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Diagnostics of fatigue fractures of building structures elements

Диагностика усталостных разрушений элементов строительных конструкций

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Ключевые слова: строительные конструкции; строительное оборудование; усталостное разрушение; фрактографии; техническая экспертиза диагностики

Аннотация. В статье рассматриваются вопросы повышения усталостной прочности ответственных деталей и узлов строительных машин и оборудования, чаще подверженных усталостному разрушению при воздействии переменного сложного нагружения. Произведена количественная оценка размеров зон усталостного разрушения в деталях и соединениях, установленных в строительных конструкциях и силовых схемах указанных строительных оборудований. Рассмотрена новая методика технической диагностики причин усталостных разрушений узлов строительных машин и конструкций выявлением закономерностей изменения микротвердостей в различных зонах усталостных изломов. Представлены результаты измерений микротвердостей в зонах усталостных изломов получены системы эталонных регрессионных уравнений, позволяющих количественно оценить параметры режима нагружения, приведших разрушению. Создана вычислительная подпрограмма, позволяющая путем обработки данных измерений микротвердостей исследуемого излома получить аналогичные уравнения, и сравнивая их с эталонными уравнениями, дать обоснованное количественное заключения о причинах разрушения.

Abstract. The article deals with the issues of increasing the fatigue strength of critical parts and components of construction machines and equipment, which are more often subjected to fatigue failure under the influence of variable complex loading. A quantitative estimate of the size of the fatigue fracture zones in the parts and joints installed in the building structures and power circuits of this construction equipment has been made. A new technique for technical diagnostics of the causes of fatigue destruction of knots of construction machines and structures is considered, revealing regularities of changes in microhardness in various zones of fatigue fractures. The results of measurements of microhardness in the zones of fatigue fractures are obtained. The systems of standard regression equations are obtained that allow one to quantify the parameters of the loading regime that led to destruction. A computational subroutine has been created that allows us to obtain analogous equations by processing the microhardness measurements of the fracture under study, and comparing them with the reference equations, give a reasonable quantitative conclusion on the causes of failure.

1. Introduction

The increase in the operation speeds, machine capacity, as well as load-carrying capacity of vehicles used for various purposes has led to the growth of production and traffic accidents, which tend to increase. Since the failures of construction elements take place when working with frequent overloads and various applied factors (atmosphere impacts, corrosive environment, heat and frequency fields, etc), they mainly have fatigue behavior (up to 75 %). Therefore, it becomes important to study the problem of the crack resistance of constructions, and give a reliable estimation of the fracture causes. The descriptive cases of failures of constructions are considered. In this field, works on the problems of theoretical and applied mechanics of fracture [1–6] and fractography are known [4] whose results are applied in strength and crack resistance calculations. The working conditions of machines and equipment with the minimal resource of service in the extreme modes and an increased level of failure probability, require in addition to complex measures of constructional, technological, and exploitation-type, a mandatory monitoring of service life and

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regular implementation of technical diagnostics of the construction state which is an actual task of the machines' working capacity assurance.

The most loaded construction elements, the details and joints are selected which work at variable complex loading in the mentioned machines, and they are subjected to fatigue fracture quite often,the types of fatigue fractures of shafts and key joints are presented and their [7–10] fractological analyse with macro and microstructural changes of fracture surface and its layers is given. The fracture samples resulted from fatigue experiments (co-rotating bending and torsion) of flat the details with fillet and surface grooves and prism key joints at different cyclic overloading are selected. Stress conditions in mentioned stress concentrators are studied and the dangerous sections are determined in case of their combined influence. The selected fractures are classified by affecting factors [11–16].

The aim of the work is to study the physico-mechanical condition of the surface layers of the the details fatigue fractures, and the development of the technical diagnostics method for revealing the causes of fracture. To achieve this goal, the following problems are solved:

a) classification of fatigue fractures of the details and joints according to the acting factors;
b) study of the the details variable complex loading impact on the certain zones of the fatigue fracture surface;
c) microhardness measurements of the fracture surface layers in the zones of plastic and brittle fracture, and obtaining strengthening regularities in these zones;
d) database creation of the microhardness measurements and obtaining their functional connections with the parameters of the fracture surface layers;
e) development of the technical diagnostics method for revealing the causes of fractures of the details and joints.

2. Methods

These measurements are processed by the methods of mathematical statistics, and regression functions are derived which are actually 4th degree polynomial equations. The Wolfram Mathematica standard computer software package is used to carry out these calculations and present the functions in 2D and 3D coordinate systems [17–21].

3. Results and Discussion

Typical cases of fatigue fracture of the details and joints, the loading condition – the joint action of bending and torsion with $\tau/\sigma = 0.6$ constant ratio, specific for midshafts of the mentioned units are considered. For the generalization and practical application of the obtained results, specific cases of the machine element constructive forms are selected – smooth the details, with fillet and V-shape surface notch, the details with keyway and transition fit. The distribution diagrams of contour and contact stresses are studied and built for the mentioned cases.

The selection of stress concentrator types and steel sample fractures tested at different levels of cyclic overloading, as well as the microhardness measurement method in different zones of fatigue fracture are introduced in detail in [4]. The expansion of the scope of work and the preferential use of construction and installation equipment with a low service life lead to an increase in the failure of individual elements and units. The case of fatigue failure of the lifting element of the crane for transportation of finished products (plates, elements of the building structure, etc.) in the construction organization is considered. ntensive operation and frequent overloading of the load-gripping device led to the formation, development and ultimate destruction of the most loaded element-the upper clamp of the load-holding device (Figure 1).

Figure 1. Fatigue fracture of the element of the load-lifting device of the construction crane

Structural fibers, fossils, character traits and proportions of dimensions, as well as the breakdown of the structural integrity of the grain, as well as the characteristics of the concentrated hormone concentrates. It was found that the three-dimensional condensation was applied to the three-dimensional concentration of the polymer (bush, slot, passage). It is prescribed that the exterior surfaces of the outer shell are contacted with the workpiece of the workpiece, leading to the primary structural shock [22–26]. Produced by the classification of the entire spectrum of action factors (Figure 2).

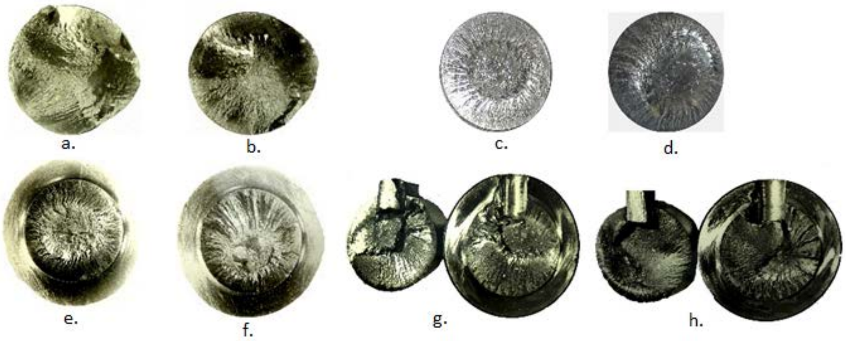


Figure 2. Heat shrinkage shafts and shaft joints (a, e, c, g) and low (b, f, d, h): a, b – glossy; e, f – with a rounding; e, d – with V-shaped knuckles; g and h – shontoons

The fractographic analysis of fatigue fractures at different overvoltage levels is given. Microstructural analysis of the surface layer indicates a change in the forms and quantitative ratio of microstructural components (Figure 3).

Thanks to the microplastic deformations caused by the maximum stresses at the top of the microcracks, as well as the contact closure of their shores, as the annular crack front moves to the center of the fracture, hardening of the surface layers occurs, the depth and degree of which depend on the cyclic loading parameters σ_i, N_i and geometric parameters of concentrators.

Structural features of fracture surfaces, shapes, character of distribution and ratio of sizes of zones of viscous and brittle fractures, as well as the influence of the type of concentrator on these parameters are given.

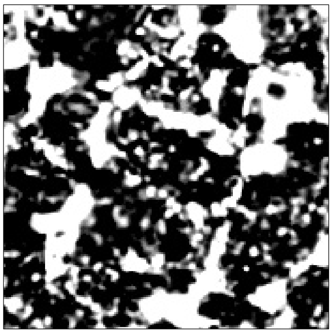
a)  **b)** 

Figure 3. Microstructure of surface fracture layers:
a – at a depth $y = 0.2$ mm, b – the initial state ($y = 1.8$ mm)

The irregular plastic flow of metal in microvolumes of the fracture surface layers forms strengthening processes, and as a result – cyclic failure initiation and propagation. Therefore, for quantitative estimation of variation of the physico-mechanical condition indices of these layers, the measurement method of their HV microhardnesses is used. The changes of $HV = f_1(y)$ and $f_2(x)$ functions are studied, which are mathematical models of the strengthening processes in the fracture surface layers of machine elements. With a glance to these changes, in the layout of HV measurement, the step by y axis is taken $\Delta y = 0.2\ mm$, and by x axis – $\Delta x = 2\ mm$ (Figure 4).

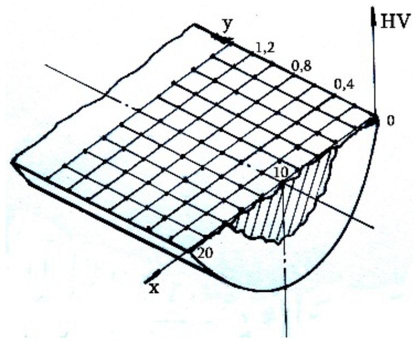


Figure 4. HV measurement layout

For the fractures of the details with fillet at $\sigma_1 = 225\ MPa$ and $\sigma_2 = 177\ MPa$ cyclic overloading, the identical form of the $HV = f_1(y)$ curves is observed, but with different HV_{max} (Figure 5a), and for $HV = f_2(x)$ curves at low σ_2 not only the symmetry is violated because of the variation of mutual arrangement of the plastic and brittle fracture zones, but also the HV_{max} values on the opposite sites of the plastic fracture zone are changed (Figure 5b). The initial state of HV_0 by y and x axes is determined at the depth of $y = 1.2 - 1.4\ mm$, therefore, obtaining the $HV = F(x, y)$ 3D function is reasonable for the complete estimation of the strengthening effect (Figure 6).

For the unification of calculation procedures, the HV measurement results of all types of fatigue fractures are processed by the method of curvilinear regression. The preliminary analysis of the function forms shows the existence of power functional relation in the form of the 4th degree equation

$$\begin{cases} HV = a_1y^4 + b_1y^3 + c_1y^2 + d_1y + e_1, \\ HV = a_2x^4 + b_2x^3 + c_2x^2 + d_2x + e_2, \end{cases} \quad (1)$$

as well as

$$HV = F(x, y) = [f_1(y) + f_2(x)]/2, \quad (2)$$

which are obtained by using the Wolfram Mathematica standard software. The $R^2 = 0.96 \ldots 0.99$ values of the determination coefficient indicate the high level regression relation.

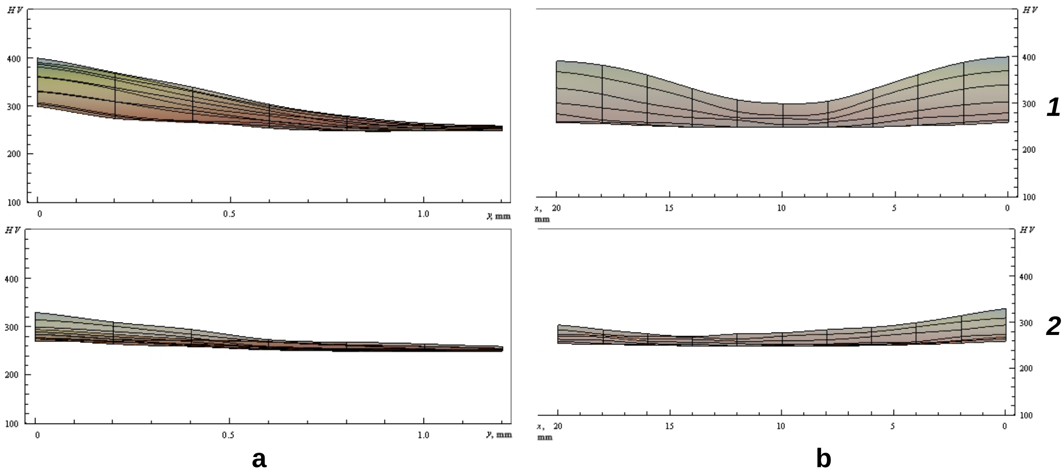


Figure 5. The changes of HV on diametric section of fracture of the details with fillet
a By y axis; b By x axis
graphs 1 refer to $\sigma_1 = 225\ MPa$, and 2 – $\sigma_2 = 177\ MPa$

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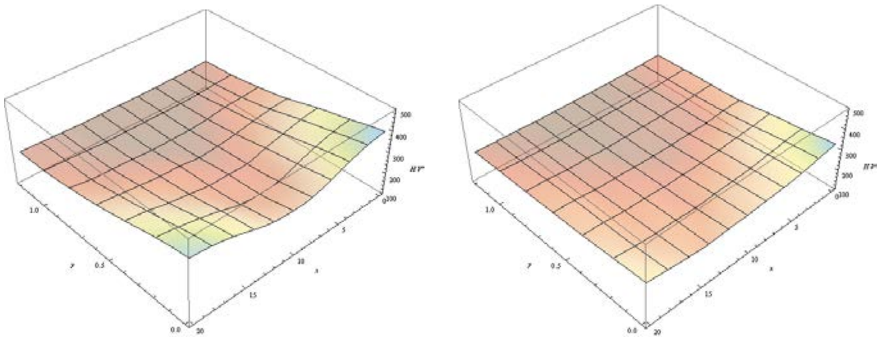

a b

Figure 6. $HV = F(x, y)$ surfaces at $\sigma_1 = 225\ MPa$ (a) and $\sigma_2 = 177\ MPa$ (b)

Similarly, the equation systems (1) are obtained for the remaining types of stress concentrators.

The $HV = f_1(y)$, $f_2(x)$, and $F(x, y)$ functions in the integral form take into account the physical-mechanical processes, flowing in fracture surface layers, and for obtaining a full picture of fatigue fracture based on the classification of fracture types and HV complex measurements, it is possible to create a database of equations (1) for carrying out expert conclusion and technical diagnostics of the fracture causes. In this work, the mentioned database is created for specific loading conditions (joint bending and torsion) and the most frequently occurring cases of stress concentrators in structural elements.

The revealed HV regularities in fatigue fracture surface layers allow to carry out quantitative estimation of fatigue fracture causes in 2 ways: firstly – estimate the loaded condition on the peak of the crack and the level of σ_i cyclic overloading, describing the real loading condition of the the details; and secondly – the strengthening effect from the contact healing of the crack edges in the plastic fracture zone, depending on N_i fatigue life which describes the lifetime of the shaft. Knowing σ_i and N_i, and using the equation of the fatigue curve, it is possible to give a substantial conclusion on the loading condition and lifetime, as well as determine the remaining life of the details.

Taking into account the variety of the acting factors and the significant volume of searching and calculation-graphic procedures, a computer software is necessary for efficient expertize and time reduction. For this, the Wolfram Mathematica standard software is used which includes a subprogram (Microsoft Office Access 2007, 0.8 MB) for carrying out the calculation procedures. The calculation algorithm includes the following blocks:

The database consists of the following sections:

1.1. Join type;

1.2. The details material;
1.3. The details diameter – $d < 20\ mm$, $d = 20 - 60\ mm$, $d > 60\ mm$;
1.4. Stress concentrator type;
1.5. Loading type;
1.6. Stress type;
1.7. Stress level;
1.8. The details fracture type;
1.9. Studied fracture zone – plastic, brittle;
1.10. Mutual arrangement of the fracture zones;
1.11. The systems of the $HV = f_1(y)$ and $HV = f_2(x)$ standard equations are grouped according to the 1.1-1.10 points;

2. Input and processing of HV measurements of the surface layers of the researched the details fracture;

3. Deriving the $HV = f_1(y)$, $HV = f_2(x)$ and $HV = F(x, y)$ functions by providing the $R^2 > 0.9$ condition;

4. The graphical presentation of the functions according to the 3rd point;

5. Compiling and inputting materials science, geometric, loading, and fractographic indices of the researched the details;

6. Comparison of the obtained data with the database according to the 3rd and 5th points, selection of the optimal variant of functions and data group;

7. Conclusion making and quantitative estimation of parameters of the acting factors leading to the fracture.

The scheme of the algorithm of the computational subroutine is given in Figure 7.

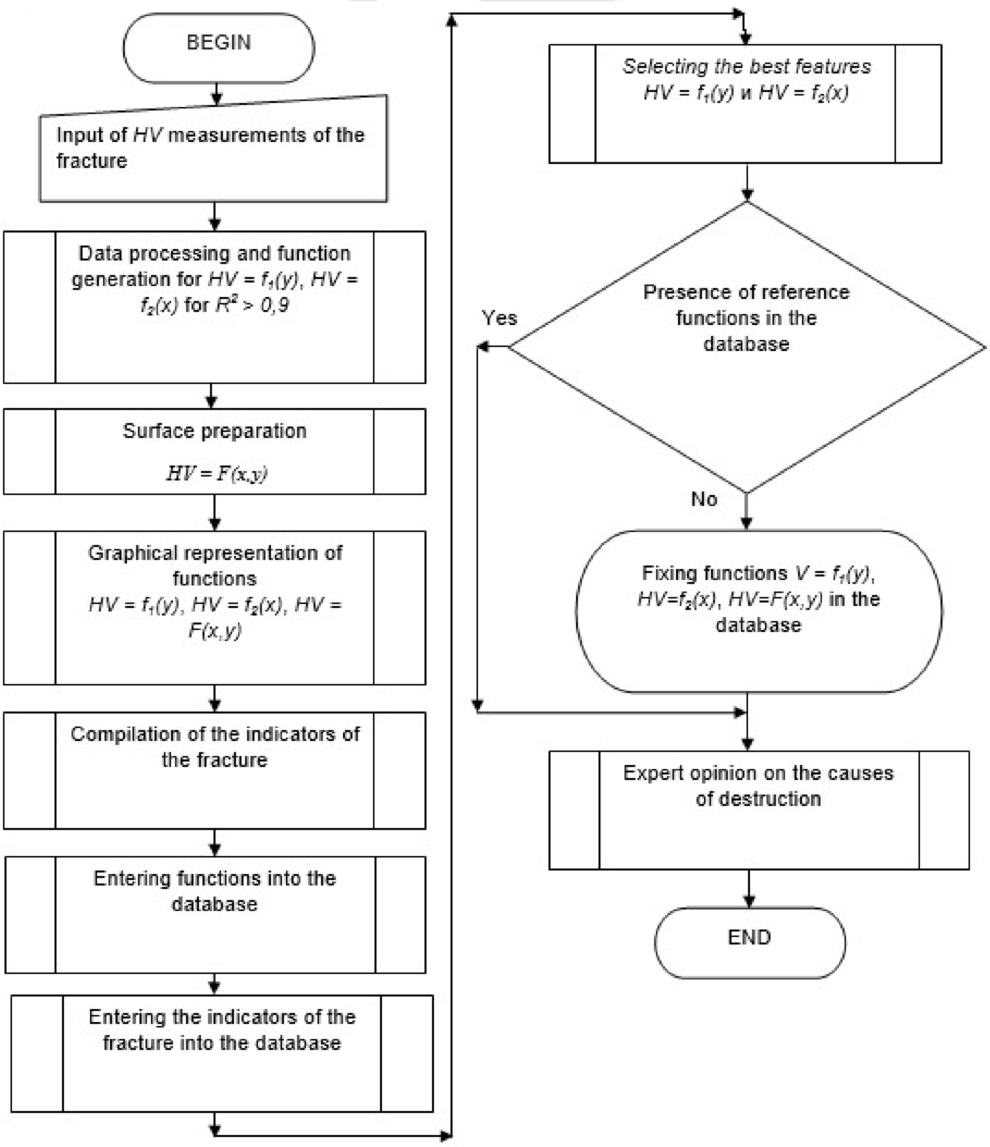

Figure 4. The algorithm of the computational subroutine

4. Conclusion

1. The article has a scientific-practical value since the methods of fractography have been applied for the real elements of construction machines, working at variable complex loading. A database is created based on the obtained systems of $HV = f_1(y)$ and $HV = f_2(x)$ parametric equations and $HV = F(x, y)$ surfaces for identifying the loading conditions and carrying out technical diagnostics of fatigue fracture causes of the details and joints. From this perspective, the systems of microhardness equations are derivatively qualifying the main parameters of fatigue fracture and can be reliable means for recovering fracture prehistory and making quantitative estimations of causes. In addition, the combined influence of joint acting stress concentrators in the fracture processes on the dangerous sections of joints and the dominant meaning of transitional precipitate under loading variability conditions in the joint that results initiation of plastic fracture zone and its propagation from the opposite fragment of key groove are considered. The system of obtained regression equations allows to formulate database for making substantiated and reliable technical diagnostics of fatigue fractures of the details and joints.

2. The results of the work can be used in 2 ways: a) including them into the maintenance processes of technical state mandatory monitoring of overloaded construction elements, and if required, carrying out current repair or replacement of a damaged machine element; b) in case of an occurred fracture,

conducting technical diagnostics of fracture causes and quantitative estimation of the acting factors by using database of the above mentioned regression equations. The second way is of practical interest for the specialists of the structures of emergency situations [26–29].

3. The general condition in many industries, including the construction industry and road and transport communications in the last decade, is characterized by the desire to increase productivity and reduce the start-up time of facilities using a significant number of technological equipment, mainly exhausted the main resource of durability. This is the reason for the sharp increase in cases of failure and destruction of building structures, as well as road accidents. In the created conditions, the primary action is the drawing up of an informed schedule for technical inspection, maintenance and repair of equipment, and in the event of an accident, an accurate assessment and technical diagnosis of the causes of destruction by a relatively accessible measurement method (a well-known PMT-3 device is used to measure microhardness according to Vickers).

4. These measures will make it possible, as far as possible, to reduce the timeframe for the failure of construction equipment and structures, and in the second case, to identify the responsible organization that has allowed the equipment to be unloaded.

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