On the experimental analysis of dissipative processes under cyclic loading of metals

V I Kapustin$^1$ and K V Zakharchenko$^{1,2}$
$^1$Novosibirsk State Technical University, Novosibirsk, Russia
$^2$Lavrentyev Institute of Hydrodynamics, Novosibirsk, Russia

E-mail address: macler06@mail.ru

Abstract. The article is devoted to the experimental study of dissipative material properties tested under homogeneous stress-strain conditions, which realized on the gage part of a smooth sample subjected to cyclic loading with increasing amplitude. A new method to estimate inelastic material properties under strain lower than the nominal strength is proposed. At the initial stages of loading, the method makes it possible to find out irreversible changes in sample characteristics and define material elastic limit under cyclic loading. Strain, longitudinal and lateral stress, as well as temperature of the gage part of a sample are the sample characteristics measured simultaneously. They make it possible to distinguish the components connected with reversible and irreversible strain processes associated with fatigue damage of material.

1. Introduction

Data on inelastic stress of metals obtained at stresses in the range between the proportional elastic limit and yield strength of the material are often applied in the preliminary estimation of fatigue damage resistance characteristics. In particular, Coffin’s formula [1] is widely used to describe the fatigue stress accumulation process. The formula includes inelastic stress characteristics which is a width of hysteresis loop. There are several methods in which damage accumulation is connected with the change of various integral parameters of metal energy dissipation, based on measurement of the absorption coefficient, logarithmic decrement of oscillation and temperature inside damage nucleus [2 - 4]. The phenomenon of elasto-plastic loosening of the material and the material model describing the formation of micropores are used in some approaches [5, 6].

There is a necessity in experimentally derived dependencies from general inelasticity concepts, for example, to identify equations describing the real inelastic strain process, which follows degradation of the material under cyclic loadings.

Modern concepts of reversible processes deal with the term “hysteresis loop”, which is widely used to describe inelastic strain cycle.

Indeed, the sigma-epsilon diagrams in Figure 1 are not closed loops (and the stress process is not cyclic) because the "loops" are broken, and the presented trajectories are closed (coincide) only at one point. From the point of view of thermodynamics such a cycle is irreversible.

The hysteresis loop for plastic materials is known to be open at stresses below the endurance limit [8]. Then a question arises: "Why does the irreversible stress not lead to destruction?" The research
which takes into account the kinetics of phase transformations in stress of metastable austenitic steels [9] shows the correlation between the density of microcracks and the amount of martensite.

![Figure 1. Stress-strain diagrams during cyclic loading.](image-url)

The research presents methods to define the characteristics of materials describing dissipative processes. The approach is based on the concepts of reversible and irreversible processes [10]. The main goal of the research is to show the possibility of experimental determination of the material’s characteristics describing its fatigue damage from the point of physics of strength.

In the research it is required to obtain the following effects under periodic loading: nonlinear stress when loaded beyond the limit of proportionality; changes in volume or shape, deterministic change of material microstructure; dissipative heating of the material.

For the research, the metastable steel 08X18H10T of austenitic class with the following chemical composition was chosen [11]: C not more than 0.08%, Si not more than 0.8%, Mn not more than 2%, Cr 17-19%, Ni 9-11%, Ti not more than 0.7%, S not more than 0.02%, P not more than 0.035%, Cu not more than 0.3%, the basic element is - Fe. The mechanical characteristics were obtained under quasistatic soft loading at a speed of 150 N/s. Modulus of elasticity is 200700 MPa, proportional elastic limit is 280 MPa, conventional yield strength is 302 MPa, temporary stress resistance is 586 MPa. Choosing austenitic steel we relied on the ability of austenite to transform isothermally into strain-induced martensite under mechanical stresses.

2. **Samples, equipment and methods**

For the research, samples of rectangular cross section of 6 x 10 mm² with a gage length of 50 mm were used which allowed fixing two extensometers for measuring axial and transverse strains.

The sample surface, intended to measure the temperature with the help of a thermal imagery camera, was preliminary blackened covering with a thin layer of soot, thus ensuring a blackness coefficient of the surface close to 1. To eliminate the influence of external thermal fields on the measurements radiant temperature screens were used.

The samples were deformed by zero-to-compression stress cycle with a stress amplitude increasing in proportion to time. The selected zero-to-compression stress cycle made it possible to obtain the stressed state characteristics and the sample surface temperature in the part of maximum stresses of a cycle and after unloading at the end of each loading cycle. Thus, the beginning of a spontaneous irreversible dissipation process was identified by the change in characteristics and was characterized by the maximum limit stress in the cycle.

The loading frequency is permanent and equal to 0.5, 1, 2, 4 Hz. The test duration is 680 seconds. During testing, the maximum stress in the cycle is 276 MPa.

During testing, the loading, axial and transverse stress, radiation temperature of the gage part of a sample are measured synchronously. The samples are loaded and the stress is recorded using the INSTRON equipment, and temperature is measured by thermal camera TKVr-IFP SVIT. The experiments are made at a room temperature.
3. The main results

According to the data of [12-14], the volume fraction of the magnetic α' phase in the process of cyclic loading of steel 08X18H10T increases in the course of material degradation that leads to a change of the elastic characteristics in fatigue. If the sample is deformed, for example, by a zero-to-compression stress cycle with a frequency of 4 Hz, recording the characteristics at the moment of unloading, then it is possible to define not only some limited critical stress, but also the property of a material when loaded above this stress.

Figure 1 shows the patterns of a smooth sample stress. Let us remark here, that the represented diagrams are not smooth curves, which are usually obtained when constructing sigma-epsilon diagrams, but a collection of points placed nearby.

![Diagram](image1)

**Figure 2.** Dependencies of the sample stress with a zero-to-compression stress cycle.
In Figure 2 a) – the interdependence of extreme axial $\varepsilon_{x,max}$, $\varepsilon_{x,min}$ and transverse $\varepsilon_{y,max}$, $\varepsilon_{y,min}$ stresses on extreme stresses $\sigma_{x,max}$, $\sigma_{x,min}$ MPa in the cycle is shown. It can be seen from the figure that periodic unloading make it possible to identify inelastic phenomena at stresses less than the conventional yield strength and proportional elastic limit. In Figure 2 b) the linear $\varepsilon_r^e$ and nonlinear $\varepsilon_r^p$ components of total stress are singled out. They make it possible to identify the critical stress level at which the dissipative processes are activated.

Figure 2 c) represents the parametric stress diagrams – in coordinates - maximum and minimum axial and transverse stresses where the parameters of the diagrams are the maximum and minimum loading, respectively. A section of elastic and inelastic stress can be distinguished in the diagram, and the unloading branch will show the change in the volume or shape of the sample after stress. For the extreme point in the diagram corresponding to unloading after the maximum loading, the coefficient of transverse stress is 0.622.

Figure 2 d) clearly shows change in the coefficient of transverse stress for the components of the total stress cycle: amplitude - $V_a = \left| \frac{\varepsilon_{y,max} - \varepsilon_{y,min}}{\varepsilon_{x,max} - \varepsilon_{x,min}} \right|$ and average stress in the cycle - $V_m = \left[ \frac{\varepsilon_{y,max} + \varepsilon_{y,min}}{\varepsilon_{x,max} + \varepsilon_{x,min}} \right]$. The ratio of stress amplitudes over the entire stress range does not change and is equal to 0.285. So, the material reacts to the loading as a perfectly elastic material in the entire range of studied stresses in the cycle. The coefficient of transverse stresses for the average stress in the cycle increases then loading for a maximum stress in the cycle exceeds 100 MPa.

Dependence of the temperature change in the cycle is represented in Figure 3. The amplitude of the temperature $T_a$ grows linearly as well as the stress and the stress amplitude in the cycle (Figure 3 a) and does not depend on the loading frequency.

The nonlinear dependence of the average component of the temperature cycle $T_m$ on stress, (Figure 3 b), is an indicator of irreversible energy dissipation in the sample and is observed in the same stress area as inelastic stress.

Division of the characteristics describing material deformation process into amplitude (linear) and average (nonlinear dependence) components allows presenting the material thermomechanical properties in the form of a surface (Figure 4).

Received reactions can be considered as a slow change in the sample stressed state under conditions of the asymmetric stress cycle and resembles the creep of a material under the periodic loading.
4. Discussion
The results are obtained under homogeneous conditions; they characterize the behaviour of the material at a point and do not contradict the known practice of tests for the material strength and structural elements.

The small inelastic components of the total stress (microplastic stress - irreversible motion of separate dislocations) during periodic stress are different from the residual stresses observed in creep where the corporate movement of the elements of the material’s structure is observed (plastic stress in the whole volume of the material - an increase in the dislocation density by more than two orders and interaction among them) [15]. In contrast to the creep observed under quasistatic loading, small inelastic stresses during periodic loading are followed by local structural changes [16], which in the literature are referred to as martensitic transformations of materials [17]. Despite the local nature of the transformations, they are unidirectional and, for a considerable number of stress cycles, can change the initial properties of the material throughout the entire gage part of the sample’s surface.
Fatigue damage - formation of a microcrack - occurs in the place where the coherence of the lattice of the material self-organized structure is disturbed. A crack can develop if under the action of mechanical stresses the next evolution of the material takes place on its top and conditions for martensitic transformations and destruction of the material on its top will be created. The martensitic structure is brittle and breaks delicately, which is observed on the surface of fatigue fractures. These arguments are confirmed by the established facts of martensitic transformations in the sample surface and data from factographic studies of the samples in which the traces of transformations phases of the material known as fish-eye and bird’s-eye are observed at the site of failure [18], as well as data on the change in the transverse strain coefficient of the samples [16].

In the authors' opinion, the results of the presented material tests can be claimed to characterize the material not only for identification of material model parameters, in which the material properties must vary from cycle to load cycle, but also for practical applications where it is necessary to measure the material's ability to deform without irreversible processes.

5. Conclusion
It has been shown experimentally that the phenomenon of dissipation under cyclic soft loading is caused by a process of monotonous accumulation of the average component of the strain cycle, ratchetting, and leads to heating of the material at stresses much lower than the yield strength of the material. Despite this, the linear dependence of the stress cycle amplitude from the stress amplitude remains in the researched area.

Acknowledgments
This work was partially supported by the Russian Foundation for Basic Research (project code 16-08-00483 A).

References
[1] Coffin L F 1962 Low-cycle fatigue: a review Appl. Mater. Res. 1 129-141
[2] Kapustin V I, Gileta V P and Tereshin E A 2010 On determination of elastic limits by dissipative heating of materials Journal of Applied Mechanics and Technical Physics 51 393-397
[3] Diaz F A, Patterson E A, Tomlinson R A and Yates J R 2004 Measuring stress intensity during fatigue cracking using thermoelasticity Fatigue and fracture of engineering materials and structures 27 571-583
[4] Luong M P 1995 Infrared Thermographics scanning of fatigue in metals Nuclear Engineering and Design 158 363-376
[5] Novozhilov V V, Kadashevich Yu I and Rybakina O G 1988 Disintegration and prospects for the construction of the strength criterion under complex loading taking creep into account From Bulletin. The Academy of Sciences of the USSR. MTT 5 108-114
[6] Shutov A V, Silbermann C B and Ihlemann J 2015 Ductile damage model for metal forming simulations including refined description of void nucleation International Journal of Plasticity 71 195-217
[7] Kotsanda S 1990 Fatigue fracture of metals (Moscow: Metallurgiya) p 623
[8] Teren't'ev V F 2003 Microscopic and macroscopic deformation of metallic materials below the fatigue limit Russian metallurgy (Metally) 5 445-451
[9] Sosnin O V 2003 Change of grain structure and phase composition of austenitic steel during fatigue loading Materialovedenie 1 p 27
[10] Prigozhin I and Condépudi D 2002 Modern thermodynamics. From heat engines to dissipative structures (Moscow: Mir) p 461
[11] Sorokina V G 1989 List of steels and alloys (Moscow: Mechanical Engineering) p 640
[12] 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 Technical Physics. The
Russian Journal of Applied Physics 60 665-668

[13] Terent’ev V F, Dobatkin S V, Prosvirnin D V, Bannikh I O, Rybalchenko O V and Raab G I 2008 Fatigue strength of austenitic steel X18H10T after equal-channel angular pressing Stress and destruction of materials 10 30-38

[14] Gorkunov E S, Zadvorkin S M, Kokovikhin E A, Tueva E A, Subachev Yu V, Goruleva L S and Podkopytova A V 2001 The effects of deformations by rolling and uniaxial tension on the structure and the magnetic and mechanical properties of Armco iron, steel 12X18H10T, and a Steel 12X18H10T-Armco Iron-Steel 12X18H10T composite material Russian Journal of Nondestructive Testing 47 369-380

[15] Wu C H, Hsu J and Chen C H 1998 The effect of surface stress on the stability of surfaces of stressed solids Acta mater 46 3755-3760

[16] Kapustin V I, Gileta V P, Zakharchenko K V and Popelyukh A I 2012 Study of the Regularities of Periodic Deformation of Metallic Materials Industrial Laboratory. Materials Diagnostics 78 50-55

[17] Terent’ev V F and Petukhov A N Fatigue of high-strength metal materials (Moscow: IMET RAS CIAM) P 515

[18] Shaniavski A A 2007 Modeling of fatigue cracking of metals. Synergetics for aviation (Ufa: LLC Monography) P 500