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Characteristics of the Dissipation of Energy at Hot Plastic Deformation of Near-Alpha Titanium Alloy

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Abstract

Change of mechanical properties of near-alpha titanium alloy is experimentally investigated at stretching in the conditions of variation of temperature and high-speed parameters of deformation. It is established that characteristics of mechanical properties, a structural state influence processes of dissipation of the spent energy. Studying of microstructure of samples before deformation by stretching allowed to install the main mechanisms of dissipative processes and to confirm a possibility of realization of superplasticity in the studied alloy.

Keywords: titanium alloy, tensile deformation, dissipation, superplasticity, microstructure

1. Introduction

Structural and phase transformations in metal alloys at deformation in the conditions of plasticity and superplasticity are a subject of long-term and systematic researches.

In scientific literature there are physical and mathematical models of deformation describing structural transformations in process as plastic and superplastic deformation of structural materials [1, 2].

However we have very few materials of publications in which results of the thermodynamic analysis directly correspond to researches of structural transformations. Authors of works [3–5] showed that one of the effective methods of studying of mechanisms of hot plastic deformation is the thermodynamic approach based on use of dynamic model of deformation of material.

According to the model of the elasto-visco-plastic environment, for any time-point the power of the mechanical energy P coming to a deformable body is defined by the sum composed by G and J . Both are connected with production of entropy. However first (G) considers dissipation of energy through forming and hardening. Second (J) is connected with the adapting reorganizations in structure of grains of

a polycrystal directly in the course of action of the deforming tension. Hence it is connected with production of entropy in material:

$$P = G + J = \sigma \dot{\epsilon}; = T(ds/dt) \geq 0, \quad (1)$$

where σ is tension, $\dot{\epsilon}$; is strain rate, T is temperature, and dS/dt is the speed of production of entropy.

Division of power of dissipation between G and J is defined by strain rate sensitivity m :

$$dJ/dG = \Delta \log(\sigma) / \Delta \log(\dot{\epsilon};) = m. \quad (2)$$

It is shown that for quantitative assessment of nature of dissipative processes and practical application, it is convenient to use effectiveness ratio of dissipation of energy (η):

$$\eta = 2m / (m + 1). \quad (3)$$

The coefficient η characterizes ability of structure of material to dissipate the brought mechanical energy in the course of hot deformation.

Size η changes in the range from zero to unit and is interpreted as the relative speed of production of entropy.

In the present article, results of the research characteristics of dissipation of energy in industrial alloys in the course of uniaxial stretching and compression on the example of near-alpha titanium alloy are stated.

During the planning and implementation, the present article used system approach which included the detailed analysis of structure of alloy before deformation and comparison of results of structural researches to results of mechanical tests and calculation of coefficient of dissipation of energy.

2. Materials and experimental methods

Mechanical tests of samples of titanium alloy cut from hot-rolled sheet products with thickness of 40 mm, the chemical composition of which is given in the **Table 1**, were made at different temperatures and speed parameters.

The initial microstructure of titanium alloy corresponded to a two-phase state which was created in the course of hot rolling.

The received structure is characterized by the large initial size of grains of a β -phase ($\sim 300 \mu\text{m}$) and represents mix of the α -plates divided by β -phase layers (**Figure 1**).

Mechanical tests on stretching at room temperature were carried out on the tensile testing machine UEN30 "Shimadzu." At increased temperatures, the modernized universal testing machine UM5 was used.

Element content, % wt.									
Al	V	Mo	Fe	Si	C	O	H	N	Ti
5.4	2.0	1.2	0.25	0.3	0.1	0.15	0.08	0.04	The rest

Table 1.
Chemical composition of the studied alloy.

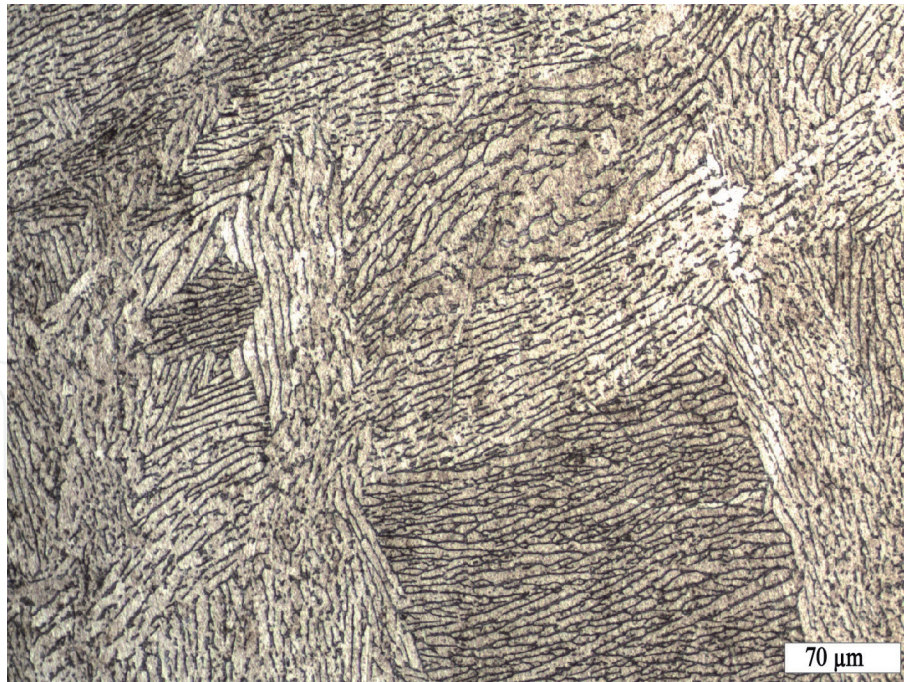


Figure 1.
Initial microstructure of alloy.

In an experiment, standard explosive samples with a diameter of 6 mm were used. For tests for compression cylindrical samples with a diameter of 5 and 10 mm on the high-temperature dilatometer DIL 805 were used.

At the same time deformation equaled $\varepsilon = 0.3$, and temperature of heating corresponded 800–1040°C. Average strain rate $\dot{\varepsilon}$; was 10^{-3} – 10 s $^{-1}$.

Calculation of effectiveness ratio of dissipation of energy at deformation of samples under various temperature and high-speed conditions consisted in formation of a matrix of values of true tension at the set extent of deformation and their logarithms.

Calculation of coefficients of m and η and calculation of intermediate values of effectiveness ratio of dissipation of energy were made by a method of spline interpolation.

Results of calculation can be presented in the tabular, analytical, or graphic style.

The most evident is representation of results of calculation η in the form of 3D plot and cards of constant levels of effectiveness ratio of dissipation of energy. Calculation and creation of cards were carried out with the use of the Mathcad 15 program.

Microstructural researches were carried out on the polished samples of the deformed samples, which are cut out in the cross-sectional and longitudinal direction with application of modern methods [5, 6].

To get images, information technologies and specialized programs have been used (“Expert Pro”, “Fractal”) [7, 8].

3. Results of researches and discussion

According to results of mechanical tests, dependences are constructed $\sigma = f(\varepsilon)$.

The received dependences and their look do not contradict the settled ideas of behavior of metal polycrystals in the conditions of hot plastic deformation. So, in the

course of process of plastic deformation of metal, tension smoothly increases and reaches a certain maximum (saturation) in which value is defined at the same time proceeding competing processes—hardening and a weakening [9]. The growth rate of tension depends on temperature of heating and speed of deformation. At low temperatures and high speeds of deformation, flow stress continuously increases with deformation growth that is caused by the prevailing process of deformation hardening.

At the increased temperatures and low speeds of deformation, flow stress reaches a maximum and then goes down, reaching a certain constant value. In such type of charts, tension deformation is characteristic of the majority of the metals and alloys deformed at temperatures exceeding half the temperature of melting [10, 11].

Current tension size (σ_s) of the studied alloy depending on temperature and the speed of deformation is presented in **Table 2**.

Values of tension of a current at the set temperature and high-speed parameters of deformation were used for the subsequent calculation of effectiveness ratio of dissipation of energy η .

Change of coefficient η from temperature and high-speed parameters of deformation are presented in the form of the volume chart (**Figure 2**) and also in the form of the card of constant levels of effectiveness ratio of dissipation of energy (**Figure 3**).

Analyzing the results of change of effectiveness ratio of dissipation of energy presented on 3D plot and the map of constant levels of effectiveness ratio of dissipation depending on temperature and high-speed parameters of deformation, it is possible to note:

Temperature dependence $\eta = f(t, \epsilon)$: It is characterized by a maximum at temperatures 900–940°C. And with increase in speed of deformation, maximum shift toward big speeds of deformation is observed.

- The studied alloy is characterized by high efficiency of dissipation of energy in the studied range of temperature and high-speed parameters of process of hot deformation. Efficiency of energy of dissipation significantly does not change with increase in extent of deformation from 0.1 to 0.3.
- Mechanical properties of alloy at hot plastic deformation substantially depend on initial structure and temperature and high-speed parameters of deformation.
- In an initial state the studied alloy has the coarse-grained (not recrystallized) structure and the increased maintenance of a β -phase in comparison with an equilibrium state.

$T, ^\circ\text{C}$	σ_s, MPa			
	10^{-4} s^{-1}	10^{-3} s^{-1}	10^{-2} s^{-1}	10^{-1} s^{-1}
800	60	100	160	240
840	44	75	130	195
880	24	53	94	149
920	14	28	60	95
960	8.0	16	30	60
1000	5.8	10	18	32

Table 2.

The flow stress of examined alloy at various temperatures and strain rate values for tensile strain of $\epsilon = 0.2$.

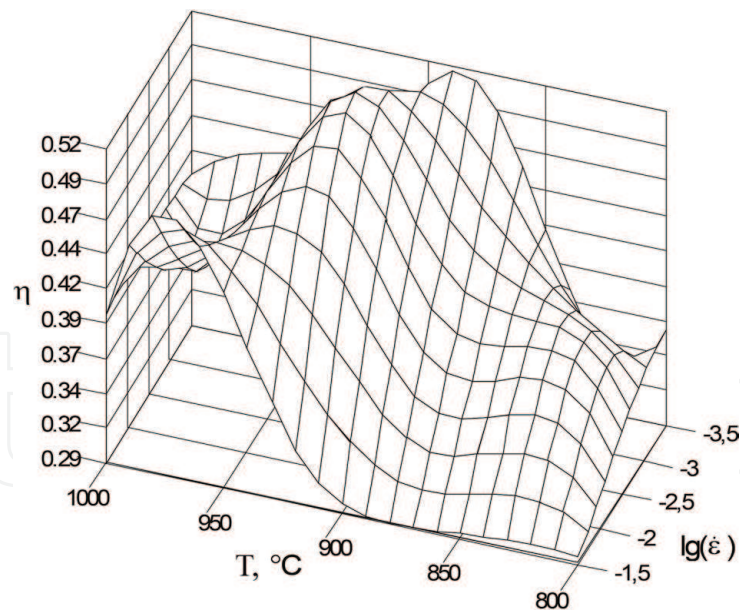


Figure 2.
 3D plot of effectiveness ratio dissipation of energy at $\epsilon = 0.2$.

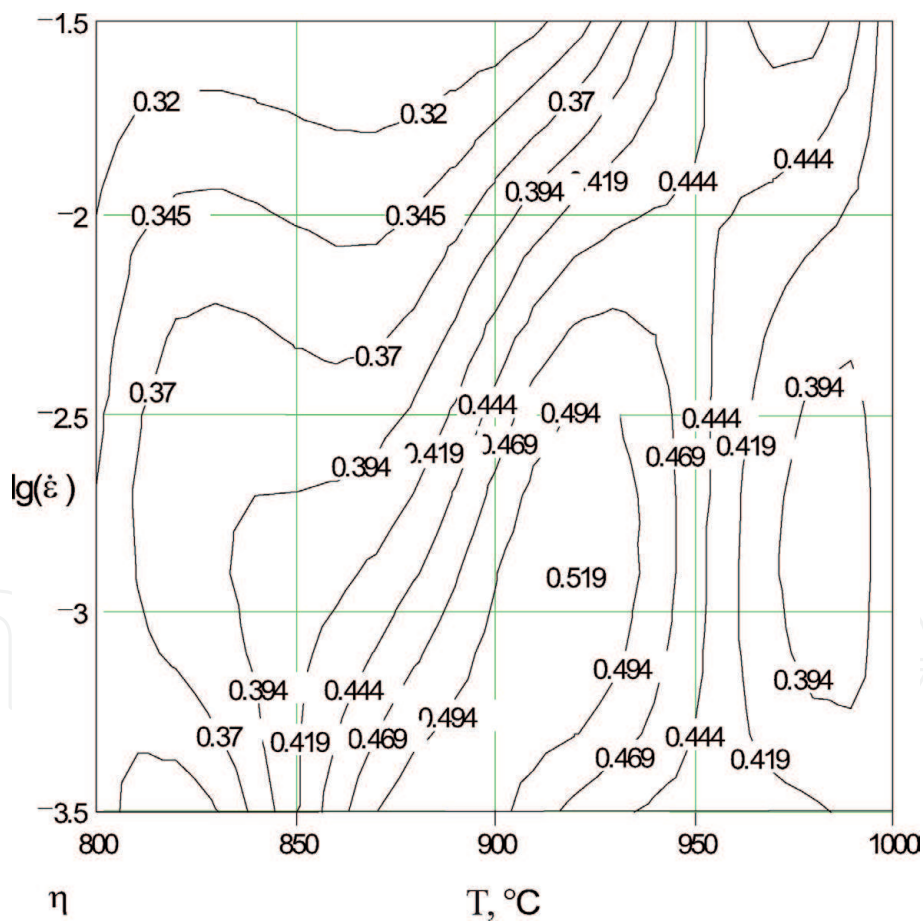


Figure 3.
 Processing map for titanium alloy. Constant levels of coefficient efficiency of dissipation at $\epsilon = 0.2$.

When heating alloy to temperature of 800°C, the first signs of recrystallization are observed, and further heating to temperatures of 920–940°C and endurance of 15 min. Process of recrystallization proceeds completely.

To process recrystallization, $\alpha \rightarrow \beta$ phase transformation is followed. An increase of the β -phase contents in the alloy when heated is represented in **Table 3**.

$T, ^\circ\text{C}$	750	800	850	900	950	1000	1040
β -phase, %	15	20	28	40	65	82	100

Table 3.

Change of volume fraction of a β -phase when heating alloy.

Increasing the heating temperature of the alloy leads to an increase in the phase change rate due to an increase in self-diffusion. The largest speed of phase transformation is observed at a temperature of heating of 900–950°C. The quantity of α - and β -phases decreases with temperature increase and increase in hold time. The quantity of a phase decreases with temperature increase and increase in hold time. At alloy heating temperatures (1040°C), the phase transformation which is followed by sharp integration of grains of a β -phase completely comes to the end (**Table 3**).

It follows from the provided data that the microstructure and phase composition of alloys undergo significant changes at a temperature of heating to temperatures more than 950°C owing to full completion of process of recrystallization and phase $\alpha \rightarrow \beta$ transformations.

Results of researches on the change of structure of alloy in the course of deformation at various temperatures and extent of deformation 0.4 are presented in **Table 4**.

Grain size change in phase $\alpha \rightarrow \beta$ transformation is characteristic for structure at hot deformation of alloy. If the size of grains α -phases decreases, then the size of grains β -phases on the contrary increases.

As appears from the data provided in **Table 4** in the course of deformation of alloy, there is an increase in quantity of β -phases. The considerable difference in the number of phases of composition of alloy is observed at deformation speeds 10^{-3} s^{-1} . Further increase in speed of deformation practically does not lead to significant change of quantity of β -phases in comparison with an initial condition of alloy. Increased rate of deformation results in intensive phase transformation in alloy at small degrees of deformation.

So, at extent of deformation $\varepsilon = 0.4$, quantity of β -phases reaches 12–20%, and at extent of deformation from 0.4 to 1.0, it reaches only 3–4%.

Change of phase composition in the course of deformation is often connected with intensity of diffusive processes. The authors of [11] note that heating to the temperature of deformation of the titanium alloy does not lead to the achievement of phase equilibrium. The reason for this phenomenon is the relatively low diffusion mobility of β -stabilizing elements. For example, the β -phase content is 49% at a strain temperature of 950°C and 30 minutes.

$T, ^\circ\text{C}$	Grain size, μm								Phase composition, %			
	$\varepsilon = 0$				$\varepsilon = 0.4$				$\varepsilon = 0$		$\varepsilon = 0.4$	
	I		II		I		II		α	β	α	β
	α	β	α	β	α	β	α	β	α	β	α	β
840	12.7	4.7	6.8	2.4	6.6	5.5	3.6	2.5	70	30	54	46
900	11.0	4.9	6.6	3.0	7.9	7.7	4.3	4.2	60	40	42	58
960	10.4	6.7	6.8	5.1	9.9	12.5	6.7	6.9	35	65	22	78

Note: I, longitudinal section of a sample; II, the cross-section of a sample.

Table 4.

The size of grain and phase composition of alloy before deformation at various temperatures.

Practically the same quantity of β -phases is observed at 2.5 min. Endurance with extent of deformation $\varepsilon = 0.5$. This circumstance allows to make the assumption that not only the increase in diffusive mobility of atoms is caused by deformation but also temperature change of phase balance is the reason of phase transformation at action of external tension.

The phase $\alpha \leftrightarrow \beta$ transformation is accompanied by a volumetric effect. It is known that various authors estimate this value to be about 0.15% [12]. Transformation of $\alpha \leftrightarrow \beta$ is accompanied by a volumetric effect and $\alpha \rightarrow \beta$ transformation-negative volumetric effect. Therefore with an external pressure, there is a temperature change of polymorphic transformation. The speed of phase transformations generally depends on the difference of free energy of an initial and final state and also the size of change of volume upon this transition. As the size of free energy and volume depend on pressure, it is possible to expect that the speed of phase transformations will also depend on pressure.

In that case when phase transformations are carried out in the diffusive way, the kinetics of phase transformations is defined by change of speed of the course of diffusive processes with a pressure.

The driving force of phase $\beta \rightarrow \alpha$ transformation in titanium alloys is shift of phase equilibrium temperature under action of external tensions. The rate of phase change is determined by the diffusion mobility of the β stabilizing elements' atoms. The interesting fact established when studying changes of a microstructure of alloys at hot deformation is transformation of initial lamellar structure in granular, which is most brightly shown at a temperature of deformation of 920°C and strain rate of $1.1 \cdot 10^{-3} \text{ s}^{-1}$ (Figure 4).

Grain shape coefficient was determined by quantitative metallography method $K_{\phi} = l_{\alpha}/d_{\alpha}$; where l_{α} is the length of the plates and d_{α} is the width of the plates α -phases. The results of the calculations showed that intensive change of grain shape occurs up to deformation of 100%; at higher deformation, K_{ϕ} stabilizes at values of $\approx 1.2-1.5$.

Equiaxial grains of structure 200 ÷ 300 microns in size are observed in the field of temperatures of β -phases ($t \geq 1040^{\circ}\text{C}$).

The nature of dissipative processes described above finally defines indicators of plasticity of alloy. Maximum stability of plastic deformation of alloy is observed at compliance of temperature-speed deformation parameters and maximum

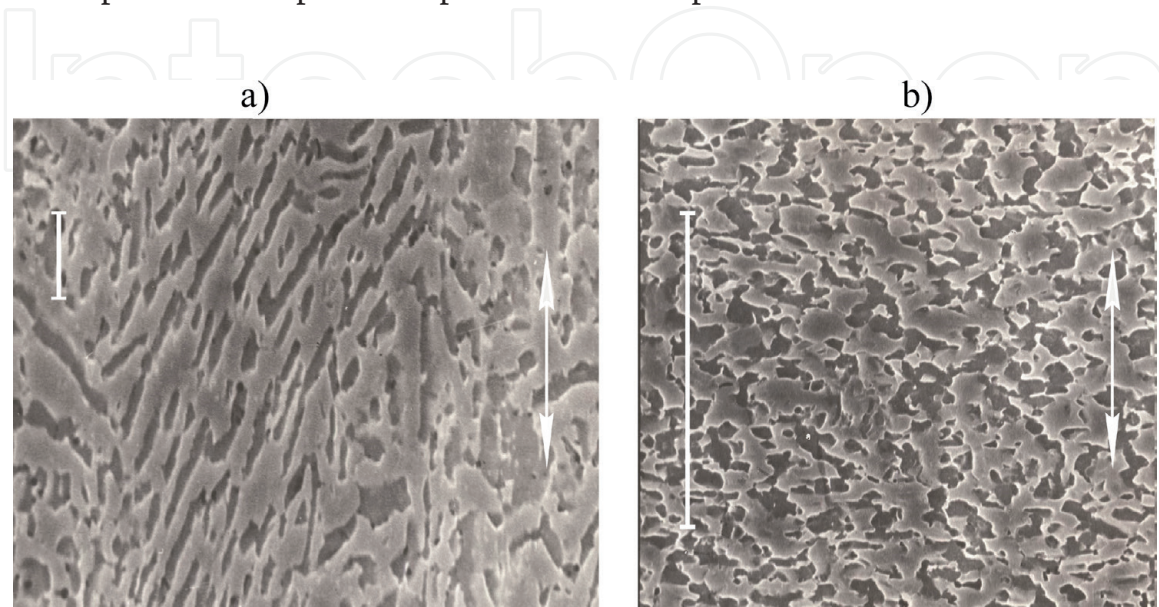


Figure 4.
An alloy microstructure after deformation at 920°C and speeds of deformation $1,1 \cdot 10^{-3} \text{ s}^{-1}$. (a) $\delta = 55\%$,
(b) $\delta = 200\%$. $\times 1000$.

coefficient of energy dissipation efficiency [10]. All signs of superplasticity state are observed at temperature of 920-960°C and deformation rate of 10^{-3} – 10^{-2} s⁻¹.

Thus, on the basis of the analysis of structural changes when heating and plastic deformation of alloy, it is possible to draw the following conclusions.

4. Conclusions

1. At hot plastic deformation of the studied titanium alloy, there are, at least, two dissipative processes—dynamic recrystallization and phase transformation.
2. The maximum of efficiency of dissipation corresponds to the simultaneous balanced course of these two processes.
3. The temperature and high-speed extremum of effectiveness ratio of a dissipation of energy corresponds to conditions of the maximum stability at a plastic strain of alloy.
4. Results of researches about development and speed of dissipative processes at a hot plastic strain of the studied alloy can be used for optimization of the technological modes of hot treatment by pressure.

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