Formation of System of Scattered Fatigue Damages and Their Effect on Fracture of Structural Silicon Steel

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Abstract. Forecasting of a residual life of machine elements and structures requires consideration of changes of a metal condition during operation. The aim of this article was to study accumulation of critical fatigue damage in structural silicon steel under operational impacts characteristic of the permafrost region. The metal of various zones of a failed main leaf of a truck spring, which was operated under the subarctic conditions, was investigated. It was revealed that formation of a system of volume scattered microdamages at a level of substructure and mesoscale damages in a form of fine and coarse pores ranging in size from a few micrometers to \(\approx 40 \, \mu m\) preceded fatigue failure of the spring. It is shown that at a stage of material prefracture a deviation of a microhardness distribution from the normal distribution is observed. For the considered operating conditions, a determining role of presence of multiple fine pores in reducing resistance to the fatigue failure as compared to the presence of the coarse pores has been established. Results can be used in development of methods for studying the structural damage of materials and identification of fatigue failure stages.

1. Introduction

The failure of the elements of metal structures and parts of machinery in the actual operation is usually due to the formation of local structural damages of material, the accumulation and fusion of which leads to initiation and development of micro- and macrocracks [1-3]. Therefore, research of the structural damage accumulation in the various metals and alloys has been and remains an urgent problem of materials science and engineering. In this case, it is necessary to carry out studies of a material damage rate taking into account the loading conditions to establish relationships between variability parameters of material characteristics and operating factors. Evaluation of an effect of the various factors (including natural and climatic ones) on reliability and safety of technical facilities, the development of various nondestructive testing methods to assess a current state of their material have important scientific and applied significance [4-6].

As is known, in most cases the parts of vehicles experience repeated and alternating loads, which lead to an appearance and development of fatigue damages. Thus, the suspension elements, which are usually made from the silicon steels, belong to machine components experiencing the fatigue failure [7, 8]. The steels of this class are widely used in the suspension elements of the wheeled vehicles.
Processes of the fatigue damage accumulation in them are practically absent, especially when they operate in the North. A characteristic feature of the operation of these elements is that they should only have elastic deformation under the considerable static and dynamic loads. Therefore, the used steels must have high values of an elasticity limit, yield strength and endurance limit. At the same time, some microdamage always appears in the structure of the metals even at the stage of the elastic deformation under the long lasting loads [9-11]. In [12] it was revealed that even at low temperatures (of a climatic range) microprocesses of the deformation take place as the result of long lasting action of cyclic and static loads with stresses, which are considerably less than the yield strength. This agrees with an insignificant reduction of the metal hardening characteristics in the inelastic range when a temperature decreases, including the case of the repeated static loading [13]. During the operation in the “elastic range”, obtainment of the certain level of the microdamage development transfers the metal to the plastic deformation range. This is followed by common phenomena of the deformation hardening and subsequent softening. Depending on the stage of the damage development, metal specimens should differ according to the number of deformation-hardened and deformation-softened crystallites, as well as discontinuities in the form of pores.

The fact of a certain discrepancy between the test results obtained under the laboratory conditions and actual operation ones is known. In connection with this, it is important to study the progressing fatigue defects of the material, formed precisely under the real conditions of the operation of the machine part. The aim of this article is to study the accumulation of the critical fatigue damage in the structural silicon steel under operational impacts characteristic of the permafrost region. This formulation of the problems allowed one to obtain new data that develop a concept of the structural damage as the factor determining the formation and occurrence of the limit state of the material.

2. Material and investigation methods

The silicon steel, which had the operating time in the subarctic road and climatic conditions, was used as the material of the study. The metal of the failed main spring of the front suspension of the truck, which was operated mainly in winter, was researched. Chemical composition of the steel is the following: Fe; Si, 1.68; Mn, 0.74; C, 0.63; Cr, 0.14; Ni, 0.09; Cu, 0.11 wt. %. The fatigue failure occurred at the stage corresponding to normal wear of the springs [14]. The crack spread near a front bracket, dividing the spring leaf into long and short fragments (Figure 1).

![Figure 1. Diagram of the failed half of the main leaf of leaf spring of the front suspension. I, II, III, specimens cutting zones.](image)

Three groups of longitudinal specimens with the different levels of damage were made from the long fragment (based on the fact that the zones near points of spring attachment to a front axle and frame of the truck are the most loaded). The specimens marked as group 1 were made of an intermediate piece between a fracture line and spring center. The operating stresses in this piece are lower compared to the ones at the attachment points; therefore the specimens of group 1 were taken as conditionally initial. The specimens from the zone near a fixation of the spring center were designated as group 2, from the prefracture zone (near the fracture) as group 3.

For the study of the damage, the parameters of the microhardness (for a description of the microdamage) and porosity (for the description of the mesoscale damage) were used [15, 16]. The sample size of the measurements of the microhardness $H_{100}$ for each spring zone was approximately 1000 prints. Statistical analysis was carried out in an electronic spreadsheet program Microsoft Excel. For the $H_{100}$ values of the specimens of all three groups, a coefficient of the structural microdamage
accumulation $k$ was calculated in accordance with a procedure described in [16]. This parameter characterizes a relative increase of a material microdamage density during the operation:

$$
k = \frac{\sum_{i=1}^{m_i} a_i n_i^*}{\sum_{i=1}^{m} a_i n_i}
$$

where $n_i$ is the number of the results per a specific interval of a microhardness histogram for the conditionally initial state of the material; $N$ is the total number of the microhardness measurements for the conditionally initial state; $n_i^*$ is the number of the results per the specific interval of the microhardness histogram for the observed state; $N^*$ is the total number of the microhardness measurements for the observed state; $i$ is the number of the current interval of the microhardness histogram; $m$ and $m^*$ are the numbers of the intervals obtained on the microhardness histograms compiled for the conditionally initial state and for the observed one, respectively; $a_i$ and $a_i^*$ are the weight coefficients, which are calculated for each interval within the numbers $m$ and $m^*$ according to formulas, respectively.

With the use of a metallographic microscope, the numbers and total areas of the pores were determined on three viewing fields of the area of $2.0 \times 1.4$ mm. According to their sizes, the pores were conditionally divided into fine (a diameter of up to 20 μm) and coarse (the diameter of the largest ones did not exceed 40 μm). Volume fractions of each group of the pores were designated as $V_{\text{fine}}$ and $V_{\text{coarse}}$, respectively, and the total porosity as $V_{\text{total}}$.

### 3. Results and discussion

Table 1 shows the results of calculations of the coefficient $k$ and the porosity characteristics for all three groups of the specimens. It can be seen that different combinations of the damage are observed in the specimens. Thus, the specimens of group 1, in the metal of which the lower stresses acted in comparison with the ones in the other two groups of the specimens, have the intermediate microhardness values and the lowest total porosity $V_{\text{total}}$. The maximum porosity and microhardness are determined in the specimens of group 2 (the metal is near the central attachment of the spring). According to the volume fraction, the porosity of the specimens of group 3 (near the fracture) is little different from the porosity of the specimens of group 1. The microhardness of the specimens of group 3 is the lowest.

| Parameter | Group 1 | Group 2 | Group 3 |
|-----------|---------|---------|---------|
| $k$        | 1.89    | 2.07    | 1.95    |
| $H_{100}$ MPa | 3720    | 3796    | 3590    |
| $V_{\text{total}} = \frac{V_{\text{fine}} + V_{\text{coarse}}}{\text{total number}}$ | 1.8 / 1081 | 2.2 / 1021 | 1.9 / 1348 |
| $V_{\text{fine}}, \% / \text{total number}$ | 0.9 / 980 | 0.8 / 857 | 1.2 / 1258 |
| $V_{\text{coarse}}, \% / \text{total number}$ | 0.9 / 101 | 1.4 / 164 | 0.7 / 90 |

Differences in the histograms shown in Figure 2 indicate the different levels of the development of the processes of the hardening and softening of the metal of the various zones of the spring. For the specimens of group 1, in spite of some asymmetry of the histogram, the law of normal distribution is not rejected (at the standard deviation $s = 265$ MPa, the $H_{100}$ values are within the interval $\pm 3s$). The distributions of the microhardness $H_{100}$ of groups 2 and 3 have a larger dispersion and skewness. For the specimens of group 2, there is a shift towards the increase of the microhardness (the hardening processes have not reached saturation, the metal is at the hardening stage). And for the specimens of
In group 3, there is the shift in the direction of decrease of the microhardness, i.e. the metal is already softened due to the microdamages.

![Figure 2. Distributions of microhardness: (a) specimens of group 1; (b) specimens of group 2; (c) specimens of group 3.](image-url)

The qualitative change in the structural state of the specimens of group 3 is confirmed by the change in the configuration of their histogram. The form of the histogram (Figure 3c) allows us to assume that the normal distribution is not true for the sample values of the metal microhardness near the prefracture zone. The test of a statistical hypothesis of the normal distribution by the criterion $\chi^2$ for the empirical distribution yielded the value $\chi^2 = 121$ for the calculated critical value $\chi^2_{cr} = 16$, i.e. $\chi^2 > \chi^2_{cr}$. Consequently, the hypothesis of the normal distribution for the microhardness of the specimens of group 3 is indeed rejected. It is fair to assume that physical reasons for the deviation of the law of distribution of the microdamage from the normal distribution in the prefracture zone are the significant changes in the structure of the material during the operation. The authors of [17] observed the fracture of the initial lath martensite structure as well as a martensitic transformation of retained austenite when studying the fatigue changes in the structure of the silicon steel of the similar composition. The formed martensite, as a stress concentrator, can become a source of microcracks. In addition to the changes in the substructure and structural-phase transformations, a distortion of the damage distribution law is obviously due to discontinuities of the material in the form of micropores [18-20].

![Figure 3. Distributions of microhardness: (a) specimens of group 1; (b) specimens of group 2; (c) specimens of group 3.](image-url)

If we consider the specimens of groups 2 and 3 from the spring zones of the greatest loading, it is seen (Table and Figure 2) that for the smaller values of the coefficient of damage accumulation $k$ and the volume fraction of the total porosity $V_{total}$, the fracture occurred in the zone characterized by:
- the lower value of the microhardness (due to the processes of the softening);
- the deviation of the law of the microhardness distribution from the normal one;
- a significant predominance of the number of the fine pores (by ≈47%);
- the significantly smaller number of the coarse pores (by ≈45%).

It follows that the multiple fine pores as well as the substructural softening contribute to the accumulation of the scattered fatigue damage. This is manifested in the change in a character of the microhardness distribution, which is affected by both the structural features of the metal and presence of the microscopic discontinuities.

4. Conclusion
It is revealed that the formation of the system of the volume scattered damage of the structure preceded the occurrence of the local limit state and fatigue failure of the silicon steel during the operation in the road-climatic conditions of the permafrost region. There are the microdamages at the level of the substructure and the mesoscale damages in the form of the fine and coarse pores ranging in size from a few micrometers to ≈40 μm.
The prefailure zone with the intermediate values of the coefficient of the microdamage accumulation and the volume fraction of the total porosity is characterized by:
- the lower value of the microhardness (due to the processes of the softening);
- the deviation of the law of the microhardness distribution from the normal one;
- the significant predominance of the number of the fine pores;
- the significantly smaller number of the coarse pores.

Under the considered operating conditions, the combination of the substructural damages with the multiple fine pores was a critical type of defectiveness with the more unfavorable effect on the resistance of the test material to the development of the fatigue failure in comparison with the presence of the coarse pores.

5. References
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