Damage accumulation in cyclically stable steel under low-cycle loading and elevated temperature

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Abstract. Based on the strain-kinetic fatigue fracture criterion, the kinetics of accumulated damages in structural carbon steel under low-cycle loading at an elevated temperature (150°C), at which the material begins to develop stress aging processes, is estimated. It is shown that stress aging, strengthening the material, narrows the durability area in which there is quasistatic destruction, the limiting case of which is the buckling failure of plastic strain, like single static destruction. This increases the fatigue fracture range, the limiting case of which is the formation of the primary fracture. The recoverable plastic strain causes the main damaging effect. Stress aging contributes to an increase in damage from elastic strain, although in the area of low-cycle failure, the share of damage from elastic strain remains small, growing with increased durability, and in the area of multi-cycle fatigue, this share becomes prevalent. Hardening from stress aging inhibits the development of damage from the one-way accumulated strain. The author confirms the validity of applying the strain-kinetic criterion of fatigue fracture to describe the damage kinetics and limit states during the cyclic elastic-plastic strain of carbon steel in the presence of weak stress aging.

1. Introduction
Damage accumulation kinetics depends on the structural state of the structural material and strain conditions.

As is known [1], structural materials can be strengthened (hysteresis loop width decreases), softened (hysteresis loop width increases), or stabilized (hysteresis loop width remains almost constant) with an increase in the number of elastic-plastic strain cycles.

Structural changes, such as stress aging, can significantly change the plastic properties of a material under load and thereby affect the damage accumulation kinetics and the limit state [1]. Structurally unstable materials can also increase their plastic properties due to changes in the structural state under cyclic loading, and then changes in the plasticity of the material must be taken into account when determining the damage accumulation kinetics and evaluating the limit state [2].

Under low-cycle loading, there can be two limiting states: the formation of macro-fissures or buckling failure of plastic strain. The latter proceeds by the type of static destruction, and in this regard it is called quasi-static.

Quasi-static fracture is characteristic of cyclic elastic-plastic strain with a given load amplitude or with an asymmetric loading cycle. When deformed with a given range of elastic-plastic strain, the destruction in all cases occurs with the fracture formation.
Quasi-static fracture is characteristic of a small number of loading cycles, which depends on the load level. Fatigue fracture (resulting from fracture formation) occurs during strain with a uniform strain before fracture.

The purpose of this work is to identify the damage accumulation kinetics in carbon steel and the possibility of applying the strain-kinetic criterion of fatigue fracture of carbon steel 22k for an elevated temperature at which the specified steel begins to develop stress aging processes that reduce the plastic properties of the material, increasing its strength indicators.

2. Materials and methods
Carbon steel 22k (chemical composition in %: C 0.22, Si 0.3, Mn 0.8, Ni 0.3, S 0.4, P 0.4, Cr 0.4, Ti 0.05, Cu 0.3, Fe – base; mechanical properties: \( \sigma_b = 530 \) MPa, \( \sigma_{0.2} = 265 \) MPa, \( \Psi = 46\% \)) at room temperature is cyclically stable. Cyclically stabilizing materials are characterized by the value of uniform strain (strain corresponding to the conditional tensile strength \( \sigma_b \)) [1]. It is widely used for manufacturing machine-building parts and assemblies.

Tests for low-cycle fatigue were carried out under tension-compression with a frequency of 3–5 cycles per minute with a symmetrical load cycle (soft loading) and with a given range of elastic-plastic strain (hard loading) at a temperature of 150°C. The sample is solid, corset type with a diameter of 12 mm. Transverse strains were measured, which were converted to longitudinal ones using the transverse strain ratios: 0.5 – for plastic strain and 0.3 – for elastic strain. The error in measuring strains did not exceed 0.5% of the measured value. The tests were carried out in a vacuum chamber \( \sim 5 \times 10^{-2} \) mm Hg placed on the columns of the testing machine.

Evaluation of damage accumulation levels with fractions of damage from cyclic recoverable (hysteresis loop width in the tensile half cycle), one-sided accumulation of plastic and elastic strains was carried out based on the previously proposed strain-kinetic criterion of fatigue fracture [1] without considering the damaging role of elastic strain for the current number of cycles (mainly quasi-static fracture) as:

\[
\eta = \frac{\varepsilon_p^2}{\varepsilon_p^2} dN + \frac{\Delta \varepsilon}{\varepsilon_p} dN
\]

In the extreme case (formation of a macrofissure or loss of stability of plastic strain) as:

\[
\int_0^{N_f} \frac{\varepsilon_p^2}{\varepsilon_p^2} dN + \int_0^{N_f} \frac{\Delta \varepsilon}{\varepsilon_p} dN = 1
\]

For the entire range of fatigue fracture durations (low-cycle and multi-cycle fatigue) as:

\[
\eta = \frac{\varepsilon_p E_p}{\varepsilon_p^2} dN + \frac{\Delta \varepsilon}{\varepsilon_p} dN
\]

Fracture as:

\[
\int_0^{N_f} \frac{\varepsilon_p E_p}{\varepsilon_p^2} dN + \int_0^{N_f} \frac{\Delta \varepsilon}{\varepsilon_p} dN = 1
\]

With the reflection of the damaging role of elastic strain, dependencies (3) and (4) can be written as:

\[
\eta = \frac{\varepsilon_p^2}{\varepsilon_p^2} dN + \frac{\Delta \varepsilon}{\varepsilon_p} dN + \frac{\Delta \varepsilon \varepsilon_p}{\varepsilon_p^2} dN
\]
and when fractured:

\[
\int_0^{N_f} \varepsilon_p^2 \, dN + \int_0^{N_f} \Delta \varepsilon \, dN + \int_0^{N_f} \varepsilon_s \varepsilon_s \, dN = 1
\]

(6)

where \( \varepsilon_p \) is the plastic strain in the tensile half cycle, \( \varepsilon_{ep} \) is the elastic-plastic strain, \( \varepsilon_e \) is elastic strain equal to \( \varepsilon_e = \sigma_a / E \), \( \varepsilon_s \) is the static strain of a single fracture corresponding to the true tensile strength (rupture strength) to the time of buckling, plastic strain (beginning of necking), \( N \) is the current number of loading cycles, \( N_f \) is the number of cycles to fracture (formation of cracks).

Depending on (1)–(6), the first term defines fatigue damage from the action of cyclically recoverable plastic strain, the second term – damage from unilateral plastic strain, and the third term – damage from the action of elastic strain. When loading with a given range of elastic-plastic strain (hard loading), the second term in the dependencies (1–6) is zero (strain is not accumulated).

For \( \varepsilon_s = \text{const} \) and \( \varepsilon_p = \text{const} \) (for example, for a cyclically stable material or when changes in the hysteresis loop width and elastic strain during loading can be ignored), the dependence (4) can be written as:

\[
\varepsilon_e e_{jm} N_p = \varepsilon^2 \quad \text{or} \quad \frac{\varepsilon_e e_{jm} N_p}{\varepsilon_s^2} = 1
\]

(7)

In dependencies (5), (6), (8), (9) the first term is damage from recoverable plastic strain \( \varepsilon_p \) (strain in a half cycle of tension), the second term is damage from unilaterally accumulating strain \( \Delta \varepsilon \) (quasistatic damage), and the third term is damage from the action of elastic strain \( \varepsilon_e \).

The criterion allows determining the levels of accumulated damage in each cycle and the total accumulated over the entire range of durations (both in the low-cycle and multi-cycle areas) and allows describing the limit states (formation of macro fissures or buckling failure of plastic strain).

Other approaches to describing the damage accumulation kinetics are presented in [3–8].

3. Results and discussion

As follows from figure 1 (a), when the temperature increased from room to 150 °C (figure 1 (a)), the material showed some tendency to harden (uniform strain at 150°C exceeds the level of uniform strain at room temperature from half of the total strain of 0.5 to 0.55).

\[\text{Figure 1. Static tension curves of steel 22k at 150°C (a) and at room temperature (b): curves in conditional (triangles), and in true stresses (circles).}\]
For steel 22k at 150°C, the limit state (buckling failure of plastic strain) was observed at a strain of about 30% (figure 1 (a)). For room temperature, the buckling failure occurred at a strain equal to 37% (figure 1 (b)).

At a temperature of 150°C, the steel showed (figure 2 (a)), as at room temperature [1], significant hardening after initial loading (in the second cycle). The subsequent cyclic strain is characterized by softening (increase in strain in the half-cycle of tension), the degree of which decays to the number of cycles that make up about half of the durability of each sample. At room temperature, this stage shows the relatively uniform strain. A further increase in the number of loading cycles (loading time) begins to manifest the processes of stress aging, accompanied by a hardening of the material (recoverable strain decreases).

The processes of hardening and softening also affect the rate of accumulation of residual strains (figure 2 (b)). At this stage of hardening, there is even a slight slowdown in accumulation (strain in the compression half-cycles is greater in absolute value than in the tension half-cycles). At room temperature, accumulation at this stage practically does not occur [1]. Starting from the level of maximum recoverable strain (figure 2 (a)), the processes of unilateral strain accumulation are activated (figure 2 (b)). At the same time, the processes of stress aging are becoming more and more active (recoverable strain is continuously decreasing). This stage of loading is characterized by active strain accumulation even at room temperature [1].

![Figure 2](image-url)  
Figure 2. Strain kinetics in the half-cycle of tension (a) and accumulated strain (b) of 22k steel at a temperature of 150°C.

Strengthening of the material from plastic strain and stress aging is accompanied by an increase in true stresses (figure 3), determined by taking into account the change (decrease) in the working cross-section of the sample from the current and accumulated strain in each cycle.

At a temperature of 150°C, significant hardening after the initial half-cycle (figure 2 (a)), and a decrease in the working cross-section, a sharp increase (jump) in true stresses is observed (figure 3). Further loading under changes in the loop width (strain in the half-cycle of tension) and one-sided accumulated strain is characterized by a slight change in the true stresses. Moreover, only in the second half of the durability, there is an active increase in true stresses.
At room temperature, on the contrary, after strain in the initial half-cycle and an extensive hardening only due to plastic strain (temperature stress aging is absent or not large) and the resulting decrease in the working cross-section, hardening occurs after the initial loading \([1]\)). Subsequent loading does not cause significant changes in the true stresses, except for quasistatic failure \((N_p = 165\) cycles), when large plastic strain develops a one-sided accumulation of plastic strain and a significant decrease in the working cross-section of the sample.

The nature of changes in the strain characteristics under low-cycle loading determines the damage accumulation kinetics. From figure 4, it can be seen that for durations from 160 (figure 4 (a)) to 2050 cycles (figure 4 (c)), the main damage to the moment of fracture (limit state) accumulates from the recoverable plastic strain. Although at the initial stage, the damage was maintained constant from the accumulated strain in the first cycle. As the number of cycles increases, the accumulation from recoverable strain (strain in half-cycles of tension) begins to prevail and becomes the main one by the time of fracture. The equality of damage from recoverable strain and accumulating with durability \(N_p = 165\) cycles is equal to loading cycles (figure 4 (a)). For \(N_p = 610\) cycles, the comparison of recoverable and accumulated damage is observed for loading cycles (figure 4 (b)). The durability of 2050 cycles shows the equality of the specified strain for loading cycles (figure 4 (b)). Damage from the elastic strain with a small number of loading cycles is not large at the initial stage, but the rate of damage growth is high. With increasing durability \((N_p = 610\) cycles), equality of accumulated and elastic strain is achieved by the moment of failure (figure 4 (b)). If the durability is \(N_p = 2050\) cycles, this equality is equal to cycles and is equal to % of the number of failure cycles (figure 4 (b)).

**Figure 3.** True stresses kinetics in 22k steel under low-cycle loading at a temperature of 150°C.
Figure 4. Damage accumulation from elastic (rhombus), recoverable plastic (square), accumulating (triangle) and total (black circle) damage to each sample (a-c) and damage from recoverable strain of three samples (d): a – $\sigma_a = 515$ MPa. $N_p = 165$ cycles; b – $\sigma_a = 475$ MPa. $N_p = 610$ cycles; c – $\sigma_a = 449$ MPa. $N_p = 1257$ cycles.

Figure 5. Damage from accumulated (a) and elastic (b) strains of 22k steel at a temperature of 150°C in soft loading.

The damage accumulation kinetics from recoverable, accumulated, and elastic strain under low-cycle loading at room temperatures [1] differs significantly from accumulation at 150°C (figure 5 (a)). If the maximum accumulated damage from recoverable strain for the considered duration is in the range of 70-80% (figure 5 (a)), then damage from accumulated strain is no more than 20% (figure 5 (b)), and for elastic strain does not exceed 10% (figure 5 (b)).

Figure 6. Maximum damage accumulation in 22k steel at 150°C for hard (a) and soft loading (b).
When loading with a given range of elastic-plastic strain (hard loading), the kinetics of damage accumulation is linear (figure 6 (a)) and is well described by the strain criterion (7). For figure 6 (a), the first cycle shows damage to the original half-cycle, which caused some nonlinearity in the first cycle.

At the same time, strain with a given load amplitude shows a nonlinear nature of damage accumulation with an increase in the number of loading cycles (figure 6 (a)) and their summation obeys the dependence (6).

4. Conclusions
1. Resistance to low-cycle loading of carbon steel at elevated temperature (150°C) is characterized by an increase in strength properties due to the development of stress aging processes.
2. Stress aging slows down the rate of increase in recoverable and accumulated strains, contributing to the growth of durability.
3. Strain-kinetic criterion of fatigue fracture describes the damage accumulation kinetics and the limit state in the presence of stress aging.

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