Investigation of Twinning Dynamics in VT1-0 Titanium Using Acoustic Emission

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Abstract—Use of acoustic emission signals makes it possible to analyze deformation processes in the bulk of a crystalline titanium structure formed under the effect of a concentrated strain created by loading of a diamond pyramid. The obtained results of the process of development of deformation twins make it possible to assert that their formation, output, and storage on the specimen's surface are possible under certain external stresses exceeding the value of internal stresses in the crystal bulk.

Keywords: titanium, twinning, glide, acoustic emission.

INTRODUCTION

Investigations of titanium VT1-0 after hot rolling with the residual deformation of ~75% and subsequent complete annealing at 700°C revealed disproportional variations in the number of twins entering the surface of a specimen and their linear dimensions under identical applied external stresses. It follows from the experimental results that stable stress concentrators formed by a diamond pyramid provide reproducibility of the overwhelming part of twinning layers with an increase in the load to an indenter. Nucleation of deformation twins near a stable stress concentrator and variations in their parameters in the process of repeated increasing loadings makes it possible to affirm the advantages of nucleation of deformation twins over glide twinning.

The aim of the paper is to study interactions of twinning dislocations with other dislocations in polycrystalline titanium and the effect of the accompanying reactions on acoustic emission (AE).

MATERIALS, EQUIPMENT, AND METHOD OF INVESTIGATION

Formation of deformation twins and their development were studied using specimens from polycrystalline titanium VT1-0 made from a strip obtained by hot rolling of a rod up to ~75% deformation at the temperature of 500°C with a 15–20% compression per pass. The specimens 10 × 10 mm in size were cut using an electric arc method on a Sodick AQ 300 L setup. The surface of the specimens was subjected to mechanical and electrolytic polishing after supercritical preannealing at 700°C. All subsequent studies were performed at room temperature.

The objects of investigations in the present study were wedge-shaped twins in a titanium crystal formed near an indentation of a diamond pyramid [1] with the help of a DM8 microhardness gage by loading on the device indenter. Nucleation of the twins were initiated by stress concentrators related to geometrical peculiarities of the indenter. In such a method of deformation, mechanical twins occupy a limited volume near the stress concentrator and never cover the entire crystal cross section. The studies were performed in three

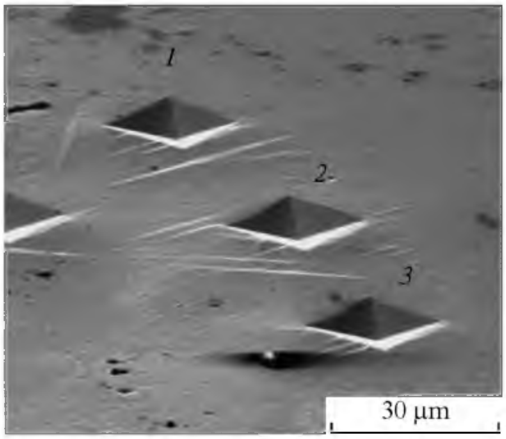

Fig. 1. Positions of indentations *1–3* of the pyramid on the parent section of the specimen surface.

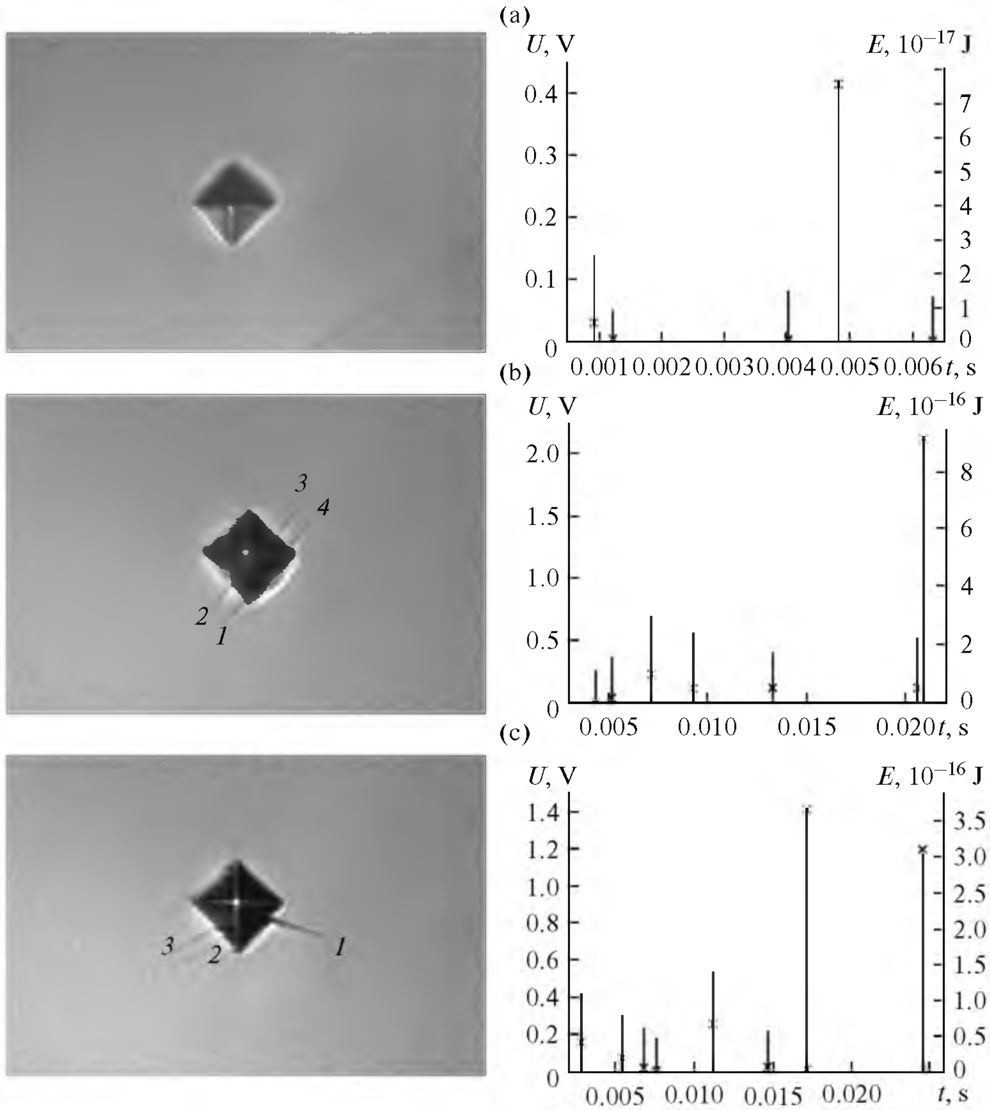

Fig. 2. State of twins, AE pulses, and energy released in the process of indentation with a 10 g load in cells *1* (a), *2* (b), and *3* (c). The figures near the indentations mark the arbitrary numbering of the twins. Magnification is ×1500. The symbol "×" marks the energy spent for nucleation of flaws at the current instant at the corresponding AE signal.

neighboring sections of one and the same crystallographic plane (0001). The orientation of the lattice to the specimen surface was determined with a Quanta 200 3D focused beam microscope using EBSD analysis. The distance between the indentation centers did not exceed 75 μm (Fig. 1, *1–3*).

Under the load imposed on the indenter, an indentation is formed on the specimen surface starting from 10 g. After photographing of the state of the surface around the indentation, 25, 50, 100, and 200 g loads were imposed on the crystal in the same place with the hold time of 15 s. After unloading, the surface was photographed again. The process of twin nucleation and development in the crystal bulk was controlled via recording of the AE signals [2]. The wedge-shaped twins were studied with the help of a Ntegra Aura scanning probe microscope. The photographs of the microstructure were obtained with the help of a JEM-2100 transmission electron microscope.

EXPERIMENTAL RESULTS AND THEIR ANALYSIS

It is known that it is necessary to have an elastic field rapidly decreasing with the crystal depth for a deformation twin to exist [3, 4]. Such a field is generated owing to the effect of the concentrated loading with the help of a diamond pyramid [5].

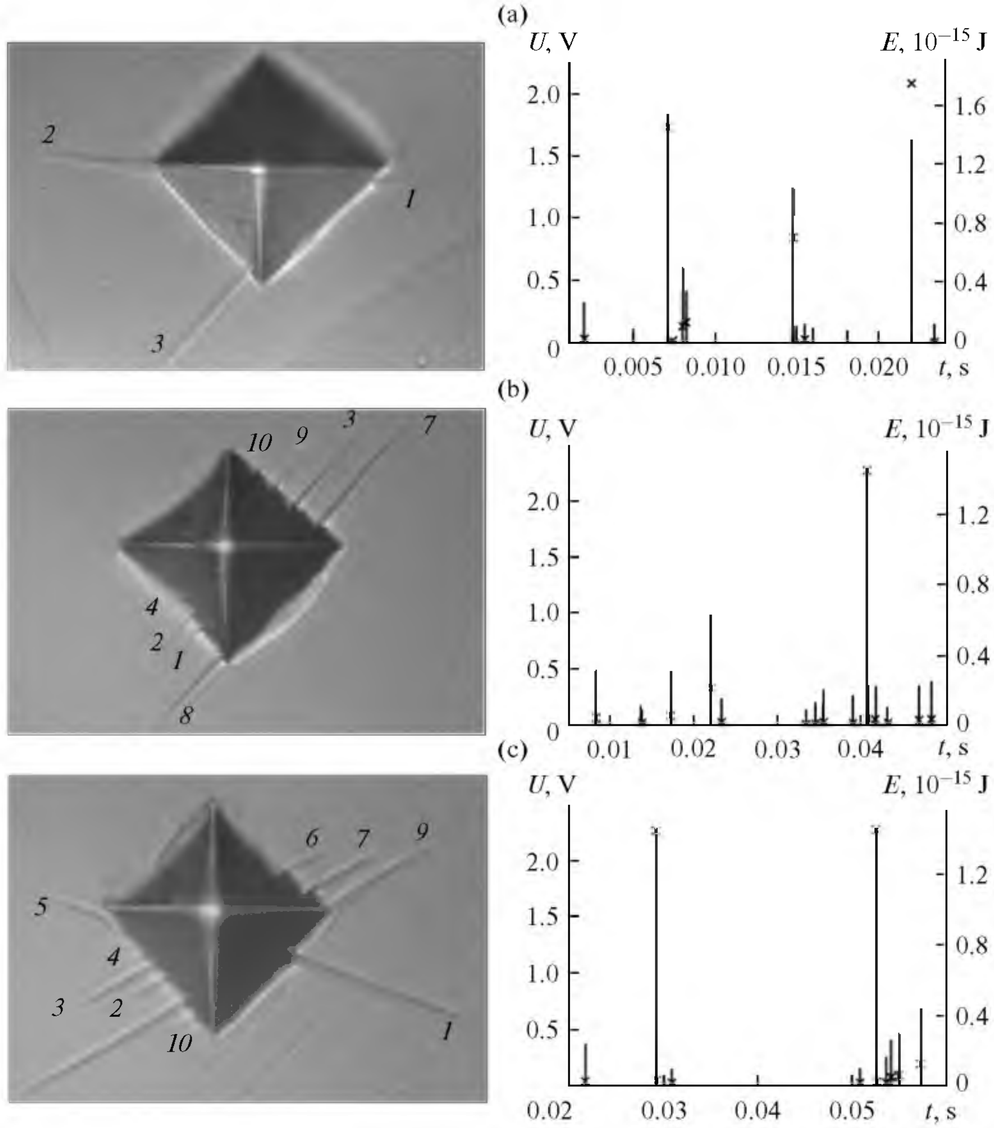

Fig. 3. State of mechanical twins, AE pulses, and energy released in the process of indentation with a 50 g load in cells *1* (a), *2* (b), and *3* (c). Magnification is ×1500. The symbol "×" marks the energy spent for nucleation of flaws at the current instant at the corresponding AE signal.

The obtained results make it possible to assert that formation of a residual twin on the surface is possible at a certain threshold value of the applied stress (Fig. 2). The AE signals confirm that deformation processes take place in the crystal bulk under the effect of the pyramid penetrating the matrix body.

A twin nucleus can be formed when the external force acting on the source of dislocations exceeds the total force of twinning dislocation deceleration in the bulk under the action of the concentrated stress including the friction force and the force of surface tension. The minimum loads observed in the experiment yield formation of several residual twins in cells *2* and *3*. However, there are no residual twins on the surface of cell *1*, which makes it possible to assert that the action of only the external concentrated stress is not sufficient for mechanical twins to be formed.

The energy spent in the process of penetration of the pyramid into the parent body of the specimen in indentation *1* is one order of magnitude lower as compared to the energy spent in indentations *2* and *3*, which is related to different counteraction to nucleation and displacement of an elastic twin in the lattice bulk [5]. The acoustic signals also differ in the time spent for penetration of the pyramid deep into the specimen until its full stop.

An increase in the external load yields an increase not only in the AE signal parameters (Fig. 3) and the number and linear dimensions of the twins (table) but also in the time of development of deformation pro-

Some characteristics of twins formed in cells 1, 2, 3 under the imposed load

Cell no.	Load, g	Number of twins	Linear twin size, mm										Total energy E, J	Amplitude of U, V
			1	2	3	4	5	6	7	8	9	10		
1	10	0											8×10^{-17}	0.45
	25	2	2.8	9.0									9.5×10^{-14}	1.8
	50	3	4.2	13.7	16.1								1.7×10^{-15}	1.9
2	10	4	4.1	4.0	4.57	4.1							9×10^{-16}	2.05
	25	6	8.4	3.2	4.3	13.6	4.2	4.4					9.5×10^{-14}	2.1
	50	8	8.4	3.2	12.0	1.2	–	–	17.7	13.6	4.5	1.5	1.55×10^{-15}	2.2
3	10	3	7.4	6.5	4.6								3.5×10^{-16}	1.4
	25	8	15.5	6.4	12.0	4.1	4.0	8.8	9.8	7.5			1.6×10^{-15}	2.05
	50	10	23.2	4.4	11.4	1.5	7.8	5.8	10.0	23.1	14.5	3.1	1.45×10^{-15}	2.2

cesses in the crystal bulk and the relative total energy as compared to the 10 g load (Fig. 4).

It is known that deformed regions which are the source of twin nucleation are formed in the crystal with the development of the glide process. Since under the same conditions the density of mechanical twins in the neighboring indentations is different, it can be assumed that there are other reasons facilitating twinning development. The state of an imperfect structure in the bulk of the concentrated stress action can be such a reason [6]. Forest dislocations are formed in glide systems. In case of twinning of crystals with a close-packed hexagonal lattice (CPH crystals), such forest dislocations are basic dislocations ({0001}⟨1120⟩ system), prismatic dislocations ({1010}⟨1120⟩ system), and pyramidal dislocations ({1122}⟨1123⟩ system). The present paper considers an interaction of the twin boundaries (twinning dislocations) with basic and pyramidal forest dislocations in the case of the transitions of the latter from a parent crystal to a twin. A twin is introduced into the specimen with the indenter on the (0001) plane. Basic dislocations were formed in the process of glide development.

The microscopic analysis (Fig. 6) of the annealed titanium revealed helical components of pyramidal dislocations with the density of $\sim 10^{-2}$ cm^{-2}.

At low (initial) loadings on an indenter, the main role is played by the glide, this process being inhomogeneous. The inhomogeneity manifests itself as follows: a plastic strain is realized as formation of glide lines and bands which are nonuniformly distributed in the specimen. In this case, the greater part of the crystal remains undeformed.

Gliding in the parent crystal mainly occurs along the base planes. The dislocations responsible for this gliding accumulate near one of the boundaries of the twin layer and in parallel base planes, thus yielding profile changes near the twin boundaries. A narrow accommodation region is formed in front of the twin

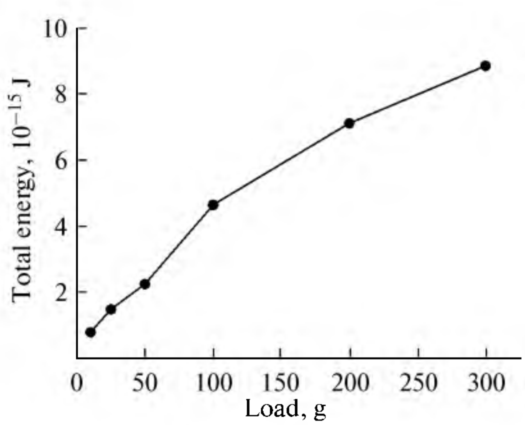

Fig. 4. Dependence of total energy of the AE pulses on the loading on the indenter.

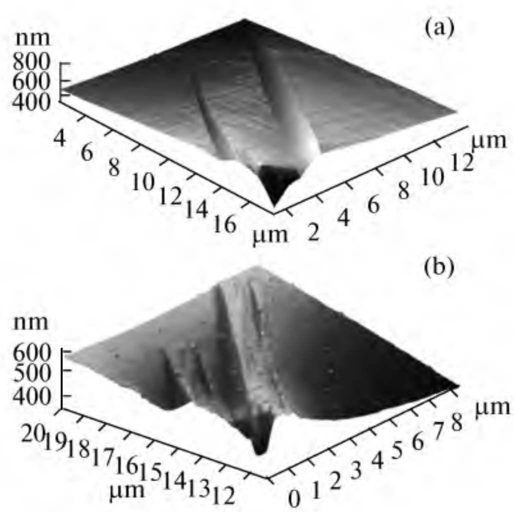

Fig. 5. Doubled wedge-shaped twin obtained as a result of indentation in titanium annealed at 700°C (a); the same twin subjected to additional chemical etching (b).

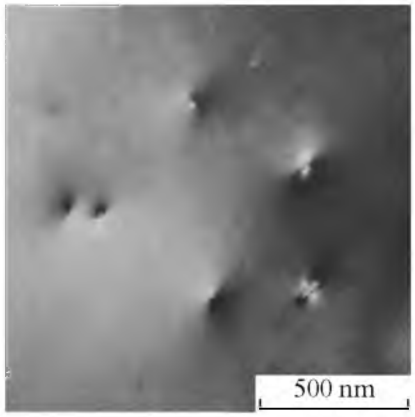

Fig. 6. Microstructure of the annealed titanium.

plane owing to the interaction of twinning and complete dislocations [7]. With increased loading on the indenter, the zone where a dislocation source is operating expands within the limits of this crystalline block. The layers of the undeformed lattice are gradually involved in the process of deformation (Fig. 5a), which yields an increase in the density of basic dislocations. The simultaneous process of gliding and twinning, as a rule, is accompanied by the interaction of complete twinning dislocations, which substantially affects the regularities of hardening [8]. This process becomes apparent in the rate of penetration of the pyramid into the crystalline structure of titanium (Figs. 2, 3).

The dislocation structure of titanium was directly investigated using the method of selective chemical etching. The characteristic shape of etching patterns on the (0001) plane, which clearly displays helical components of pyramidal dislocations, is shown in Fig. 5b.

In addition, a high density of dislocations along the crest of the twinning plane at the boundary of the accommodation region, it being the result of the glide process, is observed after etching.

The boundary of the accommodation region and the twin layer are strongly etched, which hinders determination of the yields of individual dislocations.

It follows from the experiment that the etching disproportionally increases from the source of the twin layer to its end, which points to the inhomogeneity of the formed internal stress in the process of twinning.

Complete dislocations formed under the effect of the increasing external stress are not compensated by twinning dislocations.

CONCLUSIONS

1. The distribution of twinning dislocations at the two boundaries of the twin layer is different. Namely:

(a) In front of the twin plane, the structure of the parent crystal is preserved owing to the interaction of twinning dislocations and complete dislocations; in this case, complete dislocations are repelled from the twin boundary and the region near the boundary becomes free from dislocations and takes on the orientation of the parent crystal.

(b) Behind the twin plane, the density of dislocations along the crest of the twinning region is very high, these dislocations being formed owing to the interaction of complete dislocations in a twin with twinning dislocations.

2. The high degree of etching of the boundary of the accommodation region and the twinning layer points to high stresses in the structure of the twinning region.

3. AE makes it possible to systematize the processes of dislocation transformations in the crystal bulk under the action of a concentrated stress on the surface of the studied specimen and to determine the activity and the energy state of the sources of twinning dislocations.

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