Fatigue fracture estimation of ductile structural steels.

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Abstract. The method of heavy constructions prismatic specimens testing to build fatigue fracture kinetic diagrams is described in the paper. Obtained kinetic diagrams were approximated by analytical dependences with unknown parameters which were found using least squares method.

Introduction

Fracture mechanics of structural materials study is intensively developed in the recent decades. This is caused by practical value of theoretical and experimental results obtained in that field and by its great significance for methods creation of structures service ability estimation.

For present large-size metal structures lifetime estimation the fatigue fracture kinetic diagram built for their material has the most impotent role. It provides a researcher with basic informational parameters about metallic material fatigue fracture nature like material tension diagram – about deformation process. Furthermore it is directly applicable in survivability prediction of cyclically loaded metal elements.

According to fracture mechanics conception lifetime of structure exploited in high-cycle loading regime is determinate first of all by material resistance to crack growth rate for near-threshold region which corresponds to zone I of fatigue fracture kinetic diagram [1]. That is why researchers pay a special attention to the near-threshold region when constructing fatigue fracture kinetic diagrams.

Approximating experimentally obtained fatigue fracture kinetic diagram by corresponding analytical expression $V = V(\Delta K_{\mathrm{I}})$ a residual lifetime of metal structure cracked element could be easily calculated by formula [2]

$$N_d = \int_{l_0}^{l_c} V^{-1}(\Delta K_{\mathrm{I}}[l])dl\,, \qquad (1)$$

here l_0, l_c - initial and final crack size.

The theoretical-experimental method of fatigue fracture kinetic diagram construction for st 3852 steel specimen (fig. 1*a*) taken from worked element of harbour crane arm (operating time about 250 000 hours) and from 09Г2С steel specimen (initial state) as well is described in the paper.

A testing machine shown at (fig. 1*b*) was used for experimental investigation of fatigue crack initiation and propagation in beam specimen of square cross section.

Specimens testing were conducted in condition of fixed deformation that implies stress intensity factor monotonically changing with crack growth [3] (so-called hard loading).

Test machine description. Testing machine operation principle is similar to loading scheme of Shenk-Erlinger machine type [4]. The machine can operate in both regimes cantilevered and pure bending. The machine kinematics and its common view with gage unit are shown at fig. 1*c*. The end of structure specimen *6* was fixed rigidly at immovable clamp *7* and the other end was fixed at driving lever *4*, *5* which was coupled to the eccentric *2* by connecting rod *3*. The eccentric was rigidly fixed at the motor shaft *1*. Specimen was set up in such way as to locate the notch section in the middle of the distance between clamps. The lever could rotate around its fixation axis during cyclic loading of the specimen at the knuckle bearings. The blocks and the testing machine control unit were mounted at the common base that allowed us to make a measurement of loading cycle frequency, loading volume and number of the cycles per testing period or any other specified by operator time interval.

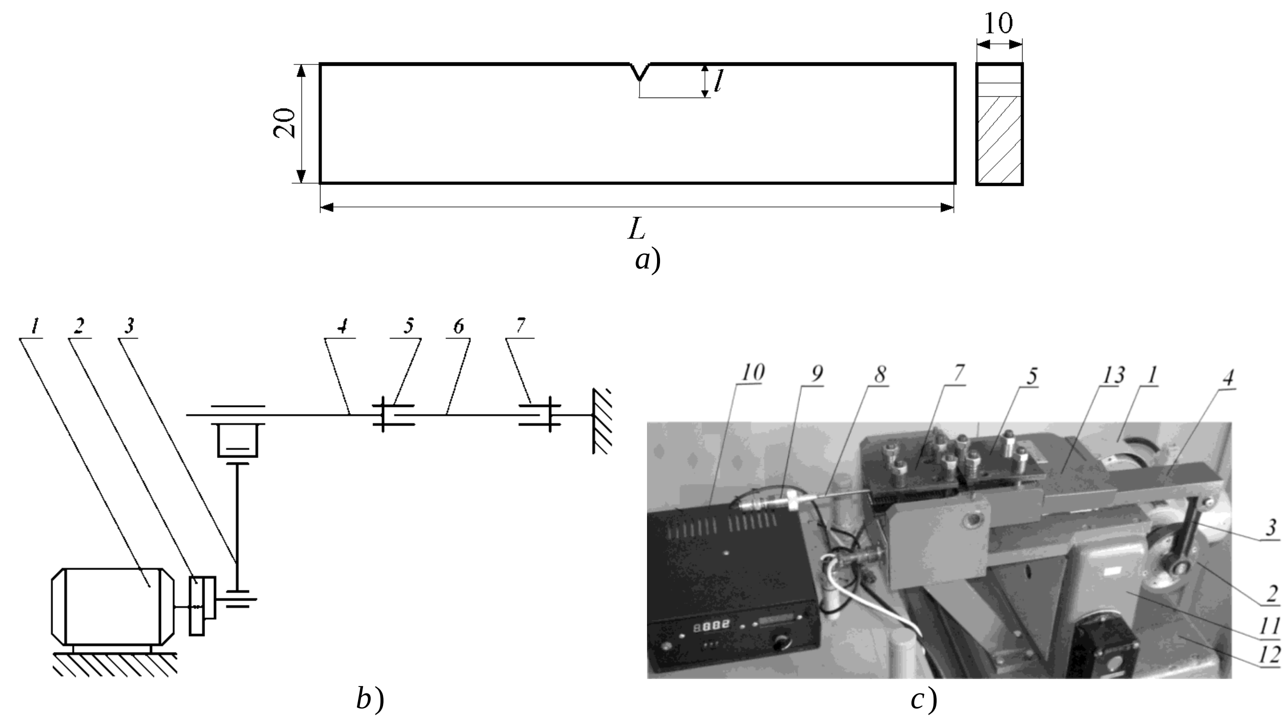

Fig. 1. Specimen scheme (*a*); testing machine kinematic scheme (*b*) and the machine common view (*c*): *1* – electric motor; *2* – eccentric; *3* – floating link; *4* – lever; *5* – movable gripper; *6* – specimen; 7 – immovable gripper; *8* – acoustic emission signal wavelet; *9* – acoustic emission primary transducer; *10* – measuring cell; *11* – upright; *12* – base; *13* – cover of tensometric measuring bridge.

The lever displacement volume is specified by operator before test stars. Using fork the lever can oscillate together with fixed in it specimen end. Lever oscillation of specified amplitude is passed by eccentric mechanism which is activated by electric motor. Loading level variation is performed by eccentric eccentricity variation. The possibility of loading level and frequency variation according to deformation variation is provided. A block scheme of testing machine control unit is shown at fig. 2.

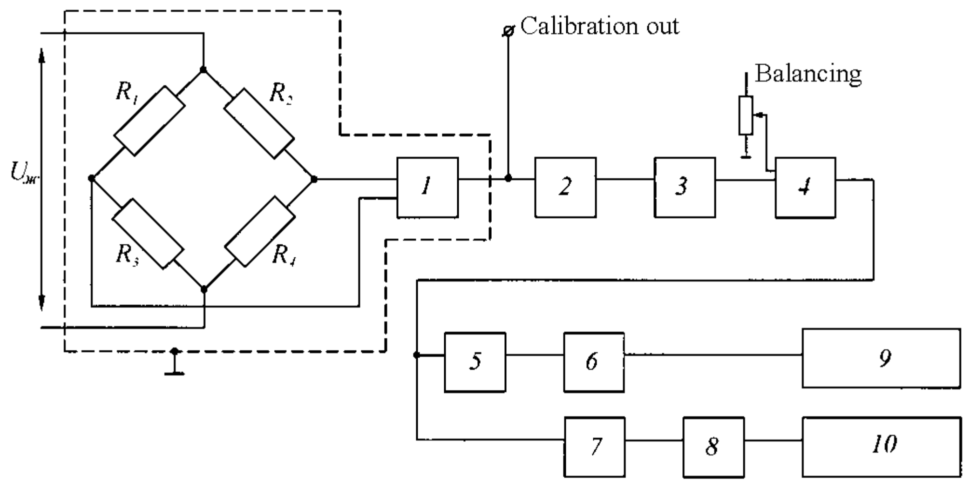

Fig. 2. Block scheme of testing machine control unit:
1 – tool amplifier; *2* – high frequency filter;
3 – band filter; *4,6,7* – amplifier; 5 – detector; *8* – comparator;
9 – voltmeter; *10* – counter; R_1 … R_4 – tensoresistors.

The control unit provides us by high accuracy measurements of cyclic loading regimes of structure material specimen. Tensometric resistors *R1*, *R2*, *R3*, *R4* are glued directly at the test machine lever in such way as to get the maximum sensibility of measuring tenso-bridge supplied by voltage of 12 V (tensoresistors resistance ~ 400 Ω). Tool amplifier AD620 *1* with amplification coefficient of $\eta = 50$ provided us by sensibility of 0,3 V per 100 kg-force for lever deformation. Tool amplifier outline was placed at the device back panel. Tool amplifier settings allow us to calibrate the device and set up specified initial loadings.

Tool amplifier outline signal is filtered by filters *2* and *3* to reduce the noises level then amplified by amplifier *4*. Mean value detector *5* sorted out signal mean value of specimen loading (by varied component) which is zoomed by amplifier *6* and measured by voltmeter *9*. Zooming process is set up in such way to indicate by voltmeter the mean value of loading variation at the lever.

For loading cycles calculation variable signal is amplified by amplifier *7* and further transformed into rectangular impulses using comparator *8*. The number of cycles is output into the counter display. 99 000 000 is the maximum possible number of loading cycles the counter is able to register.

Device technical characteristics

Maximum of the lever force…..……...3,0 kN
Specimen type……....………………..beam
Loading frequency…………..……0,1 – 100 Hz
Dimensions…..…………....680×445×490 mm
Weigh….…….………………………….560 H

Testing results analysis. Based on testing of three identical specimens of steel st 3852 the data of fatigue crack growth rate and corresponding to it crack lengths were obtained. The lengths were recalculated into corresponding values of stress intensity factor using following formulae [5]

$$\Delta K_{\mathrm{I}}(l) = (1 - R) K_{\mathrm{I}\max}(l). \quad (2)$$

Here R – loading cycle asymmetry;

$$K_{\mathrm{I\,max}}(l)=\frac{6\cdot 10^{-6}\cdot M_{\max}}{t\cdot b^{1.5}}\cdot F\left(\frac{l}{b}\right), \text{ where}$$

$$F\left(\frac{l}{b}\right)=\left(\frac{l}{b}\right)^{1/2}\left(1.99-2.47\cdot\frac{l}{b}+12.97\cdot\left(\frac{l}{b}\right)^{2}-23.17\cdot\left(\frac{l}{b}\right)^{3}+24.80\cdot\left(\frac{l}{b}\right)^{4}\right)$$ – dimensionless correction function, $M_{\max}$ – maximum value of bending moment at the crack cross section, b and t – specimen height and thickness correspondingly (fig. 1*a*).

Plotted in such way fatigue fracture kinetic diagrams for steel st 3852 are shown at fig. 3. To approximate obtained experimental data the following expression was proposed [6]

$$V(\Delta K_{\mathrm{I}})=V_0\cdot\left(\frac{\Delta K_{\mathrm{I}}-K_{th}}{K_{fc}-\Delta K_{\mathrm{I}}}\right)^{q}, \qquad (3)$$

where V_0, q – approximation parameters which are determinate by least-squares method. To plot fatigue fracture kinetic diagrams for steel 09Г2С the analogous testing were carried out (fig. 4).

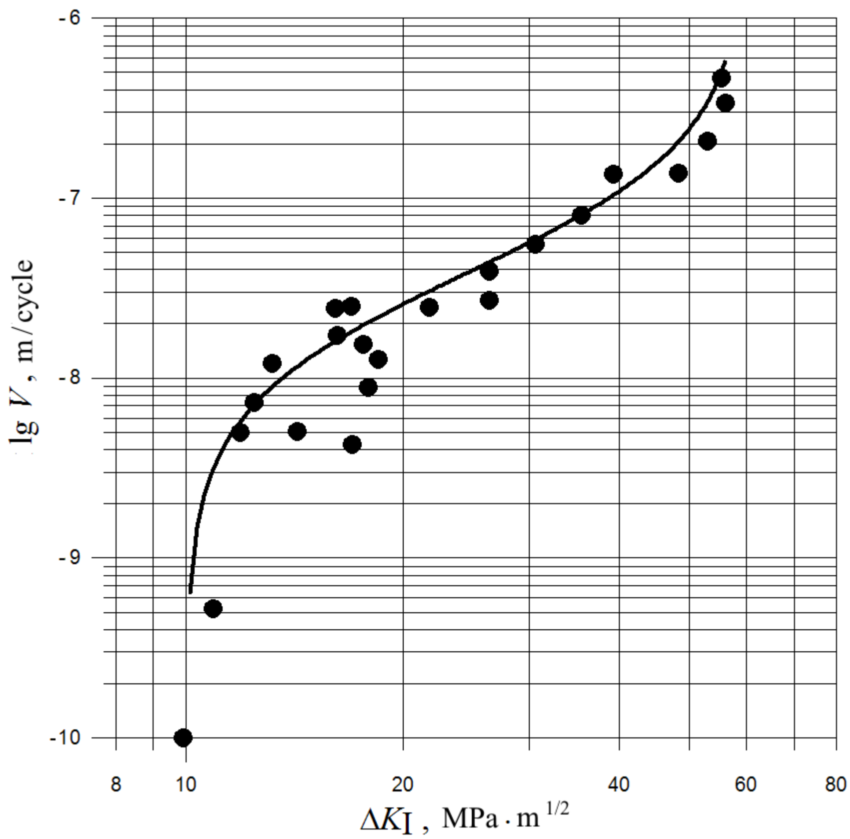

Fig. 3. Fatigue fracture kinetic diagrams for steel st 3852; points – experimental data, solid line – equation (3), where $V_0 = 7.88\cdot 10^{-8}$ (m/cycle), $q = 0.81$.

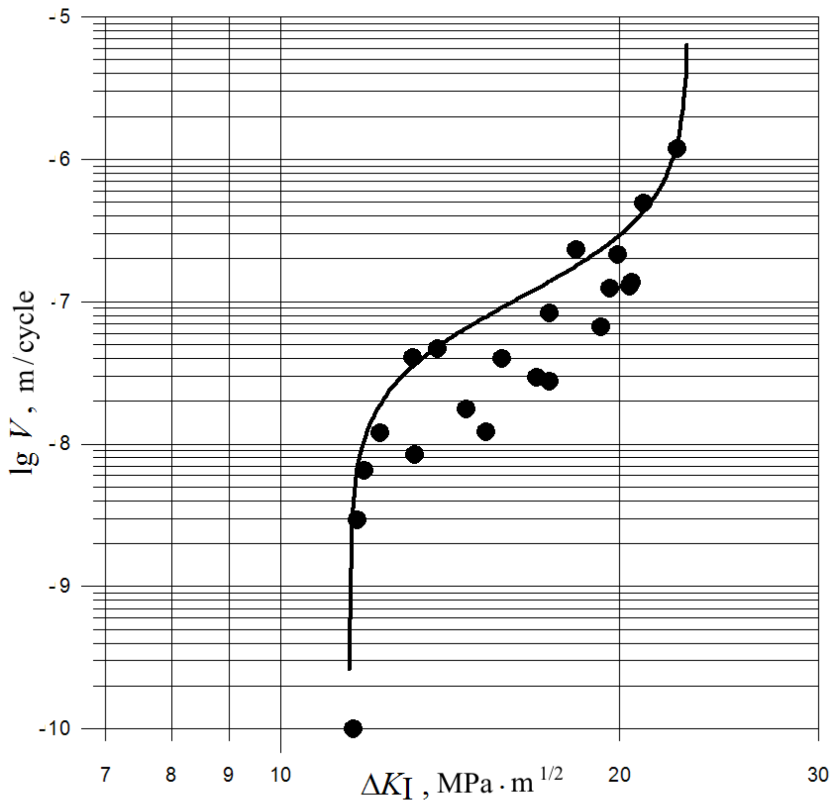

Fig. 4. Fatigue fracture kinetic diagrams for steel 09Г2С; points – experimental data, solid line – equation (3), where $V_0 = 1.36 \cdot 10^{-7}$ (m/cycle), $q = 0.74$.

Summary

It was shown that used steel st 3852 has a relatively low level of stress intensity factor (SIF) threshold K_{th}, that does not exceeds 10 MPa·m$^{1/2}$ and that is less ≈ 11 % of K_{th} value for non-used 09Г2С steel. It was found out that the critical SIF value K_{fc} in case of steel st 3852 is above the K_{fc} for steel 09Г2С and discovered also that fatigue crack growth rate for steel 09Г2С is higher then for steel st 3852. A test machine that provides structural materials specimens testing for crack initiation and propagation with simultaneous registration of necessary information (number of cycles and load level) was designed. The machine due to minimal level of self-noise can be effectively used in case of acoustic emission method application for crack growth monitoring from crack initiation up to the full specimen fracture.

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