https://dx.doi.org/10.22161/ijaers.4.4.26 ISSN: 2349-6495(P) | 2456-1908(O)

# A Phenomenon of Low-Alloy Steel Distribution Transformation Parameters at Cyclic Loading in Low-Cyclic Area

Shipachev A., Nazarova M.

Department of OGTS, Mining University, Russia, St. Petersburg

***Abstract—*** *Following on from the results of measurements of hardness, magnetizing force and the speed of ultrasonic longitudinal waves of 09G2S steel samples at various cyclic operating time values, there is a phenomenon of transformation from the normal law of speed distribution of these parameters in power-mode distribution. It shows the submission of the behavior of metal as a complex system to the theory of the self-organized criticality.*

***Keywords— Hardness, low-alloy steel, low-cycle loading, distribution, ultrasonic longitudinal waves.***

## I. INTRODUCTION

In the initial state of the metal (before the application of cyclic loads), its various structural parameters (mechanical, magnetic characteristics, velocity of ultrasonic waves, etc.) characterizing the structure of the material obey, as a rule, the normal distribution law. When investigating the cyclic damage of a metal, it is assumed that the laws of distribution of these parameters remain unchanged. Metal parts working in the machine, are a system in terms of different approaches. First, it is a system in terms of the existence of hierarchical levels of deformation and destruction, according to V. A. Panin [1]. Secondly, the presence of heterogeneities of local macrovolumes, comparable with grain sizes, having different local strength characteristics, causes a redistribution of stresses, deformations, energy in the volume of the metal between these microvolumes of the parts in an optimal way in accordance with the principles of synergetic. Thirdly, it is a system of "basic" metal and metal of the surface layer, which interact, carrying out information-energy exchange [2].

.

## II. TRANSFORMATION OF STRUCTURE PARAMETERS

If we regard the metal parts as a system, it is logical to assume that when it approaches the limit state, it will undergo certain changes. To be exact - the changes characteristic of any complex system as it approaches a critical state or a catastrophe. It can be assumed that in this case the transformation of the distribution laws of parameters takes place, characterizing the attainment of the limiting state of a metal as a complex system. According to the theory of self-organized criticality [3, 4], the system's achievement of a limiting, critical state means a change in the laws of the distribution of its characteristic parameters, a transition to a power law of distribution. In our case, this can be the transformation of the normal distribution law of the structural parameters of the macro-volumes of a metal into a power law. During the statistical processing of measurements of structural parameters, this transformation is not taken into account. A priori, it is assumed that the distribution law does not change in both the initial and limiting states of the material.

## III. INDENTATIONS AND EQUATIONS

According to the theory of self-organized criticality [3, 4], the system's achievement of a limiting, critical state means a change in the laws of the distribution of its characteristic parameters, a transition to a power law of distribution. In our case, this can be the transformation of the normal distribution law of the structural parameters of the macro-volumes of a metal into a power law. During the statistical processing of measurements of structural parameters, this transformation is not taken into account. A priori, it is assumed that the distribution law does not change in both the initial and limiting states of the material. As a result of the analysis of a large body of data on natural and man-made disasters (earthquakes, floods, major accidents at industrial enterprises and transport, etc.), as well as shocks in economic, in particular, financial areas (stock crashes, default, market dynamics modeling of goods, etc.), the basic regularities inherent in these phenomena were determined, and a theory of self-organized criticality was created. The power law of the probability distribution (SSD) of probabilities when approaching the limiting state (a statistical image of catastrophic behavior) is a distinguishing feature of many complex systems [2]. The power distribution law has a probability density of the form

$$f(x)=x^{-(1+\alpha)}. \tag{1}$$

https://dx.doi.org/10.22161/ijaers.4.4.26 ISSN: 2349-6495(P) | 2456-1908(O)

This law is an implication of Pareto distribution for which a distribution function is

$$F(x) = \begin{cases} 1 - x^{-\alpha}; & x \geq 1; \\ 0 & x \prec 1; \quad 0 \prec \alpha \prec 1. \end{cases} \qquad (2)$$

We carried out studies of the transformation of the statistical laws of hardness distribution HB, magnetic field strength H, and the speed of ultrasonic longitudinal waves V during the cyclic operating time of 09G2C steel in the low-cycle fatigue region. These studies and their subsequent statistical processing were carried out with the aim: 1. To obtain sets of uniform data of ultrasonic wave velocity measurements in the working zone along the thickness of the sample, with a fixed cyclic operating time. 2. Conduct a statistical test of statistical hypotheses based on Pearson's criterion on the distribution of the general set both in accordance with the normal law and in accordance with the power law. 3. Determine which hypotheses about the distribution laws (normal or power law) are more acceptable in accordance with the Pearson criterion (for a given level of significance) for different values of the cyclic operating time of the samples. 4. To investigate whether the phenomenon of transformation of the normal law of velocity distribution of ultrasonic waves has a power law in the course of cyclic operating time up to destruction (this proves that the behavior of a metal as a complex system in a critical state close to destruction can be described by catastrophe theory). Investigation of fatigue life in the low-cycle region was carried out under cyclic elastoplastic loading. To increase the reliability of the results obtained, the study used samples of a thickness that correlated with the actual dimensions of the apparatuses of chemical production. Samples for tests on low-cycle fatigue were made according to GOST 25502-79 from two plates of sheet metal welded by automatic welding under a layer of flux. The direction of cutting samples along the rolling was chosen from the loading conditions of the products and the technology for obtaining the material. The specimens were loaded on the original fatigue testing machine according to the scheme of pure symmetrical bending. The control of the size of the deflection was carried out with the aid of a special device with a dial gauge. Hardness measurements were made by ultrasonic hardness tester UZIT-3. The principle of operation of the device is based on the dependence of the resonance frequency of a magnetostrictive rod with a diamond pyramid at the end embedded in the surface of the controlled article with a specified force from the area of contact of the diamond with the surface of the article. The strength of the magnetic field was measured by a flux-probe flaw detector FP. Measurements of the propagation velocity of ultrasonic longitudinal waves were performed using a 36 DL Plus ultrasonic thickness gauge from Panametrics with a D-709 separate-converting transducer at each predetermined level of fatigue damage accumulation. Beforehand, a 6 × 5 mm grid was applied to each sample, and in each cell, thickness measurement was carried out using a micrometer. The method of statistical processing consisted of the following stages.

A set of uniform data of measurements of the velocity of ultrasonic waves was transformed into a variational series. The variational series is necessary for constructing an empirical distribution. The values of the intervals were chosen in such a way that the total number of intervals was not less than 7-8. The intervals were chosen to be equal. Further, all calculations were carried out in the Microsoft Excel software.

The arithmetic mean of the variational series was found

$$\bar{x} = \frac{\sum_{i=1}^{m} x_i n_i}{n}, \qquad (3)$$

where $n$ – total number of measurement data, $n_i$ – number of measurements taken in the interval, $m$ – number of intervals.

Dispersion of variation row was found (not shifted)

$$s^2 = \frac{\sum_{i=1}^{m} n_i \left(x_i - \bar{x}\right)^2}{n-1} \qquad (4)$$

and mean square deviation

$$s = \sqrt{s^2} \quad . \qquad (5)$$

The analytic expression for the normal distribution law (Gauss' law) was determined from the found parameters of the variational series $\bar{x}$ and s.

$$f(x) = \frac{1}{s\sqrt{2\pi}} e^{-\frac{(x-\bar{x})^2}{2s^2}} \qquad (6)$$

Theoretical probabilities $p_i$ were found for the random variable x (measured data) to fall into the i-th interval (equal to the theoretical frequencies of the intervals $(n_i/n)$ from expression (6) under the assumption of a normal distribution law. Then the corresponding theoretical frequencies of the intervals $np_i$ were found.

The value of Pearson's criterion (criterion "Chi-square") was calculated by the formula

$$\chi^2 = \sum_{i=1}^{m} \frac{\left(n_i - np_i\right)^2}{np_i}. \qquad (7)$$

For the selected significance level $\alpha$, which was assumed to be 0.05 and the number of degrees of freedom

$$k = m - r - 1,$$

where $r$ - the number of parameters determining the distribution (for the normal distribution $r$= 2), the critical value of the criterion was determined $\chi^2_{\alpha;k}$. The values of the empirically determined value of the criterion $\chi^2$ and the corresponding critical value $\chi^2_{\alpha;k}$ of it were compared. If $\chi^2 \le \chi^2_{\alpha;k}$ or $\chi^2_{\alpha;k} - \chi^2 \ge 0$, the hypothesis of the normal distribution does not contradict the experimental data (that is, it is accepted), but if $\chi^2 \succ \chi^2_{\alpha;k}$ or $\chi^2_{\alpha;k} - \chi^2 \prec 0$, then the hypothesis is rejected (not accepted) at a given level of significance $\alpha$ or reliability $\gamma = 1 - \alpha$.

The difference $\chi^2_{\alpha;k} - \chi^2$ can serve as an indicator of the closeness of the empirical distribution of a random variable to the theoretical distribution under consideration. The greater the value of this difference, the closer the empirical distribution to the theoretical one being considered, and vice versa.

The acceptability of the power law of distribution was found

$$f(x) = Cx^{\alpha}, \tag{8}$$

Where *a* and c are the parameters, x> 0, for the empirical variational series, or, in other words, whether it is possible to accept the hypothesis of the distribution of random variables (measurement data) in accordance with the power law. Since the power distribution is symmetric with respect to the mean (mean arithmetic variation series $\bar{x}$), only half can be investigated, for example, the region lying to the right of $\bar{x}$. It is assumed that it is legitimate to transfer the values of $\bar{x}$ lying to the left of $\bar{x}$, in the range of values lying to the right of $\bar{x}$, symmetrically relative to $\bar{x}$. That is, if $x_i \prec \bar{x}$, then the new, "corrected" value of $x_i'$ will be equal to $x_i' = 2\bar{x} - x_i$.

Or, more conveniently, you can simply combine the intervals lying at the same distance from $\bar{x}$, and sum up the corresponding empirical frequencies of these intervals. This unification operation was carried out for all the variational series found.

## IV. MEASUREMENT PARAMETERS APPROXIMATION DIAGRAMS

To ensure a high-quality product, diagrams and lettering must be either computer-drafted or drawn using India ink Point diagrams of empirical frequencies were constructed on the basis of "combined" variational series. Further, in each diagram a curve was constructed - the trend line corresponding to the power approximation, and parameters $\alpha$ and C were found for this power curve, which correspond to the parameters of the corresponding regression equation. In Fig. 1, for example, the dependence of empirical frequencies on the speed of ultrasonic longitudinal waves of the samples after operating 2500 cycles is an approximation of the power law of distribution. Figure 1 shows, as an example, a connection of empiric frequencies and ultrasonic wave speed of the samples after 2500 cycles loading – power law distribution approximation.

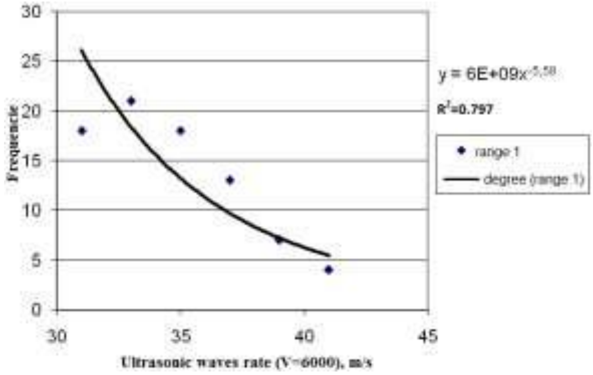


*Fig. 1: Ultrasonic wave rates empiric frequencies power approximation of samples after 2500 cycles of loading*

From dependence (8), substituting the corresponding parameters of *a* and C, the theoretical frequencies in each interval were determined.

The value of Pearson's criterion (criterion "Chi-square") was calculated by the formula (7). In this case, the significance level of *a* was also assumed to be equal to 0.05 and the parameter *r* in calculating the number of degrees of freedom was assumed equal to 2, since the power distribution also has two parameters.

In a similar manner to that described in point 7, a comparison was made between the values of the empirically determined value of the criterion $\chi^2$ and its corresponding critical value $\chi^2_{\alpha;k}$.

Figure 2 shows the diagram of the hardness HB relative to the relative cyclic damage, where Np is the number of destruction cycles, Ni is the number of cycles for a given loading stage.

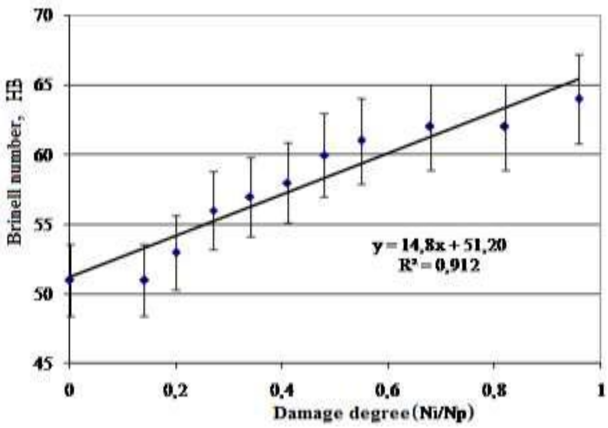


*Fig. 2: Brinell number (HB) dependences of deterioration degree*

https://dx.doi.org/10.22161/ijaers.4.4.26 **ISSN: 2349-6495(P) | 2456-1908(O)**

Figures 3, 4, 5 demonstrate the dependence difference $\chi^2_{\alpha;k} - \chi^2$ of loading cycles for hardness HB, ultrasonic waves speed V and magnetizing force correspondingly.

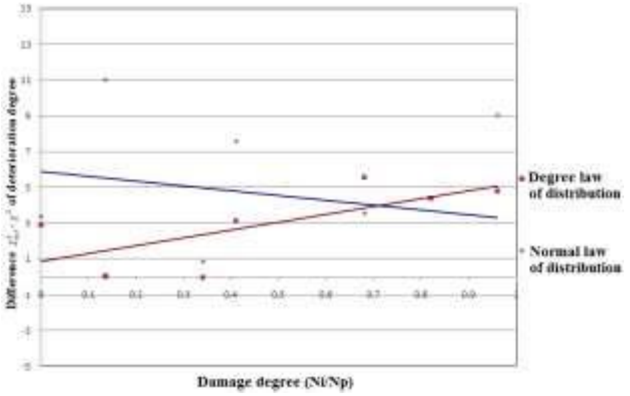


*Fig. 3: Dependence the average difference $\chi^2_{\alpha;k} - \chi^2$ of deterioration degree, hardness HB*

For each set of homogeneous measurement data on one face of the sample after a certain cyclic operating time, the differences $\chi^2_{\alpha;k} - \chi^2$ were found, respectively, to test the hypotheses of the normal and power distribution laws.

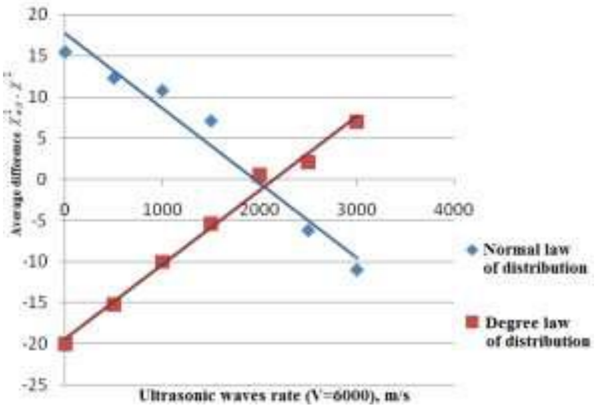


*Fig. 4: Dependence of the average difference $\chi^2_{\alpha;k} - \chi^2$ of deterioration degree, ultrasonic waves speed V*

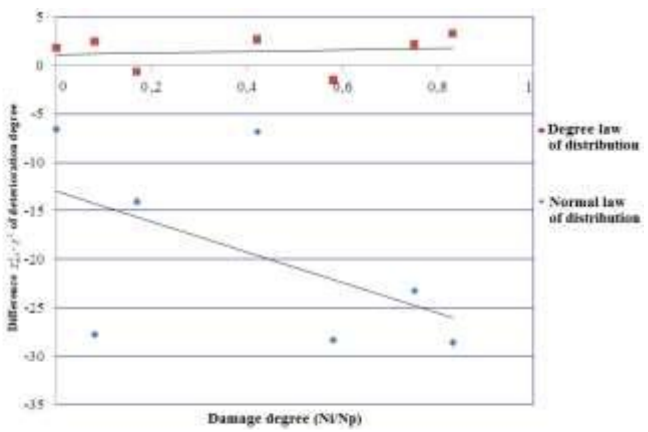


*Fig. 5: Dependence of the average difference $\chi^2_{\alpha;k} - \chi^2$ of deterioration degree, magnetizing force*

On pictures 3-5 it can be seen that the difference $\chi^2_{\alpha;k}$ - $\chi^2$ when compared with the normal distribution law decreases, but when compared with the power distribution law increases.

## V. CONCLUSION

It shows that at during cyclic loading an empiric distributions of steel physical and mechanical parameters is less correspond to normal distribution law, but more corresponds to power distribution law. The aerie higher the abscissa axis on the diagram mean the assumption of distribution law. An aerie lower means rejection of distribution law. In other words, a tendency of normal into power law distribution transformation have a place at cycling loading.

On the base of experimental results and literature sources [2, 3] we come to a conclusion that we have special case - a multiplicative process, which defines the value of $\alpha$ parameter much more than 2.

## REFERENCES

[1] Kuzeev I.R., Naunkin Y.A., Savicheva Y.S., Popova S.V. Poverhnoct I poverhnostnye yavleniya – Ufa: Neftegazovoye delo, 2008 – 144 p.

[2] Panin V.A., Lihachev B.A., Grinyaev Y.V. Strukturnye urovni deformatsii tvyordyh tel. – Novosibirsk, Nauka, 1990 – 240 p.

[3] Upravlenie riskom: risk, ustoychivoe razvitiye, sinergetica – Mocsow, Nauka, 2000 – 431 p.

[4] Malinetskiy G.G., Podlazov A.V., Kuznetsov I.V. Sinergetica I prognoz bedstvii I katastrof / Prikladnaya sinergetica – II: Sbornic nauchnyh trudov – Ufa: UGNTU, 2004. – Volume 1,p 73-104.