadays. Commercial software includes more and more complex formulas in an attempt to explain as much experimental results as possible, though just simplicity of expression implies clarity of comprehension. In this respect opinion occurs about repeated estimation of factors effecting on crack growth. Contemporary researchers overestimate crack closure effect based on known critics on Wheeler [7] and Willenborg models [8], and erroneously postulate that "closure explains everything".

According to the brittle microfracture theory [9], variability of threshold SIF range ΔK_{th} has sufficient effect on crack growth in near-threshold region. Majority of scientists which agree with variability of ΔK_{th} usually associate it with cycle ratio R or maximal SIF of cycle K_{max}. Though the brittle microfracture theory supposes to associate ΔK_{th} with residual stress close to tip [10].

It is not to be supposed if crack closure and ΔK_{th} are being changed according to hybrid mechanism of crack growth considering both those phenomena because they have similar character of the variation from a result point of view. So, take a detailed look at effect of single tensile overload embedded at constant amplitude loading (Fig. 5e).

Single overload generates monotonic plastic zone and comparatively inconsiderable cyclic plastic zone. Overload invokes instantaneous fall (due to ascending overload halfcycle), and impetuous increase (due to descending overload halfcycle) of crack closure load level P_{op}, where maximal P_{op} value is for cyclic plastic zone. Gradual decrease of crack closure load level P_{op} appears after reaching of its maximum, but P_{op} attains former, preceding overload level not directly after full intergrowth through monotonic plastic zone, but after slightly larger crack size increment. At the same time ΔK_{th} reaches maximum directly after descending halfcycle of tensile overload which induce residual compressive stress. ΔK_{th} variation during intergrowth through monotonic plastic zone has linear descending character and ΔK_{th} reaches preceding level upon intergrowth completion. In the explanation of processes which occur at "overload effect" influence of crack closure effect and ΔK_{th} has similar character. However it is prematurely to equate "overload effect" and "sequence effect".

Take a detailed look at effect of single tensile overload and following single compressive overload embedded into constant amplitude loading (dashed line on Fig. 5e). In distinct from previous case compressive overload decreases growth rate of P_{op} due to descending halfcycle of tensile overload, besides, maximum of P_{op} is smaller. At the same time ΔK_{th} decreases directly after ascending halfcycle of compressive overload. The increase of ΔK_{th} is insignificant, but it takes place in atmospheric environment and it is more sufficient in vacuum. Various effects of component mechanisms in crack growth model under variable loading are remarkable here. Single overload and following underload lead to "overload effect" after all, but this effect is blurred and delayed. These results are badly recognized in contemporary models. The brittle microfracture theory also cannot explain "delayed retardation effect" in absence of crack closure. These reflections make sense that effect of mechanisms on crack growth must be reconsidered.

5 Summary

Some conclusions may be postulated:

1. Effect of crack closure on crack growth propagation rate must be reconsidered for contemporary crack growth models in variable amplitude loading.
2. Analysis of hysteresis loops describing vertical displacement close to crack tip may lead to development of energetical approach for crack closure research and damageability of material. Shape of hysteresis loops demonstrates potential inadequacy of principle that even partial crack closure implies absence of crack growth. Thus, concept of crack closure level must be reconsidered also.
3. In view of observed imperfection of theoretical models, crack closure research should more draw on experiments. One of the best ways for crack closure estimation under the variable amplitude loading is photometrical analysis of the test in low frequency. The analysis takes much time, but result is valid.
4. Photometrical analysis of crack closure by DIC may be completed using cheap test setup. In such way webcam may be found useful alternative for expensive high-speed camera.

Acknowledgement

Authors of the present paper deeply appreciate employees of BiSS Labs (Bangalore, India) for assistance in research survey and the general manager of BiSS-ITW, Dr. Sunder R. personally for provided equipment, test materials and mentorship. Performed work is a result of abroad traineeship of PhD student Andronik A.V. in 2014 funded by Volgograd State Technical University (Volgograd, Russia). Authors are grateful to administration of the University for rendered confidence and support.

References

[1] Elber, W. "The significance of fatigue crack closure." In: *Damage tolerance in aircraft structures*. ASTM STP 486. Philadelphia. pp. 230-242. 1971.

[2] Bannantine, J. A., Corner, J. J., Handrock, J. L. "*Fundamentals of metal fatigue analysis*." New Jersey: Prentice Hall. 1989.

[3] Sunder R. "Unraveling the science of variable amplitude fatigue." *Journal of ASTM International*. 9 (1). pp. 20-65. 2012. DOI: 10.1520/JAI103940

[4] Servohydraulic machine for testing of materials BiSS Nano. Available from: http://biss.in/cms/index.php?option=com_content&view=article&id=69&Itemid=111 [Accessed: 5th January 2015]

[5] Shijve, J. "*Fatigue of structures and materials*." Delft: Springer. 2009.

[6] Newman, J. C. "A crack opening stress equation for fatigue crack growth." *International Journal of fracture*. 24 (4). pp. 131-135. 1984. DOI: 10.1007/bf00020751

[7] Wheeler, O. E. "Spectrum loading and crack growth." *ASME. Journal of Fluids Engineering*. 94 (1). pp. 181-186. 1972. DOI: 10.1115/1.3425362

[8] Willenborg, J., Engle, R. H., Wood, H. A. "*A crack growth retardation model based on effective stress concepts*." Report № AFFDL-TM-71-1, WPAFB. Ohio. 1971.

[9] Sunder, R. "Fatigue as a process of cyclic brittle microfracture." *Fatigue & Fracture of Engineering Materials & Structures*. 28 (3). pp. 289-300. 2005. DOI: 10.1111/j.1460-2695.2005.00857.x

[10] Sunder, R. "Engineering Application of Threshold Stress Intensity. "*ASTM-ESIS Annual Symposium on Fracture Mechanics*. pp. 24-48. 2013.