Significance evaluation of effect of operational changes in material on impact strength of various zones in leaf spring at low temperature

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Abstract. Significance of the effect of structural changes in spring steel arising during operation in various zones of the leaf springs on zonal resistance of the steel to a brittle fracture at temperatures of a climatic range of a permafrost region is studied. Structural damage was determined at the temperatures of 20, –20 and –60 °C and impact strength of the different zones of the leaf spring failed during the operation was estimated. Features of a fine structure of fracture surfaces of Charpy specimens and micromechanisms of their failure are investigated. To determine variability of the impact strength in the zones of the spring, analysis of variance (ANOVA) of test data was carried out. It was found that at temperatures of 20 and –20 °C the effect of the zone damage of a material on the impact strength is insignificant, and at –60 °C the effect of the zonal damage on the resistance to the brittle fracture becomes significant. The fractographic features of the fine structure of the fracture surfaces at the various test temperatures are discussed. Results can be used in a prediction of a life time of elastic elements in vehicle suspension: it is necessary to take into account zoning of the operational damage of the steel under conditions of the low climatic temperatures.

1. Introduction

One of actual problems while attempting to ensure operability of machinery in the North is a low of reliability of elastic elements of vehicle suspension at low climatic temperatures (–50 °C and below). The leaf springs of motor transport under low temperatures exhibits life time reduced by 1.5-5 times [1]. The operating life of the elastic elements of the suspension at the low temperatures is decreased because of shock cyclic loads transferred to the transport vehicles when driving on roads with uneven surfaces (winter, ice and dirt roads). These loads lead to formation of the micro- and mesodamages in a material structure, integration of which leads to emergence and development of micro- and macrocracks [2, 3, 4]. Therefore, research of accumulation of the structural damage, the formation and propagation of the micro- and macrocracks in the material of the elastic elements at the low temperatures is of great importance for diagnostic tests of their current state and forecast of the residual life time. A necessary stage in such studies is a determination of the significance of zonal heterogeneity of the structural changes arising from operation in details and the effect of the structural damage on physico-mechanical characteristics of the material, which are associated with the
operability of the elastic elements at the low climatic temperatures. A structural steel ability to resist the brittle fracture is evaluated by the results of the tests of notched specimens for impact bending at the climatic range temperatures. The aim of this article is to study the significance of the effect of the material changes occurring in different zones of the spring during the operation under the climatic conditions on the zonal resistance of the spring steel to the brittle fracture when the temperature decreases to −60 °C.

2. Material and investigation methods
The object of the research is the main spring leaf of the front suspension of a KAMAZ truck. The main leaf made of steel 60S2 underwent fatigue failure during the operation in the road-climatic conditions of Yakutia with 62,000 miles to failure [5, 6]. The fatigue crack passed near a front bracket attaching the spring to a frame of the truck. The crack divided the spring leaf into two fragments. To determine the impact strength, the Charpy specimens were made from the long fragment. The longitudinal specimens were cut from three zones of the spring, ranked according to intensity of the operating loads. Zone I is located near the fracture, i.e. near an attachment of the main leaf to the truck frame through the bracket, zone II is in the middle between the fracture and center of the leaf, where the spring is attached to a front axle, zone III is near the spring center. The transverse loads from the vehicle frame and longitudinal pushing and braking forces, as well as the lateral forces during the turn, are transferred to the main leaf when the vehicle is moving. Theoretically, zone III near a place of attachment of the spring to the front axle is the most loaded one, where the greatest internal bending moment arises from the transverse load. Near the attachment of the front spring to the frame (zone I) there is a multiaxial stress state associated with the transfer of the transverse, longitudinal and lateral forces to the spring. Zone II is considered less loaded.

Three groups of the specimens were tested for the impact bending in accordance with the standard method on a pendulum impact tester Amsler RKP 450 Zwick within a temperature chamber providing the specimen temperatures in the range of −80 °C to the room temperature. The tests were carried out at 20, −20 and −60 °C. A width of the spring allowed to cut out 6 specimens within each zone with dimensions of 10 × 10 × 55 mm (two specimens for each test temperature).

An electron fractographic investigation of the specimen fractures was also performed to reveal the fine structure of the fracture surfaces in detail (scanning electron microscopes TM 3030 Hitachi and JEOL JSM-6480LV were used).

3. Results and discussion
The test results and dispersion parameters of the impact strength KV in each zone are shown in Table 1. From Table 1 it can be seen that the decrease of the impact strength occurs more intensely in the range of the temperatures from 20 to −20 °C than in the one from −20 to −60 °C. The largest value range of the impact strength KV is observed in locations where the main leaf is attached to the frame and front axle of the truck (the most loaded zones I and III). The considerable spread of the impact strength in each zone indicates the significant differences of the metal structural and mechanical states not only along a length of the spring, but also across its width. The greatest spread of the KV values is observed at 20 °C. As the temperature decreases, the variation reduces; it will be presented below that this should be associated with a reduction in the ability of the material to deform.

To assess the effect of operational changes in the material on the impact strength of different zones of the main leaf, the analysis of variance was carried out. A level of the damage in the spring metal was taken as a dependent variable (a factor) affecting the response variable (the impact strength at the different temperatures). Considering that each zone of the spring leaf exhibits its level of the structure damage to the metal, we range the test results into three groups. A procedure of the analysis of variance of the data consists in the determination of a ratio of the systematic variance between the groups to the random variance within the groups.
When applying the single-factor ANOVA, there should be at least three levels of the independent variable and at least two observations at each level. The results of the impact strength tests at the different temperatures satisfy these requirements: a number of the levels $m = 3$ (according to the three zones) and the number of observations at each level $n = 2$. For the results at each temperature for the total number of observations $N = 6$, we obtain the following degrees of freedom: between the groups $f_{BG} = m - 1 = 2$ and within the groups $f_{WG} = N - m = 3$.

We will perform the analysis of variance at 20 °C. A subject to verification is a null hypothesis: the mean values of the impact strength within the three zones differ insignificantly, i.e. all the groups of the test results are random samples from the same population. The data for a calculation are given in Table 1. The total average for all the impact strength values is equal to 247 kJ/m². We will find a sum of the squared differences of the impact strength values from the mean within the groups $SS_{WG} = 7458.2$ and the “between-group” sum of the squared differences of the values from the total average $SS_{BG} = 1520.6$. The “within-group” mean square value is $MS_{WG} = \frac{SS_{WG}}{f_{WG}} = \frac{7458.2}{3} = 2486.1$ and the between-group mean square value is $MS_{BG} = \frac{SS_{BG}}{f_{BG}} = \frac{1520.6}{2} = 760.3$. The ratio of the between-group variance to the within-group one has an $F$-distribution. To verify the null hypothesis, we use $F$-test. An $F$-test statistic is calculated using the following formula: $F = \frac{MS_{BG}}{MS_{WG}} = \frac{760.3}{2486.1} = 0.3$. With a desired false-rejection probability $\alpha = 0.05$ and the degrees of freedom $f_{BG} = 2$ and $f_{WG} = 3$, we determine the critical value $F_{cr} = 9.6$. Since the test statistic $F$ is less than the critical value $F_{cr}$, there is no reason to reject the null hypothesis: the group averages differ insignificantly (the factor of the zone affects insignificantly at the test temperature of 20 °C) [7].

Similarly, we will perform the calculations for the test temperatures of -20 and -60 °C. The results of the calculations are given in Table 2. It can be seen that the empirical values of the $F$-test increase as the temperature decreases, and at the temperature of -60 °C this parameter exceeds the critical value $F = 10.2 > F_{cr} = 9.6$, which allows rejecting the null hypothesis and accepting that the group averages differ significantly. Thus, at the temperature of -60 °C, the variability of the impact strength is due to the studied independent variable – the factor of the spring zone with the different material damage. A physical nature of this effect is discussed below in the analysis of the parameters of the microdamage
(the substructure changes are estimated by the microhardness measurements) and mesodamage (porosity) in conjunction with the microstructure features of the fractures. A damage evaluation was carried out in [5], in which it was revealed that the metal structure of the three zones differs in the mesodamage the most. Appearance and role of the porosity in the fatigue are considered, for example, in [8, 9]. Zones I and II are characterized by the almost identical volume ratio of pores, but the small pores prevail in zone I. Zone III has the largest volume ratio of the mesodamages due to prevalence of the coarse pores.

Table 2. Analysis of variance of test results.

| Temperature | $x_m$ | $SS_{bg}$ | $SS_{bg}$ | $MS_{BG}$ | $MS_{BG}$ | $F$ |
|-------------|-------|------------|------------|------------|------------|-----|
| 20 °C       | 247   | 7458.2     | 1520.6     | 2486.1     | 760.3      | 0.3 |
| –20 °C      | 165.2 | 985.3      | 1636.9     | 328.4      | 818.5      | 2.5 |
| –60 °C      | 125   | 144.3      | 981.2      | 48.1       | 490.6      | 10.2|

The secondary cracks were found in the fractures of all the Charpy specimens (Figures 1 and 2), the microstructure of which reflects the mechanisms and energy intensity of the development of the specimen fracture as a whole.

Figure 1. Microstructure of fracture surfaces of metal specimens from zone I (a), zone II (b) and zone III (c), tested at –20 °C.

Figure 2. Microstructure of fracture surfaces of metal specimens from zone I (a), zone II (b) and zone III (c), tested at –60 °C.

As can be seen in figures 1 and 2, the cracks are formed by coalescence of the pores. The pore coalescence is particularly well traced within a dashed circle in figure 1(c). For zone III with the
coarse pores, this process was accompanied by a noticeable plastic deformation (stretching the pores till their coalescence, deforming cavity walls) even at −60 °C. The deformation of the material by stretching the pores and their fusion is also traced in the fractures of the specimens of zones I and II tested at −20 °C, but the smaller length of the secondary cracks is noticeable. At −60 °C, their trajectory becomes more broken (Figures 2(a) and 2(b)) that indicates the decrease in the ability of the material to deform. Smoothness of the walls of the resulting secondary cracks confirms the brittle mechanism of their opening by splitting crystallites. Thus, the changes in the values of the impact strength and their dispersion, depending on the spring zone and test temperature, are due to the effect of the existing structural damage on a possibility of microdeformations as the mechanism of material adaptation to the loads and, accordingly, the resistance to failure.

4. Conclusion
The analysis of variance of the data of the test on the impact strength for the Charpy specimens from the different zones of the main leaf of the KAMAZ truck spring was carried out. Comparison of the test statistic $F$ with the calculated critical value showed that with the desired false-rejection probability $\alpha = 0.05$, the factor of the zone with the different damage at the test temperatures 20 and −20 °C affects the impact strength insignificantly. At −60 °C, the differences are reliable in a statistical sense that indicates the significant effect of the structural damage of the spring zone on the zonal resistance to the brittle fracture at this temperature. The mechanism of the effect is determined by the possibility of the microdeformations as a way of the material adaptation to the loads. The obtained results point out the necessity of the zoning of the spring leaf along the length and width during the evaluation of the metal structural damage and can be used in a prediction of life time of the elastic elements in the vehicle suspension under conditions of the low climatic temperatures.

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