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To cite this article: A M Shipachev and M N Nazarova 2017 IOP Conf. Ser.: Earth Environ. Sci. 87 092017

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Phenomenon of low-alloy steel parametrization transformation at cyclic loading in low-cyclic area

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Abstract. Following the results of measurements of hardness, magnetizing force and the rate 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.

1. Introduction

Various structural parameters of the metal (mechanical, magnetic characteristics, rate of ultrasonic waves, etc.) in the initial state (before cyclic loads) characterizing the structure of the material, as a rule, are subject to the normal law of distribution. When investigating the cyclic damage of metal, the laws of distribution of these parameters are assumed to remain unchanged. Metal of a part operating in a machine is a system in terms of different approaches. [8] 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 the "basic" metal and the metal of the surface layer, which interact with information and energy exchange [2].

2. Transformation of structure parameters

If the metal of a part is considered as a system, it is logical to assume that when it approaches the limit state, it will undergo certain changes. Namely, these are the changes, which are typical for any complex system as it approaches a critical state or a catastrophe. In such case, the transformation of parameters distribution laws can be assumed to take place that characterizes the reaching of the limit state of a metal as a complex system. According to the theory of self-organized criticality [3, 4], the system's achievement of a limit, critical state means a change in the laws of the distribution of its specific parameters, a transition to a power law of distribution. In our case, this can be the transformation of the normal law of distribution of structural parameters of metal macro-volumes into a power one. During the statistical processing of measurements of structural parameters, this transformation is not taken into account. A priori, the distribution law is assumed to remain unchanged in both the initial and limiting states of the material.
3. 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 and financial areas in particular (market crashes, default, commodity market dynamics modeling, etc.), the basic regularities inherent in these phenomena were determined. Besides, a theory of self-organized criticality was created. The power law of the probability distribution (SSD) 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

\[ f(x) = x^{-(1+\alpha)} \]  

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

\[ F(x) = \begin{cases} \frac{1}{1 - x^{-\alpha}}, & x \geq 1; \\ 0, & x < 1; 0 << \alpha << 1. \end{cases} \]  

The authors carried out studies of the transformation of the statistical laws of hardness distribution HB, magnetic field strength H, and the rate 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 for the purpose of: 1. Obtaining sets of uniform data of ultrasonic wave rate measurements in the working zone along the thickness of the sample, with a fixed cyclic operating time. 2. Carrying out 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. Determining, which hypotheses about the distribution laws (normal or power law) are more acceptable in accordance with the Pearson’s criterion (for a given level of significance) for different values of the cyclic operating time of the samples. 4. Investigating the presence of the phenomenon of transformation of the normal law of ultrasonic wave rate distribution into 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). A fatigue life in the low-cycle area was studied under cyclic elastoplastic loading. To increase the reliability of the results obtained, the samples with a thickness correlated with the actual dimensions of the devices of chemical production were used in the study. 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 of samples along the rolling was chosen from the loading conditions of the products and the technology of material production. The samples were loaded on the original fatigue testing machine according to the scheme of pure symmetrical bending. The size of the deflection was monitored using a special dial indicator. Hardness was measured 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 item under control with a specified force from the diamond contact area with the surface of the item [5-7, 9, 10]. The magnetizing force was measured by a flux-probe flaw detector FP. Ultrasonic longitudinal waves spread velocity was measured using a 36 DL Plus ultrasonic thickness gauge made by Panametrics with a D-709 separate-converting transducer at each predetermined level of fatigue damage accumulation. A 6 × 5 mm grid was preliminary applied on each sample, and each cell thickness was measured by a micrometer. The method of statistical processing consisted of the stages as follows.

A set of uniform data of measurements of the rate 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.

The arithmetic mean of the variational series was found:

\[ \bar{x} = \frac{\sum_{i=1}^{m} x_i m_i}{n} \]  

(3)

where \( n \) is a total number of measurement data, \( n_i \) – a number of measurements taken in the interval, \( m \) – a number of intervals.

Dispersion of variation row was found (not shifted):

\[ s^2 = \frac{\sum_{i=1}^{m} n_i (x_i - \bar{x})^2}{n-1} \]  

(4)

as well as mean square deviation:

\[ s = \sqrt{s^2} \]  

(5)

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

\[ f(x) = \frac{1}{s \sqrt{2\pi}} e^{-\frac{(x-\bar{x})^2}{2s^2}} \]  

(6)

Theoretical probabilities \( p_i \) were found for the random variable \( x \) (measured data) to hit the \( i \)-th interval (equal to the theoretical frequencies of the intervals \( \frac{n_i}{n} \) from formula (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:

\[ \chi^2 = \sum_{i=1}^{m} \left( \frac{(n_i - np_i)^2}{np_i} \right) \]  

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

The difference \( \chi^2_{a,k} - \chi^2 \) 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:

\[ f(x) = Cx^a \]  

(8)

where \( a \) and \( c \) are the parameters, \( x > 0 \), for the empirical variational series, or, in other words, whether the hypothesis of the distribution of random variables (measurement data) could be accepted 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 \( x \). It is assumed that it is legitimate to transfer the values of \( x \) 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 \( x_i < \bar{x} \), then the
new, "corrected" value of $x_i$ will be equal to $x_i = 2\bar{x} - x_i$. Or, more conveniently, the intervals lying at the same distance from $\bar{x}$ can be simply combined and the corresponding empirical frequencies of these intervals can be summed up. This unification operation was carried out for all the variational series found.

4. 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, which is the trend line corresponding to the power approximation, was constructed, and parameters $\alpha$ and $C$ were found for this power curve, which correspond to the parameters of the corresponding regression equation. Figure 1 shows a dependence of empiric frequencies and ultrasonic wave rate of the samples after 2500 cycles loading – power law distribution approximation as an example.

![Figure 1](image1.png)

**Figure 1.** Empiric frequencies power approximation of ultrasonic wave rates of samples after 2500 cycles of loading.

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

![Figure 2](image2.png)

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

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 $r$ when
calculating the number of degrees of freedom was assumed to be equal to 2, as the power distribution also has two parameters.

Similarly to the above-mentioned, the values of the empirically determined criterion $\chi^2$ and its corresponding critical value $\chi^2_{a,k}$ were compared.

Figure 2 shows the diagram of the hardness HB dependence on the relative cyclic damage, where Np is the number of destruction cycles, Ni is the number of cycles for a given loading stage. Figures 3, 4, 5 demonstrate the dependence difference $\chi^2_{a,k} - \chi^2$ of loading cycles for hardness HB, ultrasonic waves rate V and magnetizing force correspondingly.

![Figure 2](image)

**Figure 2.** Diagram of the hardness HB dependence on the relative cyclic damage, where Np is the number of destruction cycles, Ni is the number of cycles for a given loading stage.

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

![Figure 3](image)

**Figure 3.** Dependence the average difference $\chi^2_{a,k} - \chi^2$ of deterioration degree, hardness HB.

![Figure 4](image)

**Figure 4.** Dependence of the average difference $\chi^2_{a,k} - \chi^2$ of deterioration degree, ultrasonic waves rate V.
Figure 5. Dependence of the average difference $\chi^2_{a,k} - \chi^2$ of deterioration degree, magnetizing force.

Figures 3-5 shows that the difference $\chi^2_{a,k} - \chi^2$ decreases when compared with the normal distribution law, but when compared with the power distribution law — increases.

5. Conclusion
Following the analysis of the results, a conclusion that distribution of physical and mechanical parameters of material tends to transform from normal distribution law to a power one can be made. The area over the abscissa axis on the diagram means that the assumption of distribution law (normal or power, refer to the curve) is accepted, if lower — it is rejected.

It is also can be concluded that the authors have evidenced a special case - a multiplicative process, which defines the value of $\alpha$ parameter which is much more than 2.

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