Local damage to structural materials under low-cycle loading

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Abstract. The damage accumulation kinetics in plastic (metals) and brittle materials (concrete) at the stages of fracture formation and development under cyclic loading is considered. The regularities of damage accumulation at microlevels due to structural and strain heterogeneity with the achievement of the limit state – the formation of micro-cracks are shown. The early formation curves of micro- and macro-fractures on the fatigue curves, the areas of dispersed fracture formation and development are determined.

1. Introduction
The stage of fracture formation is preceded by distributed crack formation associated with the heterogeneity of strain processes in separate volumes of the deformable material. The objectives of this study are the investigation of heterogeneity of damage formation and development in local areas of structural materials under cyclic strain with an increasing number of loading cycles and development of methods for estimating limit states at the macro- and micro levels under cyclic loading of plastic materials.

2. Material and methods
The authors used tubular samples made of single-phase austenitic steel Kh18N10T, two-phase steel 45 with a partial perlite structure, and pearlite steel TC to study the features of the local strain development and assess structural heterogeneity. Micro-hardness measurement prints were applied to the working part of the sample using a diamond pyramid on the PMT-3 device. The strain was performed under cyclic tensile-compression loading with a frequency of 1 cycle per minute. The strain on the working base was measured using a longitudinal strain-meter with an error of no more than 2% of the measured value.

Heterogeneity of cyclic plastic strain $K_{\mu\delta}$ and one-way accumulated plastic strain $K_{\mu\varepsilon}$ were defined as:

$$K_{\mu\delta} = \delta_i / \delta_{av} \quad \text{and} \quad K_{\mu\varepsilon} = \varepsilon_i / \varepsilon_{av}$$

where $\delta_i$ is the local plastic strain in the cycle; $\delta_{av} = \delta_k$ – the average value of the width of the hysteresis loop in the cycle, measured over the entire working base; $\varepsilon_i$ – local one-way accumulated strain in the load cycle under consideration; $\varepsilon_{av} = \varepsilon_k$ – average one-way accumulated strain.

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The structural heterogeneity of the material causing strain heterogeneity can be estimated by measuring the micro-hardness of the material in the initial state. The heterogeneity of the structure and local strain in single-phase (steel Kh18N10T) and two-phase materials (ferrite-pearlite steel 45 and pearlite steel TS) was studied. Based on statistical processing data, the estimation of the structural heterogeneity ratios based on the probability curves of the micro-hardness distribution is carried out. In this case, the heterogeneity ratios of the structure by scattering of micro-hardness values $H_{\text{μ}}$ were determined as:

$$K_{H_{\text{μ}}} = \frac{\bar{H}_{\text{μ}}}{H_{\text{μ}i}}$$

(2)

where $H_{\text{μ}i}$ and $\bar{H}_{\text{μ}}$ are the minimum and average micro-hardness values.

Following the scattering of measurement values, there is also a spread of indicators by the heterogeneity ratios of micro-hardness values (figure 1).

Heterogeneity of cyclic plastic strain $K_{\mu \varepsilon_p}$ and one-way accumulated plastic strain $K_{\mu \varepsilon}$ defined as:

$$K_{\mu \varepsilon_p} = \frac{\varepsilon_{pk}}{\varepsilon_{pm}}$$

and

$$K_{\mu \varepsilon} = \frac{\varepsilon_k}{\varepsilon_m}$$

(3)

where $\varepsilon_k$ is the local plastic strain in the cycle; $\varepsilon_{pm}$ – the average value of the hysteresis loop width in the cycle measured over the entire working base; $\varepsilon_{pk}$ – local one-way accumulated strain in the considered loading cycle; $\varepsilon_m$ – the average one-way accumulated strain for this cycle on a large measurement base.

The heterogeneity of the strain development, both recoverable and non-recoverable (one-way accumulating) depends on the nature of the material and its structural state, determined by the final processing.

In multiphase steels or alloys, the heterogeneity of micro-strains will be localized in the least durable stage, and damage accumulation will occur mainly in these areas, and for them, the strain heterogeneity ratios should be estimated.

3. Results and discussion

Following the scattering of measurement values, there is also a spread of indicators by the heterogeneity ratios of micro-hardness values (figure 1).

As can be seen from figure 1, a, during the first (initial) elastic-plastic strain in the half-cycle of tension ($K = 0$) in separate areas of 200 µm in size, with an average strain on the base of 40 mm, strains in the range from 0 to 5.0% are observed.

3. Results and discussion

Figure 1. Distribution of micro-hardness heterogeneity ratios of TC, steel 45 and Kh18N10T steels (a) and local strains in TC steel in the first and second cycles (b).
The strain heterogeneity of the main volume (up to 80% of the accumulated probability) of two-phase steel with sufficient accuracy for practice can be considered to obey the normal distribution law. However, unlike a single-phase material, steel containing a pearlite component is deformed more heterogeneously, especially two-phase steel having both pearlite and ferritic structure (steel 45).

At 150°C exceeds the level of uniform strain at room temperature from half of the total strain of 0.5 to 0.55).

For pearlite steel TC (100% perlite), the strain in local areas is more uniform than steel with a partial share of perlite (steel 45).

The distribution of local strain and corresponding concentration ratios and values of microhardness in the initial state obey the normal law.

\[ P, \% \]

![Figure 2](image)

**Figure 2.** The statistical distribution of strains on the bases of 30 µm, 100 µm and 200 µm of TC steel in the half-cycles of expansion and contraction of the first and second cycles and the tensile half-cycle of the third cycle.

Statistical processing has established that the heterogeneity of plastic strain can be estimated using the parameters of the probability curves of the normal distribution, defined as:

\[ K_{\mu e} = (U_p S + \varepsilon_{pk}) / \varepsilon_k \]  \hspace{1cm} (4)

where \( U_p \) – quantile, \( S \) – mean square deviation, \( \varepsilon_{pk} \) – the value of the local strain in the half-cycle \( k \), \( \varepsilon_k \) – limit strain under static fracture obtained on a large base (in this study, it was 40 mm).

For single-phase steel Kh18N10T \( U_p = 2.79 \), and then through the parameters of the distribution of local strain, the heterogeneity ratios can be obtained as:

\[ K_{\mu e} = \frac{(2.79S + \varepsilon_{pk})}{\varepsilon_{pk}} \]  \hspace{1cm} (5)

The heterogeneity ratios for cyclic recoverable, one-way accumulated strain and microhardness values were the same:

\[ K_{\mu e} = K_{\mu e, p} = K_{H_{\mu}} = \frac{H_{\mu}}{H_{\mu} - U_p S} \]  \hspace{1cm} (6)
The greatest heterogeneity is observed in the first loading cycles. Further loading is accompanied by a decrease in the heterogeneity of both recoverable and accumulating strain (figure 2). The maximum strains are preserved in the same sections. The strain heterogeneity ratios are stabilized, remaining equal for both recoverable and accumulated strains.

In areas with high local strain with an increasing number of loading cycles, micro-fractures and formation of the main fracture in the surface of the material is covered with numerous micro-fractures (spread fracture formation). In single-phase materials, micro-fractures cover the loaded surfaces relatively evenly (figure 3).

For pearlite steel TC (100% perlite), the strain in local areas is more uniform than steel with a partial share of perlite (steel 45).

In two-phase materials such as steel 45, micro-fractures are formed mainly in ferritic areas (figure 4). During processing, for example, rolling, ferritic and perlite areas take the form of strips, and micro-fractures, located in these areas, have an extended form, as shown in figure 4.

![Figure 3.](image1.png)
![Figure 4.](image2.png)

**Figure 3.** The nature of the formation of micro-fractures under low-cycle loading: under tension-compression (a), under torsion (b).

**Figure 4.** Micro-fracture formation of low-cycle steel fatigue in the ferritic area during cyclic torsion.

When micro-fractures reach specific sizes and densities, the main fracture is formed by fusion and interaction (figure 5), the development of which in the damaged material proceeds at an accelerated rate.

The damage accumulation in structural steels under cyclic loading is defined as [1]:

$$\eta = \int_0^\infty \frac{\Delta \varepsilon}{\varepsilon'_h} dN + \int_0^\infty \frac{\Delta \varepsilon}{\varepsilon'_h} dN$$

(7)
In the extreme case (formation of a macro-crack or loss of stability of plastic strain), the damage is described as:

\[
\frac{N_f}{0} \frac{e_p}{e_{st}} \frac{dN}{dN} + \frac{N_f}{0} \frac{\Delta e}{e_{st}} dN = 1
\]

(8)

where \(e_p\) – plastic strain in a cycle, \(e_{ep}\) – elastic-plastic strain in the tensile half cycle, \(e_{st}\) – strain with a single (static) fracture, corresponding to the true tensile strength, \(\Delta e\) – one-way accumulated plastic strain in the cycle, \(N\) – number of load cycles, \(N_f\) – number of fracture cycles.

The evolution of the structural state and the damage accumulation kinetics at the stages of fracture formation and development in brittle materials (concrete) under cyclic loading is presented in [4,5]. Other approaches to the description of damage accumulation kinetics are considered in [4-9].

**Figure 5.** Formation of a main fracture in the strain heterogeneity areas under cyclic torsion.

At the stage of fracture propagation, the damage accumulation rate is estimated following the dependence [1]:

\[
\eta = \int_0^N \frac{V_{ep}}{V_p} \frac{dN}{dN} + \int_0^N \frac{\Delta V}{V_p} dN
\]

(9)

In the extreme case (fracture):

\[
\int_0^{N_{ff}} \frac{V_{ep}}{V_{st}} \frac{dN}{V_p} + \int_0^{N_{ff}} \frac{\Delta V}{V_{st}} dN = 1
\]

(10)

where \(V_p\) – plastic (residual) exposure (margin displacement) of a fracture, \(V_{ep}\) – elastic-plastic fracture exposure in the tensile half-cycle, \(\Delta V_p\) – the accumulated one-way exposure of fracture
margins in the cycle, \( V_c \) – limit fracture exposure (margin displacement), corresponding to the maximum load in a single rupture of the sample (part) with a fracture, \( N \) and \( N_f \) – the current and destructive number of cycles, respectively.

Figure 6 shows the limit values of damage in ferrite-pearlite steel at the fracture formation stage (a) and aluminum alloy[3] at the fracture propagation stage (b). In figure 6 (b) the load in the aluminum alloy sample was reduced after the first hardening cycles (shown by triangles on figure 6 (b)).

Taking into account the heterogeneity of plastic strain under dependencies (7) and (8), the fracture condition (appearance of micro-cracks) without taking into account damage from elastic strain (quasi-static fracture) can be written as follows [2]:

\[
\sum_{\eta} \left( \int_{0}^{N_f} \left( \frac{K \mu \varepsilon_p^2}{\epsilon_{st}} \right) dN + \int_{0}^{N_f} \frac{K \mu \Delta \varepsilon_p}{\epsilon_{st}} dN \right) = 1
\]

(11)

Figure 7 shows the fatigue curve of ferritic-pearlite steel under loading with a given range of elastic-plastic strain (hard loading). The red line represents the moments of formation of initial micro-cracks, determined by the dependence (6) with the strain heterogeneity ratio equal to 1.1. Dash blue line indicates the moments of macro-crack formation depending on the number of fracture cycles. The area indicates the moments of macro-crack formation depending on the number of fracture cycles.

![Fatigue curve](image)

**Figure 6.** Limit damage accumulations calculated by criterion (8) of ferrite-pearlite steel (a) and calculated by criterion (10) of aluminum alloy AD33 (b).

The area between the red and the dashed line is the area of dispersed crack formation, the ultimate development of which is the formation of a macro-crack. The area between the dashed blue line and the fatigue curve (black line) is the area where the main macro-crack propagates until complete fracture.

Thus, the studies have shown that the nature of the development of strain processes and the nature of damage accumulation is determined by the structural state of the deformable material and its phase composition.
Figure 7. The fatigue curve of ferrite-pearlite steel under rigid loading.

4. Conclusion
1. The strain heterogeneity of materials depends on their structural heterogeneity and can be estimated from the indicators of structural heterogeneity determined by micro-hardness measurements.
2. Damage accumulation kinetics and limit states at the micro-level (micro-crack formation) and macro-level (main macro-crack formation) under cyclic loading of plastic materials (metals).
3. The ability to determine the limit states at the micro- and macro-levels allows indicating the limit state curves on the fatigue curves (the beginning of the formation of micro-and macro-cracks).

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