

INVESTIGATION OF APPLICABILITY OF TIN FATIGUE GAUGES FOR MONITORING OPERATIONAL LOAD OF CULTIVATOR SPRING STRUT

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Abstract. The problem of increasing the reliability of agricultural machinery is considered. To prevent fatigue failure of the most loaded parts, it is proposed to monitor their operational load with the help of fatigue gauges. As a result, the amplitude of cyclic stresses is determined, which is equivalent in terms of the damaging effect to the spectrum of operational stresses. If the actual loads are significantly higher than the design values, it is necessary to increase the strength of the overloaded parts or reduce the operating loads. Fatigue gauges, which are fragments of copper or aluminum foil, are widely known. Fatigue gauges made of stannum with addition of antimony are used in this work. Tin fatigue gauges were proposed by the author; they have high sensitivity and they quickly react to relatively low stresses. The evaluation of the applicability of tin fatigue gauges for monitoring the operational load of the cultivator spring strut was carried out experimentally in laboratory conditions. Test specimens of the same material as the spring strut were used. These specimens were tested according to the symmetrical bending scheme. One specimen was subjected to a load that reproduced the operational load spectrum. This spectrum is known from the results of measurements by resistive-strain sensors. The sequence of application of the load was determined by random sampling. Another specimen was tested under symmetrical bending conditions with constant amplitude. The fatigue gauges were monitored visually with a microscope at 100^x magnification. Calibration specimens and the scheme of the testing stand are shown. Photos of surfaces of fatigue gauges after tests are presented. The Palmgren-Miner linear damage theory was used. It is shown that the use of highly sensitive fatigue gauges made of tin foil together with the linear damage theory provides sufficient accuracy of the results: the discrepancy was less than 3 %.

Keywords: reliability, fatigue gauge, monitoring.

Introduction

Improving reliability, reducing the number of breakdowns and downtime of used equipment are important factors to ensure profitability in agricultural production. To prevent fatigue failure of the most loaded parts, it is proposed to monitor them using fatigue gauges made of tin foil. In comparison with strain sensors, the use of fatigue gauges does not require expensive electrical and electronic equipment. A fatigue gauge is a fragment of foil that reads, summarizes, stores and indicates data about the cyclic stress parameters acted on the part surface [1; 2].

The author's attempts to apply the known fatigue gauges, made of copper electrodeposited foil [3; 4] or of aluminum foil [5] to monitor the load of agricultural machinery were unsuccessful. The use of such gauges at relatively low stresses requires a large number of load cycles. Due to the tight deadlines of fieldwork, these gauges do not have time to form a response.

The problem of increasing the sensitivity of fatigue gauges was considered and partially resolved in the works [6; 7]. But it was possible to solve the problem radically only on the basis of a systematic approach, which is described in [2]. The principles of the general system theory [8; 9] were applied. This made it possible to better understand the work of the existing fatigue gauges, identify the trends in their development, offer new materials and designs of fatigue gauges and new techniques to control them.

Particularly based on the principle of consistency (systemness, systemic nature) [2], it is necessary to use all existing effects and manifestations of fatigue to create new ways to control fatigue gauges. Many studies [10-18] have been conducted in accordance with this principle. In [10] the fundamental characteristics of slip initiation and surface roughening phenomena in aluminum fatigue gauge were investigated. In [11] the stress measurement method using control of the microhardness was examined. In [12] "the crystallographic orientations of individual grains that undergo grain growth in copper foil subjected to cyclic loading were analyzed by electron backscatter diffraction". In [13] "the stress measurement method using the fractal analysis was examined". In [14] the stress measurement method using control of the electrical conductivity by eddy-currents was examined. In [11; 15-18] the methods of surface appearance control of fatigue gauges were investigated.

Materials and methods

The paper [2] describes the criterion and results of the forecast, according to which the fatigue gauges made of tin foil should have high sensitivity. This was experimentally confirmed in [1; 2; 19].

Tin foil of industrial production was used. It was manufactured according to the Russian standard GOST 18394-73. Foil thickness was 20 μm . According to this standard, tin foil is made of an alloy of stannum with antimony, in which antimony is 1.9-3.1 %. In addition, this foil was annealed at a temperature of 200-203 $^{\circ}\text{C}$ for 10 hours.

The known results obtained by the traditional method are necessary to assess the accuracy of the application of fatigue gauges. For this purpose, the results of the study of the spring strut “КПЦ-190” of cultivator “КПЦ-4” [20; 21] were used. The spring strut is shown in Fig. 1. Monitoring of operating stresses was performed using resistive-strain sensors. The nonzero mean stress cycles must be converted to equivalent completely reversed cycles [22]. The distribution of the transformed amplitudes of operational stresses for the dangerous cross-section of the spring strut is obtained in [20; 21]. These results are presented by the curve 1 in Fig. 2.

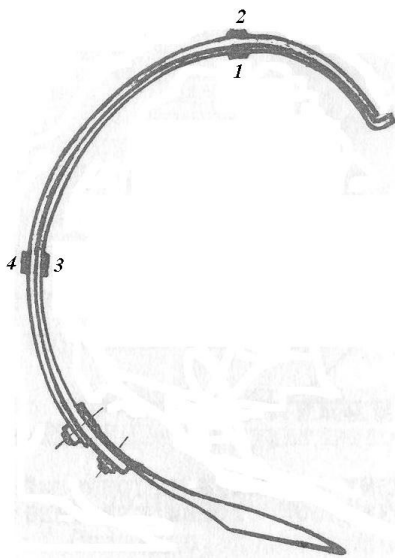


Fig. 1. Spring strut “КПЦ-190” of the cultivator “КПЦ-4” [20]: 1-4 – resistive-strain sensors

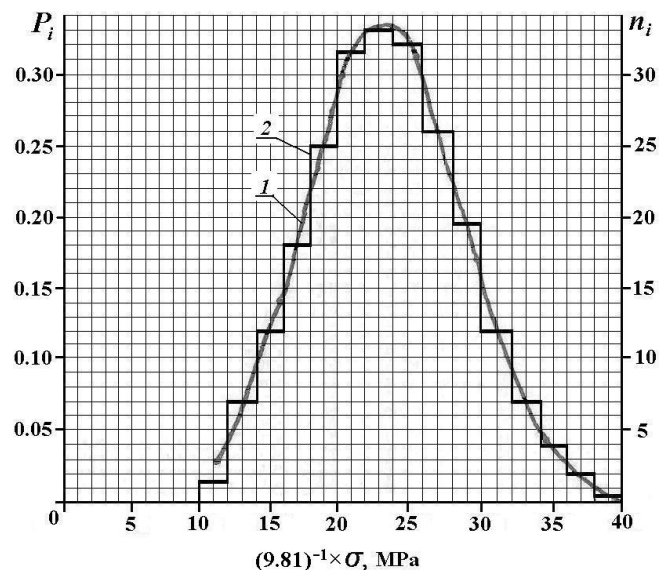


Fig. 2. Distribution of the transformed amplitudes of operational stresses σ in the spring strut: 1 – probability of stress action $p = p(\sigma)$ [20; 21]; 2 – number of cycles n of each stress range in the loading block

The spring struts are made of steel “65Г”. Steel “65Г” is non-alloy steel. According to the Russian standard GOST 14959-2016, the chemical composition of steel “65Г” is (weight %): 0.62-0.70 C, 0.90-1.2 Mn, 0.17-0.37 Si, up to 0.25 Cr, up to 0.25 Ni, up to 0.20 Cu, up to 0.035 P and up to 0.035 S. And the mechanical properties of this steel are: tensile strength 980 MPa, yield strength 785 MPa, minimum elongation 8 %, minimum reduction in area 30 %. The endurance limit of the spring strut was set experimentally [20; 21] and was 206 MPa. Parameters of the fatigue curve of the spring strut’s steel: $N_0 = 2 \cdot 10^6$, $m = 4$.

As a result of calculations, it is established that the safety factor in relation to the endurance limit is only 0.7 [20; 21]. Therefore, the amplitude of the cyclic stress, which is equivalent to the operating stress spectrum (according to the damaging effect), is $206/0.7 = 294.3$ MPa.

In this paper, the continuous distribution 1 of the transformed stress amplitudes was replaced by a discrete spectrum 2 (Fig. 2). This replacement was made approximately, with rounding to a half-cycle (Table 1). The resultant loading block is $\nu_{\delta} = 231$ cycles. For this spectrum, the amplitude of the cyclic stress σ_{II} was determined, which is equivalent in terms of damaging effects to operating stresses. As a result of summation of fatigue damages by means of the Palmgren-Miner law [22], it was received:

$$N_C = \frac{\sigma_{-1}^m N_0}{\frac{1}{\nu_\delta} \sum \sigma_i^m \nu_i} = \frac{206^4 \cdot 2 \cdot 10^6}{\frac{1}{231} (7.9427 \cdot 10^{11})} = 1.0477 \cdot 10^6 \text{ cycles}, \tag{1}$$

$$\sigma_{II} = \sigma_{-1} \sqrt[m]{\frac{N_0}{N_C}} = 206 \sqrt[4]{\frac{2 \cdot 10^6}{1.0477 \cdot 10^6}} = 242.1 \text{ MPa}, \tag{2}$$

where N_C – calculated number of stress cycles over the cultivator’s service life, cycles;
 N_0, m – parameters of the fatigue curve of the spring strut steel;
 σ_{-1} – endurance limit of the spring strut, MPa;
 ν_δ – total number of cycles in the loading unit;
 σ_i – transformed stress amplitude of level i of the operating spectrum, MPa;
 ν_i – number of acting cycles of stress σ_i in the operating spectrum;
 σ_{II} – amplitude of the cyclic stress, which is equivalent to the damaging effect of the operating stress spectrum, MPa.

Table 1

Spectrum of operating stresses

Amplitude σ_i , MPa	Number of cycles ν_i	Amplitude σ_i , MPa	Number of cycles ν_i	Amplitude σ_i , MPa	Number of cycles ν_i
382.6	0.5	284.5	19.5	186.4	25
363.0	2	264.9	26	166.8	18
343.4	4	245.3	32	147.2	12
323.7	7	225.6	33	127.5	7
304.1	12	206.0	31.5	107.9	1.5

Additionally, the calculation was performed using the corrected linear hypothesis of fatigue damage summation [23]. The peculiarity of this hypothesis is to plus into account some stresses that are less than the endurance limit: $\sigma_i \geq K\sigma_{-1}$. For the considered spectrum, $K = 107.9/206 = 0.5238$. As a result, it was received:

$$N_C = \frac{a_p \sigma_{-1}^m N_0}{\frac{1}{\nu_\delta} \sum \sigma_i^m \nu_i} = \frac{0.44094 \cdot 206^4 \cdot 2 \cdot 10^6}{\frac{1}{231} (7.9427 \cdot 10^{11})} = 0.46196 \cdot 10^6 \text{ cycles}, \tag{3}$$

$$\sigma_{II} = \sigma_{-1} \sqrt[m]{\frac{N_0}{N_C}} = 206 \sqrt[4]{\frac{2 \cdot 10^6}{0.46196 \cdot 10^6}} = 297.2 \text{ MPa}, \tag{4}$$

where $a_p = \frac{\max \sigma_i \cdot \zeta - K\sigma_{-1}}{\max \sigma_i - K\sigma_{-1}} = \frac{382.6 \cdot 0.5986 - 0.5238 \cdot 206}{382.6 - 0.5238 \cdot 206} = 0.44094$;

$$\zeta = \frac{\sum \sigma_i \cdot \nu_i}{\max \sigma_i \cdot \nu_\delta} = \frac{52905.3}{382.6 \cdot 231} = 0.5986.$$

The evaluation of applicability of tin fatigue gauges for monitoring the operational load of the cultivator spring strut was carried out experimentally in laboratory conditions. Test specimens of the same steel “65Г” as the spring strut were used (Fig. 3). One specimen was subjected to a load that reproduced the operational load spectrum, but the stress values were reduced by 3 times. Another specimen was tested under symmetrical bending conditions with constant amplitude.

Proportional stress reduction was performed to match the values and the number of cycles in the loading block with the properties of tin fatigue gauges. Thus, the principle of compatibility [2] was used. In real operating conditions, to reduce the bending stresses, the sensor is shifted either to the neutral axis of the beam, or in the direction of reducing arm of the force. If there is a stress concentration, the sensor moves away from the concentrator.



Fig. 3. Test specimens with fatigue gauges

The scheme of the testing stand is shown in Fig. 4. Alternating application of the weight P to the bowls 5 or 7 creates a variable bending moment with the amplitude $P\ell$ in the cross sections of specimen 1. The number of stress cycles was fixed by help of the electronic counter 6. The sequence of application of the load was determined by random sampling (Fig. 5).

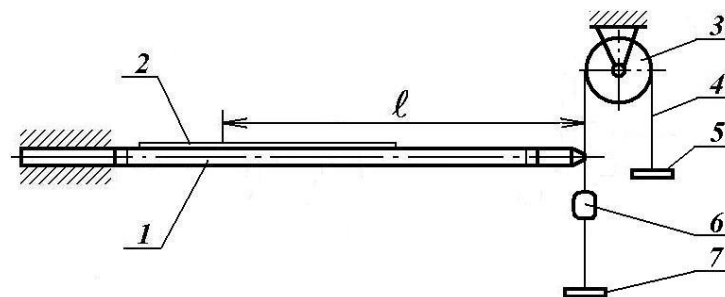


Fig. 4. Scheme of testing stand: 1 – test specimen; 2 – fatigue gauge; 3 – guide roller; 4 – thin steel cable; 5, 7 – bowls for loads; 6 – counter of stress cycles

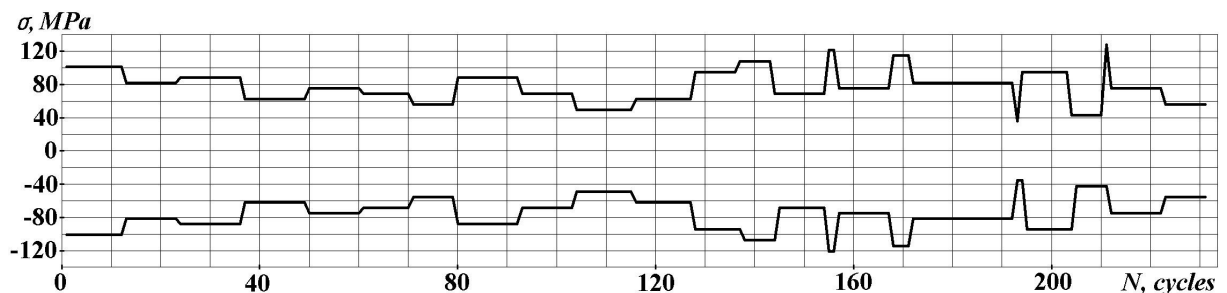


Fig. 5. Diagram of imitated operating stresses

After each loading block (i. e. after 231 cycles of stresses), inspection of the surface of the fatigue gauge was carried out. An optical microscope “МБС-9” was used with magnification of $100\times$ and direct illumination.

The amplitude of cyclic stresses on the specimen surface was calculated in MPa by the formula [22]:

$$\sigma_a = \frac{6P\ell}{bt^2}, \quad (5)$$

where P – weight of the load, N;

ℓ – distance from the line of gravity of the load P to the inspected cross-section of the specimen, mm;

b – width of the inspected cross-section of the specimen, mm;

t – thickness of the inspected cross-section of the specimen, mm.

Results and discussion

As a result of the tests, after the first load block, the value of the cyclic stress amplitude of $\sigma_{II} = 82.6$ MPa was established. This answer is obtained by comparing the appearance of the surfaces of two fatigue gauges: 1) the gauge after 231 cycles of loading by the operational stress spectrum; 2) the gauge after 231 cycles of loading at constant stress amplitudes. Taking into account the applied decrease ratio $\sigma_{II} = 82.6 \times 3 = 247.8$ MPa. This result practically coincides with the stress value (2) obtained by the Palmgren-Miner fatigue damage summation hypothesis: the discrepancy is only + 2.3 %. The deviation from the result (4) of the corrected hypothesis is more significant: - 19.9 %.

Fragments of the foil surfaces with practically equal damages are shown in Fig. 6 a, b. Typical damages are circled. The sizes of the damages and their number on both fragments are almost equal.

The appearance of the fatigue gauge after 231 loading cycles at constant stress amplitude of $\sigma_{II} \approx 297.2/3 = 99.1$ MPa (4) is significantly more damaged (Fig. 6 c).

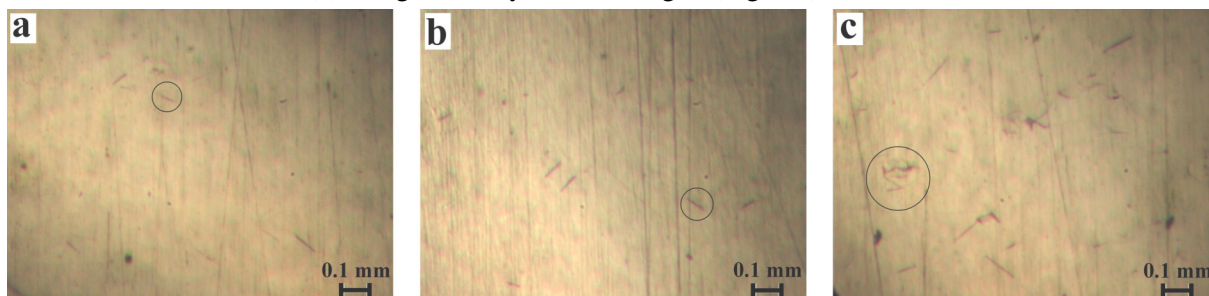


Fig. 6. **Appearance of the gauge surfaces:** a – after loading by operational stress spectrum; b – after loading at constant stress amplitude 82.6 MPa; c – after loading at constant stress amplitude 101.8 MPa

Conclusions

1. Fatigue gauges made of tin foil quickly react to operating stresses. The technology of application of fatigue gauges to estimate the values of the acting cyclic stresses is available to farmers and students-trainees.
2. The use of highly sensitive fatigue gauges made of tin foil together with the linear damage theory provides sufficient accuracy of the results: the discrepancy is less than 3 %.

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