Determination of babbit mechanical properties based on tin under static and cyclic loading

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Abstract. Based on the results of studies of babbit on the basis of tin under static loading under three types of stress state, the parameters of the criterion for the equivalence of stressed states were refined and a single diagram of the babbit deformation was obtained. It is shown that the criterion of equivalence for static loading should contain the first principal stress and stress intensity. With cyclic loading, the first main voltage can be used as a criterion. The stages of development of fatigue cracks are described and it is logical to use a statistical approach to reveal the boundary of the transition from short cracks to macrocracks, based on a significant difference in the characteristics of the dispersion of the crack speeds at these two stages. The results of experimental studies of the cyclic crack resistance of babbit are presented and the parameters of this boundary are obtained.

1. Introduction
An increase of friction units durability is an urgent task. One of the ways to solve this problem is the computational modeling of contact interaction and accumulation of damages on the friction surface. The availability of such calculation methods allow one to evaluate the durability of friction units at the design stage and to reduce the time of their development in order to achieve the required durability parameters. Plain bearings are selected as an example of friction unit.

Fairly common methodology of plain bearings durability estimation with consideration of the fatigue and wear-contact damages and interference of all damaging factors [1] was previously proposed. The generalized model of damage accumulation and the destruction of the material by V.V. Bolotin [2], as well as numerical techniques of V.V. Grib [3] for the calculation of wear of surfaces are the theoretical basis of damage calculation. The schemes of connections between the areas are analyzed in accordance with the classification of the kinematic conditions of wear in areas [1, 3 - 5].

For many years the author has carried out the research on the various mechanical properties of antifriction materials for sliding bearings. In particular, the properties of babbit B83, containing, in addition to Sn 10 .. 12% Sb and 5.5 .. 6.5% Cu, have been investigated. The results of experimental studies are generalized in the author's monograph [1]. Studies [6] of the properties of this babbit, necessary to perform an estimation of the stress-strain state and the durability of the babbit layers of bearings, are continuing [1]. The proposed article presents the results of recent studies.

2. The influence of the stress state on the elastoplastic properties of the material
Antifriction materials in bearings are almost always loaded with a multiaxial stress-strain state.
Therefore, in order to realize the possibility of performing stress calculations in an elastoplastic setting, it is necessary to carry out experimental studies of the influence of the stress state on the elastoplastic properties of the material. A criterion for the equivalence of stresses must be obtained. In addition, in order to perform the calculations, one needs a material deformation diagram, constructed in the coordinates "equivalent stresses - equivalent deformations", called the generalized deformation diagram.

The simplest criterion of stress equivalence postulates that a hazardous material state occurs when one of the main stresses reaches the ultimate strength of the material. The first main stress is compared with the tensile strength of material \( \sigma_1 \leq \sigma_s \), and third principal stress \( \sigma_3 \geq \sigma_s \) (usually negative) is compared with the compressive strength. The theory of the equivalence of stressed states, which in the theory of plasticity has received the name of the Huber-Huber-Genka-Mises, is widely used \([7]\). The criterion of equivalence is the intensity of stresses \( \chi \sigma_i \leq 1 \).

There are unified theories of strength, the distinguishing feature of which is the use in the criterial expression of not one but several stress parameters. As a result of the analysis of a large number of experimental data, G.S. Pisarenko and A.A. Lebedev \([8, 9]\) proposed and demonstrated a high accuracy of equivalence criterion \( \chi \sigma_i + (1 - \chi) \sigma_1 \leq \sigma_s \), where the \( \chi \) parameter can be determined from the results of experiments with two different types of uniaxial stress states. For example, if the ultimate stresses are obtained in tension, compression and torsion \( \sigma_1, \sigma_3, \tau \), then \( \chi = \sigma_3 / \sigma_s \) or \( \chi = (\sigma_3 - \tau) / (\sqrt{3} - 1) \).

And if the material is plastic, then \( \sigma_1 = \sigma_s \) and \( \chi = 1 \), and \( \sigma_3 \leq \sigma_s \) become the criterial expression usually applied to ideally plastic materials. If the material properties approach the ideal brittle, its compressive strength \( \sigma_3 \) tends to infinity, and the \( \chi \) parameter tends to zero. The criterion for ideally brittle materials is valid, which in this case has form \( \sigma_3 \leq \sigma_s \).

To study the properties of a material under a complex stress state, the thin-walled tubular samples \([8; 9]\) are applied. The author carried out tests of tubular samples made of babbitt B83 with a ratio of the working part diameter to its length of 1:2.5 and with a smooth fillet transition to threaded gripping areas with three kinds of uniaxial stress state: tension, compression and torsion. The following average values of the limiting stresses are obtained: tensile yield stress \( \sigma_{ys} = 49 \) MPa, yield stress under compression - \( \sigma_{yc} = 75 \) MPa, yield stress under torsion \( \tau_{yt} = 27 \) MPa; tensile strength \( \sigma_t = 65 \) MPa, compressive strength - \( \sigma_c = 96 \) MPa, torsional strength \( \tau_t = 49 \) MPa. Calculated for many combinations of pairs of tested samples, the \( \chi \) parameter after averaging is taken equal to 0.78. The criterion for the equivalence of strained states for babbitt B83 has form \( \sigma_{equ} = 0.78 \sigma_s + 0.22 \sigma_1 \). Equivalent deformations are calculated by the formula, where \( \varepsilon_i \) is the strain intensity, \( \varepsilon \) is the first major deformation.

3. The construction of a generalized babbitt deformation diagram

Three diagrams of deformation of tubular babbitt samples (under tension, compression and torsion) are converted to the coordinates "equivalent stresses \( \sigma_{equ} \) - equivalent deformations \( \varepsilon_{equ} \)" and the points from these diagrams are plotted on the corresponding coordinate plane (Figure 1). It can be seen that all the points are grouped close enough to some single curve line. Thus, the validity of the Pisarenko-Lebedev equivalence criterion \([8, 9]\) for babbitt B83 at the value of parameter \( \chi = 0.78 \) is confirmed. Consequently, babbitt showed the properties of quasi-brittle material. The existence of a single (generalized) deformation curve for a babbitt is also confirmed.
Figure 1. A Babbit deformation diagram, constructed based on the results of tests with three types of uniaxial stress and its approximation by a 6th degree polynomial

Figure 2. Results of fatigue tests of tubular samples made from babbit B83 under symmetrical loading by axial load (▲) and torque (■)

The criterion for the equivalence of stresses under cyclic loading was also evaluated. According to the recommendations of [8, 9], tubular samples were made from babbit B83, some of which were tested under axial loading in a symmetrical cycle; the other part was tested under loading acting with symmetrical torque with amplitudes in the range of 20 ... 90 Nm. The results of the tests are shown in Figure 2. It can be seen that when under torsion and loading with the axial force, the durability of tubular samples are practically identical. The fatigue curve is approximated by power function 

\[ N(\sigma, \tau) = 0.387 \times 10^3 \]

The absence of tests for more complex types of loading makes it possible at the present time to formulate only approximate conclusions about the influence of the form of the stressed state on babbit fatigue durability. Namely, at this stage of the study, it can be assumed that with the durations from \(10^4\) to \(10^7\) cycles \(\sigma = \tau\). This means [8, 9] that as the criterion for the equivalence of stressed states in the multi-cycle babbit loading, the first principal stress \(\sigma_1\) can be applied.

4. About the model of calculating the life of an antifriction bearing layer

Based on the combined model of V.V. Bolotin [2], the author proposed [1] a model for calculating the accumulation of damage, the nucleation and development of a system of cracks in antifriction layers. The following simplified gradation of cracks in size is used. Cracks are usually called small (or microcracks), if their length does not exceed the grain size of the material. The stress concentrations at their vertices are comparable with the microstructural concentration of stresses. The criterion for assigning a crack to the category of macroscopic (long) ones is a high concentration of stresses at its apex in comparison with the microstructural concentration of stresses. Typically, the macrocrack embryo exceeds the dimensions of the structure elements several times (up to 10 or more times). Short cracks are commonly those having dimensions larger than the grain size, but smaller than the size of the macrocrack embryo. The size of a short crack can also be conditionally estimated by parameter \(m\) - the number of merged (nearby) disintegrated grain structures (microcracks). This parameter can be counted from \(m=2\) (two microcracks combined) and up to \(m^*\) corresponding to the size of the macrocrack nucleus \(l^*\).

At a high stress level, the growth of cracks begins with the very first loading cycles. This also happens at lower stress levels, if already before the beginning of the part operation there is a significant amount of crack-like defects in its volume and on the surface. Moreover, the concentration of initial and newly appeared microdefects in the near-surface layers may be several orders of magnitude higher than in the deep layers [10 - 13]. If one plots the increments in the lengths of individual cracks (figure 3), then it is evident that most short cracks stop, not reaching the size of the
The processes of development of short and macrocracks can be combined on the kinetic diagram of fatigue (figure 5). Here, the so-called generalizing scheme of the stages of development of fatigue cracks is presented, based on sufficiently representative experimental studies and review publications [11 - 13].

On the horizontal axis, the length of the crack or the change (scale) of the stress intensity factor can be measured along the vertical - the rate of the crack development. In Figure 5, solid lines are plotted: 1 - kinetic diagram, characteristic for macrocracks; 2 - describes the development of short effective cracks that grow into macrocracks; 3 - characterizes the development of non-propagating (inefficient) cracks. The dashed lines 4', 4", 4''' delineate the boundaries of the scattering area of the experimental values of the rates of development of all cracks. Moreover, 4''' boundaries do not often occur, which means the presence in the material of non-propagating cracks of very small dimensions. In fact, in the pre-threshold region, there is a system of short cracks, and the rates of their development differ significantly (by several orders of magnitude).

In the mechanics of the development of long fatigue cracks, it is assumed that there is a certain threshold value of the stress intensity factor (and the corresponding value of the crack length at each stress level) - point 5 on the abscissa axis, to the left of which cracks do not develop. In the fatigue fracture, it is possible to distinguish three zones corresponding to different stages of development of macrocracks: the zone of development of a crack with an insignificant effect of plastic deformations (conditionally called elastic deformation) $e$; the zone of crack development with the effect of $ep$ plastic; the zone of sample fracture $fr$.

The strong influence of the statistical nature of the development of cracks, the dispersion of the criterial values of the transition parameters from one stage to another clearly demonstrate the complexity of the application of deterministic models and methods for processing experimental data. Statistical models and methods for processing the experimental results are promising. In particular, the dimensions of the macrocrack nucleus can be determined by analyzing the parameters of the dispersion of the rates of development of cracks of various sizes.
The author proposes using the generalized kinetic diagram shown in Figure 6. In addition to lines 1, 2 and 3, corresponding to the probabilities of 99%, 50%, and 1%, a series of vertical sections and lines 5-11 is plotted, representing the differential distribution functions of crack growth rates for different values of the stress intensity factor. If the sections corresponding to different scattering laws are allocated on such graphs, then it is possible to draw line 4 connecting the transition boundaries from one normal law (with large dispersion) to another normal law (with less scattering). The value of the stress intensity factor (length of cracks) at which such transition is realized at a probability of 50% can be regarded as the transition threshold from short to macroscopic cracks. This value of the stress intensity factor corresponds to the size of the embryo of the microcrack at the given load.

**Figure 6.** Schematic representation of the probabilistic kinetic fatigue diagram: 1, 2, 3 - kinetic fatigue diagrams corresponding to the probabilities $p = 99\%, p = 50\%, p = 1\%$; 4 - a line connecting the boundaries of the transition from one normal to another normal distribution of fracture rates for different $K_{\text{max}}$; 5-11 - graphs of differential functions of the distribution of the rates of development of cracks.

**Figure 7.** A kinetic diagram of the fatigue of the babbitt layer applied to the steel substrate

**Figure 8.** Statistical representation of developmental speeds in the babbitt layer of cracks of different sizes.

The author has processed the results (Figure 7) of experimental studies of the development of independent fatigue cracks in babbit layers of bilayer samples [1]. Fig. 8 shows statistical data on the rates of the development of cracks of the same size in the babbit layer. These results correspond to the observed regularity: a transition from a normal law with a large dispersion to a normal law with a smaller scattering is realized. The boundary of the transition from short cracks to macrocracks can be considered as the value of the stress intensity factor of $1 \text{ MPa} \sqrt{\text{m}}$.

5. Conclusion

Thin-walled tubular samples from babbit B83 were tested with three types of uniaxial strain-stress state analysis (SSSSA): tension, compression, and torsion. It is received that parameter $\chi = 0.78$, and
the criterion expression of Pisarenko-Lebedev has form \( \sigma_{equal} = 0.78 \sigma + 0.22 \sigma \). In accordance with this criterion, a generalized diagram of babbit B83 deformation "equivalent stresses \( \sigma_{equal} \) - equivalent deformations \( \epsilon_{equal} \)" is constructed on the coordinate plane.

Characteristics of the fracture toughness of babbit B83 samples (under static loading) are \( K_c = 3.0 \pm 3.2 \) MPa\( \sqrt{\text{m}} \). With cyclic loading of babbit samples, the transition to the stage of elastoplastic development of the crack is realized at \( K_{\sigma} \approx 2.0 \ldots 2.8 \) MPa\( \sqrt{\text{m}} \).

It was revealed that the lower boundary of the development stage of macrocracks corresponds to the level of the stress intensity factor of 1 MPa\( \sqrt{\text{m}} \). The transition to the unstable development of the fracture and the dolom of the monometallic samples is realized at a stress intensity level of 3 MPa\( \sqrt{\text{m}} \). For two-layer samples after reaching the value of the stress intensity factor, the values of 3 MPa\( \sqrt{\text{m}} \) of the crack growth rate are stabilized. This value of the stress intensity factor corresponds to a change in the mechanism of development of cracks, but supporting the influence of the steel substrate does not allow the sample to collapse. Such different behavior of the cracks in zone III for bimetal and monometall is indicated in Figure 8 by two branches of the graphs after reaching the value of the stress intensity factor equal to 3 MPa\( \sqrt{\text{m}} \).

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