Method for studying the kinetics of plastic deformation and energy dissipation during fatigue of structural materials

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Abstract. The evolution of mechanical properties of Russian steel St3 subjected to cyclic elasto-plastic deformation is analyzed under a broad spectrum of loading conditions. This particular material is chosen due to its wide use in industrial facilities operating in Arctic and Russian North. Basic state parameters are determined, including the true strains, secant and tangent moduli, heat generation due to plastic dissipation, thus characterizing the evolution of the thermo-mechanical state. The temporal evolution of kinetic parameters during each loading block provides insights into the hardening and damage accumulation. These data form an experimental basis for development, calibration, and validation of new material models. The main effects are identified and discussed, and the modelling approaches are assessed.

1. Introduction
The operational safety of hazardous industrial facilities like oil storage tanks and gas pipelines operating in the Arctic region and Russian North is one of the most important scientific and technical priorities. During the construction of these facilities, steel grade St3 is actively used [1]. New methods are constantly developed for a rational assessment of accumulated damage in such metal structures. The methods which allow for assessment of remaining life time without a detailed knowledge of the loading history are especially valuable for practicing experts working in the field. This motivates the current study.

In this work, a method of analysis of damage accumulation under low cycle fatigue is discussed. To increase the information content of experiments, the procedure deviates from the standard fatigue test. The provided experimental data are suitable for development, calibration, and validation of corresponding constitutive equations.

A critical analysis of structures with unknown operational history is only possible based on detailed study of the damage accumulation kinetics. It includes the interrelation between the accumulated ductile damage and the shape of the stress-strain hysteresis loops as well as dissipation-induced heating. Such a study allows to develop damage criteria and damage markers, useful for predictions of the residual life of analyzed structures.
The method based on the analysis of the inelastic strain per cycle [2] is well known; the inelastic strain corresponds to the width of the hysteresis loop in the stress-strain space. Thermography enables the detection of dissipative processes through dissipation-induced heating already at the early stages of the deformation [3]. As a measure of accumulated damage, one may use the defect energy, the density of defects, the residual magnetization as well as structural changes. To a certain extent, this allows one to make predictions of the remaining life and to control their safe operation. On the other hand, the cyclic deformation of St3 is accompanied by numerous interacting mechanical phenomena, including non-linear isotropic and kinematic hardening, strain softening, plasticity plateau, and deterioration of elastic stiffness. Thus, in spite of a big number of fatigue experiments, the standard tests do not provide sufficient data about the kinetics of damage accumulation and its relation to stress-strain behavior. Obviously, this prevents progress in theoretical analysis of residual fatigue life.

In 1805 Gough was the first one who established the interrelation between mechanical strain and heat. In 1855, Lord Kelvin provided a theoretical description of this effect. In 1965, Belgen demonstrated that the infrared radiation can be used in a practical study of the stress. The analysis of dissipation-induced heating opens up a possibility for detailed study of crack nucleation and growth under fatigue conditions [4, 5]. It is also suitable for analysis of energy storage and transformation in deformed materials [6, 7]. However, a presence of singularities and a small volume of the active plastic zone ahead of the crack tip prevent a systematic study of structural transformations. Some other approaches which study the regularities in energy transformations under periodic loading [8] aim at the identification of the endurance limit of the material. In contrast to this, the current study develops a method to track the interrelation between stress-strain curves, the accumulated damage, and the dissipation-induced heat. In this work we determine the true strains and stresses, the secant and the tangential moduli, as well as the dissipation-induced temperature increase. The temporal evolution of these parameters allows a characterization of the block-like loading [9-11].

2. Tested material, samples, experimental set-up, and methods

2.1 Testing samples

A batch of samples was made from a sheet of steel St3. The chemical composition of St3 is: Fe-0.18C-0.45Mn-0.1Si. Samples of type IV are employed according to the Russian standard GOST 25.502-79 (Fig. 1). The length of the gage area is 50 mm; the gage area is large enough for two extensometers, measuring axial and lateral strains. The sample cross section is 6.8 mm x 7 mm.

![Figure 1. Sample shape and dimensions.](image)

The surface of the gage area, intended for temperature measurements with a thermal imager, was covered with a thin layer of amorphous carbon. This layer reduces the emissivity and makes it close to one. Experiments with measured two coordinates of the strain tensor as well as radiation temperature on the surface provide a big amount of relevant information.

2.2 Equipment

For the mechanical non-monotonic loading of the samples of St3 a universal testing machine Instron 8801 was used. The loading was force controlled. For the in situ measurement of the coordinates of the strain tensor, standard extensometers No 2620-601 “Dynamic Extensometer” and
No W-E-404-F “Transverse/Diametral Extensometer” were employed. The temperature was measured with the TKVr-IFP “SWIT” thermography camera.

2.3 Method for identification of mechanical properties under cyclic loading

Fig. 2 presents a diagram of the implemented block-like loading, which resulted in the sample failure shortly after block 5; the loading frequency is 4 Hz. The first three loading blocks (blocks I, II, and III) consist of 2000 harmonic cycles. Each of these blocks lasts for 500 seconds; the stress amplitude is increasing linearly with time. Blocks IV and V take 750 seconds. They differ from blocks I, II, and III as they have additional 1000 cycles with a constant stress amplitude (Fig. 2). After each block, there is a short holding period of few seconds implemented for cooling the samples back to the room temperature.

![Figure 2. Force-controlled block-wise loading program.](image)

The size of the engineering stress amplitude increase within each cycle by the amount \( \sigma_{a \, cycle} \); it is computed by the formula: \( \sigma_{a \, cycle} = \frac{\sigma_{a \, max}}{N_{cycle}} \), where \( \sigma_{a \, max} \) is the maximum engineering stress amplitude within the block (the maximum engineering stress equals \( \sigma_{a \, max} = 178.5 \) MPa ), \( N_{cycle} = 2000 \) is the number of cycles within blocks I, II, and III.

During the loading there was a simultaneous measurement of the axial force, axial and transversal strain as well as the temperature in the gage area of the sample. The tests were carried out at the room temperature. After the loading program was complete, the results were processed and analyzed.

3. Experimental results

Fig. 3 shows the overall trajectory in the stress-strain space during the entire experimental program; every fifths cycle is shown for clarity. Due to accumulation of the plastic strain, moderate axial strain is observed. Since the effect of geometric nonlinearity becomes essential, true strains and true stresses are depicted in Fig. 3. Please note that the use of true stresses accounts for the reduction of the cross-sectional area; the reduction of the cross section is computed as the inverse of the axial stretch. The experimental measurement of the strain in transversal direction justifies this procedure since the material behavior is nearly incompressible. Although the maximum force amplitude within each block is the same, there is an increase of the true stress; it is caused by the reduction of the cross section. As is seen from Fig 3, block I is characterized by a strong acceleration of the plastic flow due to the presence of the plasticity plateau with decreased rate of strain hardening. After the plastic plateau is over, the accumulation of the strain slows down to relatively small values. Note that, since the true stress amplitude increases, the material clearly exhibits cyclic hardening. Another important aspect is that some amount of plastic deformation occurs during unloading. In other words, the Bauschinger effect in St3 is so strong, that an elastic unloading is impossible in some cases. The holding period between blocks IV and V is almost invisible in Fig. 3 due to strain hardening of the material.
Figure 3. Trajectory in the stress-strain space for blocks I,…,V. Every fifths cycle is shown.

Fig. 4 shows the maximum and the minimum strains within each cycle. In order to account for geometric nonlinearities, true (logarithmic) strains are used as well. The accumulation of the plastic strain is apparent. We refer to this effect as to ratcheting under non-zero mean stress. The strong acceleration of the ratcheting is evident during block I as the sample passes the plastic plateau. Again, at the late stages of the deformation, there is a secondary acceleration of the ratcheting.

Figure 4. Experimental results for the maximum and minimum axial strain within each cycle versus the cycle number. The entire experimental program is shown.

Fig. 5(a) presents the dependence of the secant modulus $E_s$ as a function of the cycle number. Here, $E_s$ is the ratio of the true stress amplitude to the true strain amplitude within each cycle. Due to the scatter of the experimental data, $E_s$ is not shown for cycles with a very small strain amplitude. Clearly,
Es is decreasing within each block. The evolution of Es is a product of two competing processes: the strain hardening and ductile damage. Although the material exhibits cyclic hardening, the ductile damage prevails in the long term. Next, Fig. 5(b) shows the evolution of the tangent modulus Et. For each cycle, Et is computed as the maximum inclination of the hysteresis loop in the (true-strain vs. true-stress) space. Again, Et is not shown for cycles with a low load intensity. Since the elasticity modulus is a function of the crystalline structure, it remains constant in undamaged materials. The reduction of Et during the experiment is a clear indicator of the damage accumulation. For St3 we report the reduction of Et of 8% shortly before failure of the sample.

Figure 5. The secant modulus Es (a) and the tangent modulus Et (b) as functions of the cycle number. Both moduli exhibit a substantial reduction during the experiment.

For the sample in as-received state, Fig 6 combines the average temperature $\Delta T_m$ caused by dissipation-induced heating, the secant modulus Es, and the tangential modulus Et as a function of the engineering stress amplitude $\sigma_a$. The high-frequency oscillation of the temperature due to thermoelastic effect is not shown.
Figure 6. Temperature evolution and material moduli versus the amplitude of engineering stress. Left: secant modulus (a). Right: tangent modulus (b). Block number is indicated with Roman numerals.

Figure 6 shows that during loading of the pre-stretched material by blocks II and V, the activation of heating (and the activation of irreversible deformation) starts at lower stress amplitudes than in block I. This indicates active microstructural changes under stresses, which are essentially lower than the nominal (technical) yield stress. This is a counterintuitive result since St3 is cyclically hardening material (see Fig. 3). Although the material was hardened during block I, some part of the stored energy gets dissipated into heat during block II, thus contributing to early temperature increase.

4. Discussion and conclusion
A non-standard experimental program is considered including cyclic force-controlled loading of the sample made of steel St3. The material exhibits a clear isotropic and kinematic hardening. The nonlinear Bauschinger effect is clearly pronounced. The impact of the previous loading history on the temperature increase and accumulation of the plastic strain is studied to establish interrelations between stress-strain curves and the accumulated damage. The monotonic reduction of the tangent modulus $E_t$ in the course of the experiment is a clear indicator of the damage. Although the material is cyclically hardening, the secant modulus $E_s$ exhibits a clear reduction as well. However, since $E_s$ depends both on damage and hardening (both are competing processes), this parameter is less suitable as a damage marker.

The temperature increase shows a counterintuitive systematic pattern: in pre-strained materials, it starts at much lower stress amplitudes than in the as-received material. We assume that this early temperature increase is due to dissipation of the lattice defect energy, stored in the material microstructure during block I loading.

The ductile damage model of Rousselier type predicts that the reduction of the elasticity modulus is of the same order of magnitude as the porosity. However, through the entire loading, the experimentally measured volume is nearly constant. This, phenomenological models of Rousselier type should not be used for St3. Moreover, the process of damage accumulation is essentially accelerated near the complete failure. Such a behaviour is more characteristic for models of Gurson-Tvergaard-Needleman type.

Although the presented experimental program contains valuable insights, it is not complete. In the follow up paper, a geometrically nonlinear thermo-plastic ductile damage model will be developed, based on principles from [12], [13]. Identification of material parameters and sensitivity analysis will dictate the choice of further experiments, aiming at reliable calibration of the model parameters [14], [15].

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References
[1] Bol’shakov A M and Andreev Y M 2016 A local method for loading a tested object during acoustic-emission diagnostics Russ. J. Nondestruct. 5 24 206-11
[2] Troshchenko V T 1996 High-cycle fatigue and inelasticity of metals Multiaxial Fatigue and Design (ESIS21) (London) 335-48.
[3] Mishakin V V, Klyushnikov V A and Gonchar A V 2015 Relation between the deformation energy and the poisson ratio during cyclic loading of austenitic steel The Russ. J. App. Phys. 60 5 665-68
[4] Rosakis P, Rosakis A, Ravichandran G and Hodowany J 2000 A thermodynamic internal variable model for the partition of plastic work into heat and stored energy in metals J. Mech. Phys. Solids 48 581-607
[5] Diaz F A, Patterson E A, Tomlinson R A and Yates J R 2004 Measuring stress intensity factors during fatigue crack growth using thermoelasticity FFEMS 27 571–83
[6] Oliferuk W, Maj M and Raniecki B 2004 Experimental analysis of energy storage rate components during tensile deformation of polycrystals Mater. Sci. Eng. 374 77-81
[7] La Rosa G and Risitano A 2000 Thermographic methodology for rapid determination of the fatigue limit of materials and mechanical components Int. J. Fatigue 22 65-73
[8] Boulanger T, Chrysochoos A, Mabru C and Galtier A 2004 Calorimetric analysis of dissipative and thermoelastic effects associated with the fatigue behavior of steels Int. J. Fatigue 26 221-29
[9] Kapustin V I and Zakharchenko K V 2017 On the experimental analysis of dissipative processes under cyclic loading of metals J. Phys.: Conf. Ser. 894 1 012128
[10] Zakharchenko K V, Kapustin V I and Shutov A V 2020 On the analysis of energy dissipation and ratcheting during cyclic deformation of the titanium alloy VT6 (Ti-6Al-4V) J. Phys.: Conf. Ser. 1431 012025
[11] Zakharchenko K, Kapustin V, Zverkov I, Legan M, Larichkin A and Lukyanov Ya 2020 On the effect of plasma electrolytic oxidation on the fatigue strength of V96Ts1 (Al-Zn-Mg-Cu) aluminum alloy J. Phys.: Conf. Ser. 1666 012019
[12] Shutov A V and Ihlemann J 2011 On the simulation of plastic forming under consideration of thermal effects Materialwiss. Werkst. 42 7 632-38
[13] Shutov A V, Silbermann C B and Ihlemann J 2015 Ductile damage model for metal forming simulations including refined description of void nucleation Int. J. Plasticity 71 195-217
[14] Shutov A V and Kaygorodtseva A A 2019 Parameter identification in elasto-plasticity: distance between parameters and impact of measurement errors ZAMM 99 8 1-13
[15] Shutov A V and Kaygorodtseva A A 2020 Sample shapes for reliable parameter identification in elasto-plasticity Acta Mech. 231 11 4761-780