On the analysis of energy dissipation and ratcheting during cyclic deformation of the titanium alloy VT6 (Ti-6Al-4V)

K V Zakharchenko¹,², V I Kapustin¹,² and A V Shutov¹,³

¹Lavrentyev Institute of Hydrodynamics, pr. Lavrentyeva 15, 630090, Novosibirsk, Russia
²Novosibirsk State Technical University, pr. K. Marks 20 136, 630073, Novosibirsk, Russia
³Novosibirsk State University, ul. Pirogova 1, 630090, Novosibirsk, Russia
E-mail: alexey.v.shutov@gmail.com

Abstract. The paper is focused on the analysis of deterioration of strength properties during cyclic deformation of the titanium alloy VT6, which is widely used in numerous engineering applications. A set of experimental data is obtained, regarding stress-controlled cyclic loadings with variable R-values; the influence of the mean stress on the irreversible processes is estimated. The impact of a previous loading history on ratcheting and dissipation-induced heating is clarified. The use of the obtained experimental data for creation and calibration of constitutive models is discussed.

1. Introduction
The main goal of the study is to analyse the energy dissipation and strain accumulation taking place under inelastic cyclic deformation of the titanium alloy VT6 in case of constant nonzero mean stresses. Toward that end, the impact of previous loading history on the mechanical properties is revealed. Further goals include a discussion of modelling approaches as well as discussion of methods of calibration and validation based on the obtained experimental data. In accordance to these goals, the testing results are presented in a form suitable for further use in theoretical studies.

Various mechanical effects observed in experiments on cyclic deformation can be attributed to a number of micromechanical mechanisms. For instance, deterioration of macroscopic strength can be a consequence of material softening and damage, while softening is primarily related to kinetics of dislocations and damage – to creation, growth and coalescence of voids and cracks. Thus, in order to create a sufficiently accurate material model, one needs to clarify the impact of each of the mentioned mechanisms. Toward that end, a broad experimental program is required.

A comprehensive material model intended for use in practical applications should account for a number of mechanical phenomena, for each of the phenomena a special constitutive assumption should be made. A short (not exhaustive) summary of the phenomena, employed modelling assumptions and required experiments is provided in Table 1.
Table 1. Short summary of relevant mechanical phenomena, corresponding modelling assumptions, and required experimental data.

| Mechanical effect/phenomenon | Modelling approaches/assumptions | Required experimental evidence |
|-----------------------------|----------------------------------|-------------------------------|
| Increase of elastic domain in a course of plastic deformation | Isotropic hardening (Voce, Swift, Baltov-Savchuk, etc.) | Hysteresis loops on the $\sigma - \varepsilon$ diagram |
| Shift of elastic domain in a course of plastic deformation / Bauschinger effect | Kinematic hardening (Armstrong-Frederick, Mroz, Chaboche, etc.) | Hysteresis loops on the $\sigma - \varepsilon$ diagram. Tests with load reversal |
| Accumulation of the mean strain under asymmetric cyclic loading / ratcheting | Refined models of kinematic hardening suitable for ratcheting (Chabohe, Ohno and Wang, etc.) | Hysteresis loops on the $\sigma - \varepsilon$ diagram and/or $\varepsilon(t)$ – curve |
| Yield surface distortion, cross-hardening effect | Distortional hardening (Ortiz-Popov, Dafalias-Popov, Plesek, Shutov and Ihlemann, etc.) | Stress-strain curves for non-proportional loading, evolution of the yield surface |
| Dissipation-induced heating | Local heating term in equation of heat conduction (Taylor-Quinney, Helm, etc.) | Temperature evolution during inelastic deformation |
| Ductile damage as nucleation, growth and coalescence of micro-voids and micro-cracks | Damage-dependent yield criterion (Rousselier, Gurson-Tvergaard-Needleman, etc.); damage-dependent elastic properties and hardening parameters; evolution equations for damage | Hysteresis loops on the $\sigma - \varepsilon$ diagram, microstructural observations |
| Damage-induced porosity | Assumptions in model kinematics, introduction of porosity strains | Data on volume changes during plastic deformation |
| Material softening | Assumptions opposite to isotropic hardening; elastic properties remain unchanged | Temporal evolution of the elastic domain |

Cyclic loading may trigger inelastic processes even for stresses below nominal (technical) yield stress. Most of metallic materials subjected to cyclic loading exhibit expanding/contracting elastic domain. In order to capture this important effect, a suitable model should account for isotropic hardening/softening. Next, each inelastic cycle near to a steady state induces two yielding events during the forward and reverse loading. For that reason, a material model must account for the nonlinear kinematic hardening [1], [2], [3], [4]. Unfortunately, classical kinematic hardening rules like the one of Armstrong and Frederick may overpredict ratcheting; therefore refined kinematic hardening models are required [3], [5]. Next, it is well known that the yield surface exhibits a larger curvature in the loading direction and a flattening on the opposite side; this manifests itself in the cross-hardening effects.
effect. Therefore, if non-proportional loadings are considered, directional distortion of the yield surface plays an important role [6], [7], [8], [9], [10]. Fortunately, in many practical cases the loading is proportional or even uniaxial, therefore multi-axial fatigue lies beyond the scope of the current paper. Another important aspect is the dissipation-induced heating. Although the temperature increase is often too small to have any significant impact on the material properties, the temperature evolution by itself carries a large amount of information concerning the activation of dissipative processes and energy storage on the microstructural level. In particular, this information can be used to estimate the defect energy of the crystal lattice [11]; the defect energy itself is a measure of damage. Finally, damage-induced porosity must be accounted for in a correct way to enable correct predictions of the hydrostatic component of the stress tensor.

Another challenging problem is treatment of large strains. Although fatigue damage usually takes place under small strain conditions, geometrically nonlinear models can be used to take the manufacturing part into account. In the current paper a data set is obtained, suitable for the calibration and validation of comprehensive models covering the aforementioned effects. For the general techniques of parameter identification the reader is referred to [12]; methods of parameter identification and assessment of reliability of material parameters can be found in [13], [14].

2. Material, samples, experimental set-up, and methods

2.1 Material and testing samples

A batch of testing samples was machined from a sheet of titanium alloy VT6 (which is a close analogue of the Ti-6Al-4V alloy). This particular material is chosen for the analysis due to its wide use in aircraft manufacturing; it is also used for compressor blades of turbojet engines. The material can be ordered in various forms like forgings, stampings, rods, plates and sheets. These products may exhibit different mechanical properties since the deformation history is induced at the production stage when the material is subjected to technological processes like rolling, drawing, forging, machining, heat treatment etc. Thus, the technological steps preceding the actual testing of the sample have a significant impact on the durability of the sample.

The titanium alloy which is used in discs and blades of the compressor is attributed to two-phase alloys of type \( \alpha + \beta \). Therefore, the form of such a two-phase microstructure can be mixed (lamellar and globular). The microstructure, in turn, affects the critical stress level at which the deterioration of strength properties starts; within a single sample a number of various deterioration mechanisms can run in parallel.

For the experimental analysis, samples of type IV are used according to GOST 25.502-79, see Figure 1. The sample gage length equals 50 mm, which allows us to install two extensometers for measuring axial and transverse strains.

![Figure 1. Geometry of the sample.](image)

The surface of the gage area of the sample, intended for temperature measurements by a thermography camera, is covered with a thin layer of amorphous carbon. The blackness coefficient is close to 1.
Two components of the strain tensor, the axial stress, and the radiant temperature on the surface are measured and recorded with a frequency of 100 Hz; a large data set is thus obtained. This experimental data set is sufficient for calibration (parameter identification) of advanced material models, which account for damage accumulation, damage-induced dilatation, deterioration of elastic and plastic properties, plastic heating as well as ratcheting.

2.2 Equipment
In order to determine the mechanical properties of the VT6 titanium alloy under cyclic loading, a universal testing machine Instron 8801 is used. The loading is stress controlled. For in situ measurements of the strains, standard extensometers N2620-601 “Dynamic Extensometer” and “Transverse/Diametral Extensometer” W-E-404-F are employed. The temperature evolution is measured using a thermographic camera TKVr-IFP “SWIT”.

2.3 Method for identification of mechanical properties under cyclic loading
In order to determine critical stresses in the material sample, a special method is used. Within the method, the limiting stresses can be identified using a diagram of accumulation of irreversible strains or, alternatively, by the temperature of the dissipation-induced heating [15].

A sample which was in a thermodynamic equilibrium (i.e. viscous effects and temperature field heterogeneities are negligible) is subjected to a stress-controlled loading. The mean stress is held constant with a monotonically increasing stress amplitude; the stress amplitude is a linear function of time. This loading scheme allows us to exclude the impact of the mean stress within each single test. Thus, each individual test provides the dependence of the mechanical properties and temperature evolution on the stress amplitude.

A typical loading program is presented in Figure 2; each loading block consist of 4 steps as follows:
- quasi-static monotonic loading (Step 1),
- holding under constant stress for 180 seconds (Step 2),
- stress-controlled loading with a linear increase of the stress amplitude (Step 3),
- unloading to zero stress (Step 4).

Step 3 comprises 2400 harmonic loading cycles with the frequency of 4 Hz; thus, the overall duration of Step 3 is 600 seconds. The holding stage at Step 2 is necessary to get rid of viscous effects which could be induced during Step 1.

The increment of the stress amplitude on each cycle $\sigma_{a,\text{step}}$ equals $\sigma_{a,\text{step}} = \frac{\sigma_{a,\text{max}}}{N_{\text{cycle}}}$, where $\sigma_{a,\text{max}}$ is the maximum stress amplitude within Step 3, $N_{\text{cycle}} = 2400$ is the overall number of cycles within Step 3. During each test, the axial stress, radiant temperature as well as the axial and transverse strains are measured and recorded. All tests are carried out at room temperature.

![Figure 2](image)

**Figure 2.** A single loading block. Step 1: quasi-static loading; Step 2: holding under constant stress; Step 3: harmonic cyclic loading with linearly increasing stress amplitude; Step 4: unloading.

After each loading block is complete, the measurements are analyzed and extreme values of strains and temperature are identified. Irreversible (inelastic) strains are computed using these data. Due to a
high resolution, it is possible to subdivide the temperature evolution into components caused by the thermo-elastic effect, dissipative heating as well as heat conduction.

3. Basic results and discussion

Figure 3 contains experimental results for samples made of as-received material. It shows the temperature increase $\Delta T_m$, mean plastic strain $\varepsilon_{xm}$ and plastic strain amplitude $\varepsilon_{xa}$ as functions of the stress amplitude $\sigma_a$. Here we set $\varepsilon_{xm}^P = \varepsilon_{xm} - \varepsilon_{xm0}$ and $\varepsilon_{xa}^P = \varepsilon_{xa} - \frac{\sigma_a}{E_{do}}$, where $\varepsilon_{xm} = \frac{\varepsilon_{x_{max}} + \varepsilon_{x_{min}}}{2}$ is the mean total strain, $\varepsilon_{xa} = \frac{\varepsilon_{x_{max}} - \varepsilon_{x_{min}}}{2}$ is the amplitude of the total strain, $\varepsilon_{x_{max}}, \varepsilon_{x_{min}}$ are the extreme values of the total axial strains; $\varepsilon_{xm0}$ is the total axial strain reached after Step 2; $E_{do}$ is the dynamic secant modulus computed at the beginning of Step 3 where inelastic strains are negligible. In Figure 3 different curves are marked by numbers depending on the mean stress $\sigma_m$ applied in the particular test: numbers 1, 2, and 3 correspond to the mean stresses of 420, 530, and 635 MPa, respectively. The data shown in this figure allow us to estimate the impact of the mean stress on the magnitude of the stress amplitude at which dissipative heating starts and the accumulation of irreversible strains becomes active. In other words, these curves indicate at which stress amplitudes the deformation becomes irreversible.

Figure 3 shows that for increasing mean stress the stress amplitude needed to activate the plastic yielding is decreasing; a non-linear evolution of the inelastic strain and dissipation-induced heating are observed. This result is in a good agreement with the softening effect of the mean stress observed in metals; this softening effect is usually estimated by the Haigh diagram.

In order to clarify the interrelation between the dissipation-induced heating and progressive accumulation of the mean stress (also known as ratcheting), the sample is loaded by two blocks of the type shown in Figure 2. The use of numerous blocks allows us to study the deterioration of strength properties including the history effect. At the beginning of the second loading block, the material is subjected to a smaller stress amplitude than at the end of the first block. The linear damage accumulation is known to fail at such a scenario, often providing a wrong prediction of the fatigue strength [16], [17].

Figure 4 plots the temperature, the amplitude of the plastic strain and the mean value of the plastic strain versus the applied stress amplitude. The first block, which corresponds to the as-received state, is denoted by 1; the second block is marked by 2. The experimental curves in Figure 4 are obtained by cyclic loading with a constant mean stress of 420 MPa.
Figure 4. Dependencies on the stress amplitude for two different states. Mean stress equals 420 MPa. 1 marks the as-received state; 2 marks pre-loaded state after a single loading block. a) evolution of temperature and mean plastic strain. b) evolution of temperature and plastic strain amplitude.

Figure 4 indicates that in pre-loaded material the increase of the plastic mean strain (ratcheting) happens much later than the plasticity-induced heating. Recall that these results correspond to a fixed mean stress of 420 MPa. Similar tests with a higher value of the mean stress provide a similar result, see, for instance, Figure 5 for the mean stress of 635 MPa.

Figure 5. Dependencies on the stress amplitude for two different states. Mean stress equals 635 MPa. 1 marks the as-received state; 2 marks pre-loaded state after a single loading block. a) evolution of temperature and mean plastic strain. b) evolution of temperature and plastic strain amplitude.

The evolution of the dynamic secant modulus $E_d$ and the temperature $\Delta T_m$ are plotted in Figure 6 versus the applied stress amplitude $\sigma_a$. Results for the as-received sample are denoted by 1 and for the sample pre-loaded by a single loading block they are marked by 2. Just as in Figure 5, these results are obtained for the constant mean stress level of 420 MPa.
Figure 6. Dependence of the temperature increase and the dynamic secant modulus on the applied stress amplitude. Mean stress equals 420 MPa.

Figure 6 reveals that under cyclic loading with a constant positive mean stress the decrease of the dynamic secant modulus takes place simultaneously with the temperature increase. For the sample made from as-received material this happens for stress amplitudes larger than 350 MPa; for the sample already pre-loaded by a single block, this process starts at stress amplitudes above 200 MPa. Moreover, the dynamic secant modulus of the pre-loaded sample is smaller than that of the original sample. These effects indicate deterioration of strength under cyclic loading.

The following two effects are exhibited by the presented experimental data. The first effect is ratcheting under constant non-zero mean stress; this phenomenon is similar to creep observed under constant stress. The second effect is the simultaneous increase of the amplitude of the plastic strain and the dissipation-induced temperature growth, accompanied by deterioration of the strength properties. This deterioration requires further analysis, in particular, in order to separate the ductile damage and eventual softening effects.

The temperature increase and the accumulation of the mean plastic strain share the same tendency: these processes start at smaller stress amplitudes for larger mean stresses.

4. Conclusions
A broad set of experimental data concerning cyclic loading of the titanium alloy VT6 with a constant mean stress and variable stress amplitudes is obtained. The impact of the mean stress and the previous loading history is characterized. The chosen experimental programs allow us to cover a broad range of loading scenarios; a spectrum of different R-values is obtained within each test.

The damage accumulation under stress-controlled cyclic loading leads to a reduction of the dynamic secant modulus; the damage accumulation is accompanied by ratcheting and dissipation-induced heating. An unexpected counterintuitive result is that in pre-loaded samples the dissipation-induced heating starts well before ratcheting, see Figures 4 and 5.

Acknowledgments
This work was partially supported by the Russian Foundation for Basic Research and Novosibirsk region, project No. 19-48-543028 (conduction of the experimental research and estimation of technology impact), as well as the Russian Science Foundation within project No. 19-19-00126 (analysis of modelling assumptions and interpretation of experimental results).
References

[1] Kadashevich Yu I, Novozhilov V V 1958 Theory of plasticity accounting for residual microstresses. [in Russian] *Applied Mathematics and Mechanics* vol 2 pp 78-89

[2] Armstrong P J and Frederick C O 1966 A Mathematical Representation of the Multi Axial Bauschinger Effect. CEGB Report RD/B/N 731

[3] Chaboche J L 1991 On some modifications of kinematic hardening to improve the description of ratchetting effects *International Journal of Plasticity* vol 7(7) pp 661-678

[4] Shutov A V and Kreißig R 2008 Finite strain viscoplasticity with nonlinear kinematic hardening: Phenomenological modeling and time integration *Computer Methods in Applied Mechanics and Engineering* vol 197 pp 2015-2029

[5] Ohno N and Wang J-D 1993 Kinematic hardening rules with critical state of dynamic recovery, part I: formulation and basic features for ratchetting behavior *International Journal of Plasticity* vol 9(3) pp 375-390

[6] Dafalias Y F and Popov E P 1975 A model of nonlinearily hardening materials for complex loading *Acta Mechanica* vol 21 pp 173–192

[7] Ortiz M and Popov E P 1983 Distortional hardening rules for metal plasticity J. Engng Mech. vol 109 pp 1042 – 1058

[8] Rokhgireh H and Nayebi A 2012 Cyclic uniaxial and multiaxial loading with yield surface distortion consideration on prediction of ratcheting *Mechanics of Materials* vol 47 pp 61–74

[9] Plesek J, Feigenbaum H P and Dafalias Y F 2010 Convexity of yield surface with directional distortional hardening rules *Journal of Engineering Mechanics* vol 136(4) pp 477-484

[10] Shutov A V and Ihlemann J 2012 A viscoplasticity model with an enhanced control of the yield surface distortion *International Journal of Plasticity* vol 39 pp 152-167

[11] Shutov A V and Ihlemann J 2011 On the simulation of plastic forming under consideration of thermal effects *Materialwissenschaft und Werkstofftechnik* vol 42(7) vol 632-638

[12] Beck J V and Arnold K J 2007 *Parameter Estimation in Engineering and Science* (John Wiley and Sons)

[13] Harth T, Schwan S, Lehn J and Kollmann F G 2004 Identification of material parameters for inelastic constitutive models: statistical analysis and design of experiments *International Journal of Plasticity* vol 20 pp 1403-1440

[14] Shutov A V and Kaygorodtseva A A 2019 Parameter identification in elasto-plasticity: distance between parameters and impact of measurement errors *Zeitschrift für Angewandte Mathematik und Mechanik* vol 99(8) pp 1-13

[15] Kapustin V I and Zakharchenko K V 2017 On the experimental analysis of dissipative processes under cyclic loading of metals *Journal of Physics: Conference Series* vol 894(1) P. 012128

[16] Chechulin B B and Khesin Yu D 1987 *Cyclic strength and corrosion resistance of titanium alloys* [in Russian] (Moscow: Metallurgiya)

[17] Collins J A 1981 *Failure of Materials in Mechanical Design* (New York: John Wiley and Sons)