TITANIUM AND IT ALLOYS

UDC 669.295.5

TWINNING OF ALLOY VT1-0 AFTER TOTAL ANNEALING

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Twinning, that occurs in titanium VT1-0 crystals under the action of a concentrated stress, is studied by micro-indentation methods, recording of acoustic signals and probe microscopy. Some parameters and description of forms of a twinned interlayer in polycrystalline titanium VT1-0 are provided. The possibility of studying this process by recording acoustic emission signals is demonstrated.

Key words: indentation, twinning, slip, stress concentrator, stress field, acoustic emission.

INTRODUCTION

A qualitative study of plastic strain in metals is difficult due to their opacity and intense slip preceding and accompanying twinning. For this reason in order to reveal the features of twin generation and growth in metals a considerable series of experiments under strictly controlled conditions is necessary.

Wedge-shaped deformation twins may be caused by the action of a concentrated load, for example indentation of a diamond pyramid in the plane of a specimen. Their generation is initiated by a stress concentrator that is connected with the geometric features of the indenter. Here with this method mechanical twins occupy a limited volume at stress concentrators. However, the concentrators formed by the stress field within the volume of titanium crystals, elastic twins and other defects remain inaccessible for study by means of optical instruments.

The aim of this work is to study the effect of thermal annealing on formation and development of twins formed as a result of the occurrence of an external concentrated stress within the volume of polycrystalline titanium, by means of acoustic emission and probe microscopy.

METHODS OF STUDY

The material used for the study[3] was titanium VT1-0 in the form of bar ∅ 6 mm. Bar was rolled at 500°C to a thickness of 1.5 mm. Electro-erosion was used to cut specimens with a size of 10 × 10 mm from the plates obtained and they were annealed in a vacuum furnace at 700°C for 60 min. Annealed specimens were ground and electropolished.

An area with the size of 1 × 1 mm was selected in specimens where by means of a Quanta 200 3D scanning electron microscope the orientation of the crystal lattice was determined in each of the test grains. Processing of the results was carried out using an OIM Analysis 5.2 program. Within grains with an orientation of (0001) by means of a DM-8B microhardness instrument a concentrated elastic stress field was created with action of loads of 0.1, 0.25 1.0, 2.0, and 3.0 N lasting 15 sec. The distance between indentations did not exceed 100 μm (Fig. 1*a*). After each loading with a diamond pyramid in the metal the region around an indentation was photographed, after which repeated loading was made in the same place with a higher load. The AE signals were recorded during loading. An experiment was carried out as follows: a titanium specimen was placed directly on the AE piezoelectric transducer and the whole specimen – trans-

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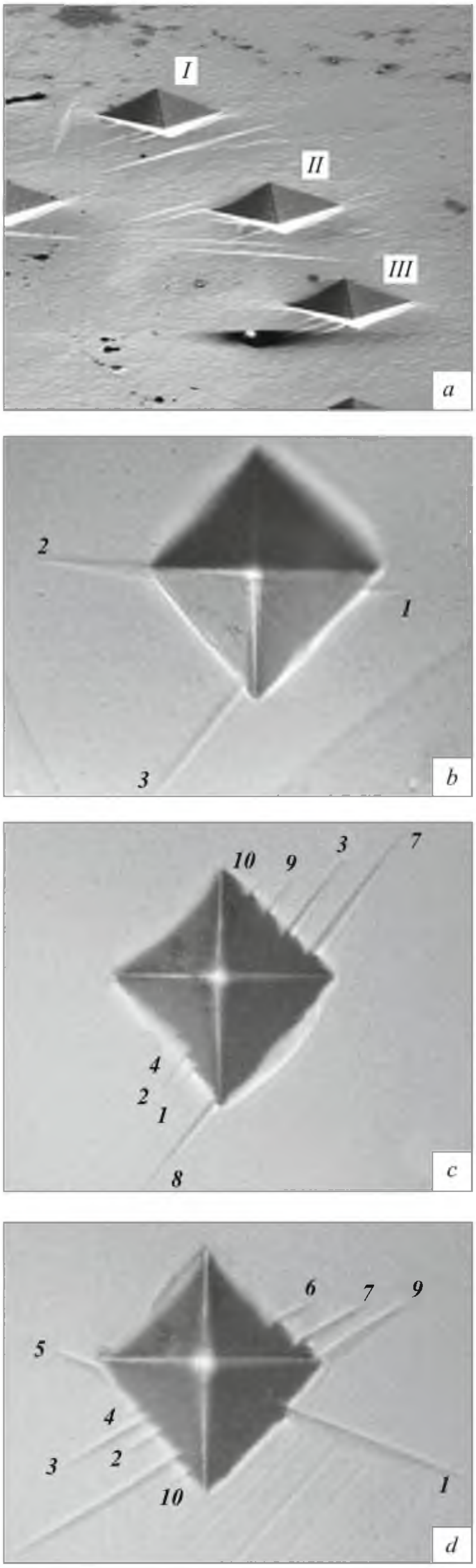

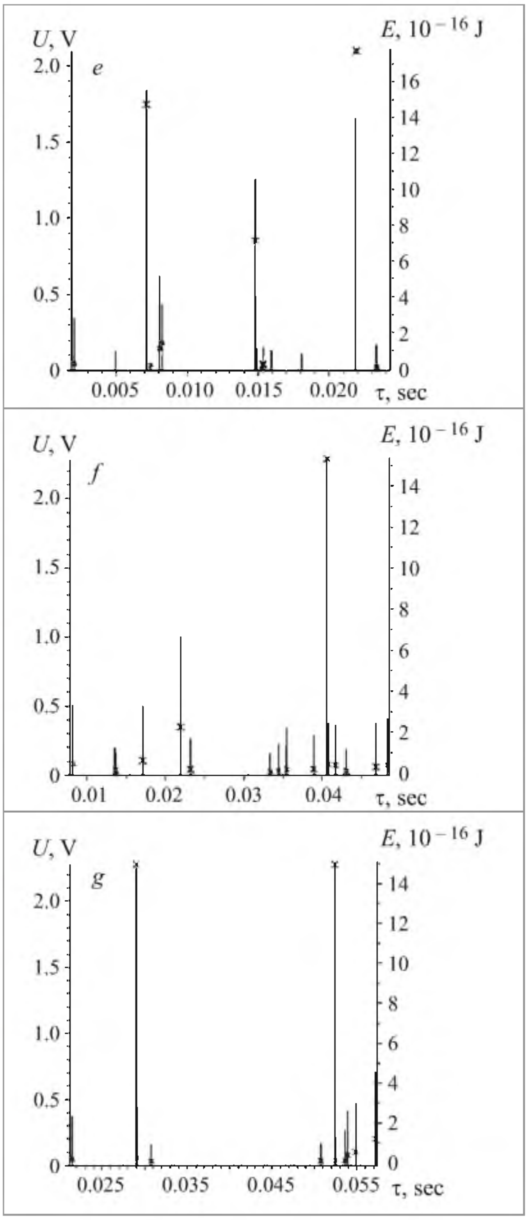

Fig. 1. Pyramid impressions in a martensitic surface area (*a*), mechanical twinning around indentations *I* (*b*), *II* (*c*), *III* (*d*), formed as a result of the action of a load of 0.5 N on an indenter, (× 1500) and curves for the change in AE parameter (*e* – *g*): τ is time; *U* is stress of recorded AE signals (thin lines); *E* is AE signal energy (points ×).

ducer system was installed on the table of a microhardness instrument.

Twins that formed after indentation were studied by means of a digital camera of the microhardness instrument and an Ntegra Aura probe microscope. Images (SPM-images) obtained by means of the scanning probe microscope were analyzed by means of an Image Analysis 2 program.

TABLE 1. Parameters of Twins and Indentation Dimensions, Formed Under the Action of Stepped Loading in the Same Cell

Impression	P, N	n_{tw}	Twin* linear dimensions, μm										l, μm	h, μm
			1	2	3	4	5	6	7	8	9	10		
I	0.10	0											9.3	1.878
	0.25	2	2.8	9.0									16.6	3.350
	0.50	3	4.2	13.7	16.1								26.27	5.308
II	0.10	4	4.1	4.0	4.6	4.1							10.83	2.188
	0.25	6	8.4	3.2	4.3	13.6	4.2	4.4					17.7	3.576
	0.50	8	8.4	3.2	12.0	1.2	–	–	17.7	13.6	4.5	1.5	25.92	5.236
III	0.10	3	7.4	6.5	4.6								10.5	2.121
	0.25	8	15.5	6.4	12.0	4.1	4.0	8.8	9.8	7.5			18.08	3.652
	0.50	10	23.2	4.4	11.4	1.5	7.8	5.8	10.0	23.1	14.5	3.1	25.97	5.246

* For arrangement see Fig. 1.

Notations: P is load on indenter; n_{tw} is number of twins; l is indentation diagonal size; h is pyramid immersion depth.

RESULTS AND DISCUSSION

In order to form a mechanical twin presence of a nonuniform, decreasing quite rapidly over the depth of a crystal, elastic stress field is necessary, that was created in this experiment by an external load on a diamond pyramid. Here with this deformation method mechanical twins occupy a limited volume at stress concentrators and do not embrace the whole crystal cross section. In order to estimate the size of the region within which twinning dislocations are generated, a stepwise increase in loading on a pyramid was provided, that promoted creation of conditions for stagewise development of wedge-shaped twins.

Results of experiments showed that a source of twinning dislocations is different areas of test specimens with the same crystal lattice orientation in a martensitic crystal may embrace zones that are different in magnitude (Fig. 1).

It is possible to assess the size of zones within which a dislocation source operates drawing on twinning of new layers of the crystal lattice during an increase in load on the indenter.

It has been established that sources of twinning dislocations in different areas of pyramid action with the same crystal lattice operation in a parent crystal, differ with respect to activity and AE development intensity (Fig. 1, *e* – *g*).

It may be assumed that the activity of the source of twinning dislocations depends on stress created by other barriers, that may be dislocations at the boundaries of a crystal block, etc.

The lack of a rigid functional connection between the size of indentations, the amount and magnitude of mechanical twins around indentations and their dimensions (see Table 1), has been established.

All of the twins around an indentation have a wedge-shaped form with a reduction from the mouth to the tip of both thickness and slope of the plane (Fig. 2*a*). Typical profilograms are presented in Fig. 2*b* for the slopes of a twin plane with respect to the parent crystal. The crown of a twinning plane here has a saw-tooth form (Fig. 2*c*).

During indentation of a pyramid into a plane of a specimen in all three indentations the site of twinning develops, whose presence and development is recorded by means of AE signals (Fig. 1, *e-g*). The first signals have similar parameters within limits of 0.2 – 0.5 V. The amount and magnitude of signals increase with deeper penetration of the pyramid into the parent surface of a specimen.

The duration of pyramid penetration before total stopping in grains with the same orientation (0001) and AE activity is different. In the first indentation with a load of 0.5 N there is movement of twinning dislocations lasting about 0.025 sec and further action of this stress for the next 15 sec does give rise to development of acoustic signals. In a second indentation this process lasts 0.045 sec, and the third 0.053 sec with a simultaneous emergence at the surface in areas of load operation of several mechanical twins. This feature of AE development may be explained by the structural state within the volume of action of a concentrated stress. Thus, annealing at 700°C does not resolve the problem of uniform distribution of internal stresses within the volume of titanium.

However, after ceasing action of an external load in the first indentation with a load on the indenter of 0.1 N no mechanical twins are detected at the surface (see Table 1), that were only recorded with a load of 2.5 N. AE signals in the second and third indentations differ markedly with respect to parameters from signals in the first indentation. The magnitude of the load on a pyramid of 0.1 N apparently is insufficient in order to overcome barriers opposing twin generation, that is indicative for the first impression. Formation of a mechanical twin is possible with a load greater than some threshold value. A twin nucleus may form when the magnitude of the external force operating on a dislocation source exceeds the total force for retarding twinning dislocations, including mainly frictional sources and surface tension. In

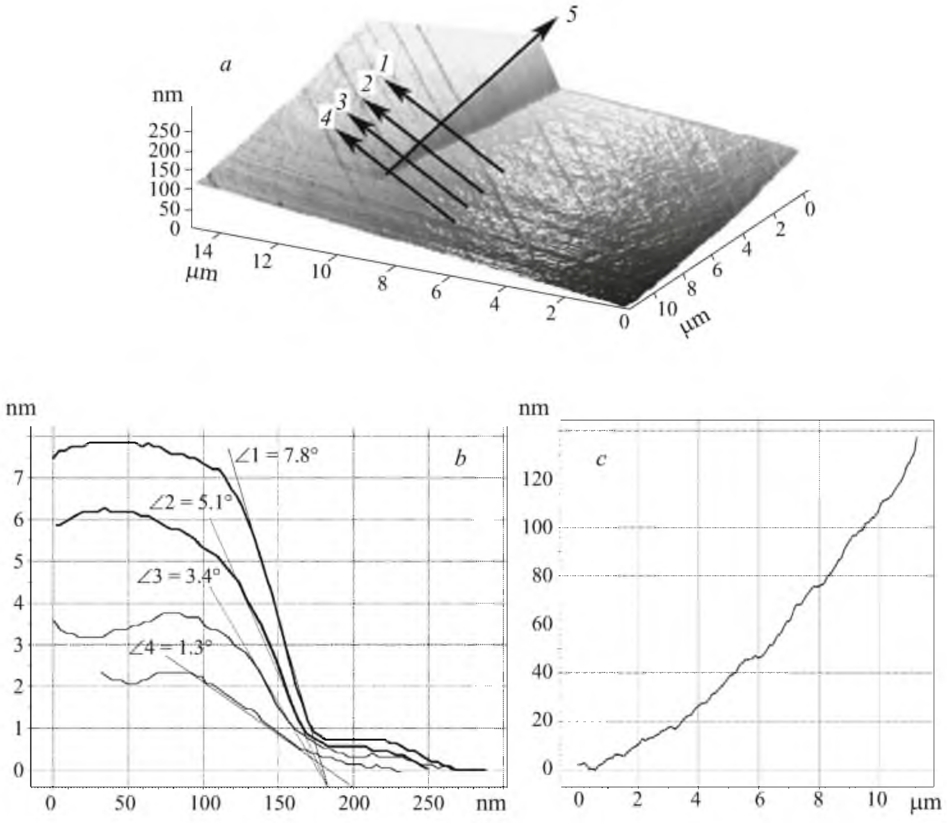

Fig. 2. General form of a twin (SPM-image) (*a*), profilograms (*b*), from which twinning plane slope with respect to the mother zone was determined (numbers *1*, *2*, *3*, *4* in Fig. 2*a* indicate the area of recording the corresponding profilograms), and profile of a section along the edge of a twinned interlayer over line *5* (*c*).

order to from a mechanical twin, apart from the opposing forces indicated, with presence of a concentrated stress in the area of indenter action, it is necessary to overcome forces due to other random factors, that vary from specimen to specimen and even within the same specimen in different areas [1].

In view of this subsequent increases in load on an indenter and action of a concentrated stress in the same indentations leads not only to reproducibility of existing twins in an indented area, but also to emergence at the surface of newly existing twins with a simultaneous change in linear dimensions.

The data obtained indicate that in the test range of loads an assembly of twinning dislocations, forming at an interface, behave as a single whole. Movement of a group of advancing dislocations in this zone at the tip of a twin depends on distantly operating forces of repulsion between dislocations of the same sign at boundaries. As a rule, a stepwise increasing change in external force leads to marked growth of individual twins.

However, sometimes there is a disproportionate rapid increase in the dimensions of individual twins, that with a subsequent increase in load cannot be distinguished from their neighbors. Apparently elastic twins are encountered with an internal stress concentrator, sharply increasing shear stresses in the twinning plane. This concentrator together with a force with an external stress promotes activation of twinning processes in a dislocation region. temporarily, when action of stoppers is not neutralized by an increasing external stress, around them there may be formation of an accumulation of twinning dislocations of one sign, due to which after overcoming internal stresses there is sharp jump or generation of a new mechanical twin, or a marked increase in an existing one.

A change in linear dimensions and shape of a twin interlayer with an increase in concentrated stress corresponds to the dislocation theory criterion [1].

Preservation of twins after removing a load is connected with formation of friction forces. Presence of friction forces, preventing twin recovery, is specifically caused by distortion of the lattice at twinning dislocation interfaces and is caused by slip, accompanying twinning. In particular, this is indicated by the acoustic signals within the limits of 0.2 – 0.5 V, preceding discharge of a powerful acoustic signal accompanying emergence of a mechanical twin at a surface.

With an increase in loading rate formation of twins remains almost constant, but the number emerging at a surface and linear dimensions of mechanical twins increase markedly. The feature observed is apparently connected with the deep penetration of a concentrated stress and capture of new dislocation interlayers, on whose basis there is elastic twin formation [2].

Propagation of a twin interlayer into polycrystalline titanium is accompanied by slip, both in the parent crystal, and within the body of a twin. Lines of basic slip, preceding twinning, pass through the whole field of a crystal, intersect-

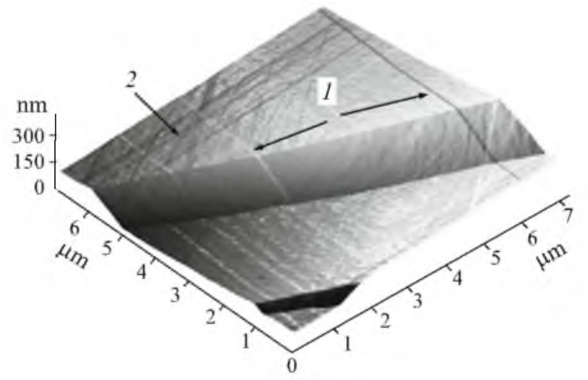

Fig. 3. SPM-image of a wedge-shaped elastic twin, obtained as a result of micro-indentation: *1*) slip bands; *2*) accommodation bands.

ing a twin interlayer arising after slip (Fig. 3). Traces of these lines as a result of twin layer development, change their orientation. Dislocations accomplishing this slip, stop at the boundary of a twin interlayer. The angle between basic slip lines in a parent crystal and traces of them in a twin interlayer is 6°.

Ahead of the boundary of a twin interlayer a depression forms with transition into a little convexity (Fig. 2*b*). Ahead of the peak of twin layer a swelling also forms, and the surface of a crystal in the accommodation region is also inclined with respect to the crystal surface at an angle whose magnitude depends on the size of the twin formed. The angle between twin interlayers and the parent plane does not remain constant, and it changes from the mouth to the tip of a twin interlayer within the limits from about 8° to 0°.

Similar studies have been performed for zinc single crystals in [3]. Here it was noted that formation of an accommodation region ahead of the twin interlayer plane is separated from the twin by a thin layer of parent crystal with a width of several microns, due to whose presence there is repulsion of the accommodation region from a twin [4].

Repulsion of the accommodation region is explained by reaction of twinning dislocations and total dislocations in the accommodation region, as a result of which a region close to the boundary is liberated from dislocations and takes the orientation of the parent crystal [4]. The angle between the accommodation plane and the basic parent plane is also not constant, and it depends on the length and width of a twin, that in turn affects the magnitude of the accommodation zone beyond the plane of twinning interlayer occurrence [5].

CONCLUSIONS

1. It has been established that the annealing temperature regime adopted at 700°C for titanium VT1-0 does not resolve the problem of uniform distribution of defects, that affect the intensity of mechanical twin development during action of a concentrated stepped load.

2. A source of twinning dislocations in different area of a test specimen with the same crystal lattice orientation in the parent crystal may embrace zones that are different in magnitude.

3. Absence of a rigid functional connection has been established between the dimensions of indentations, the number and size of twins, that form around them in titanium.

4. The acoustic emission method makes it possible to determine the sequence of slip development preceding formation of a mechanical twin in titanium.

5. The intensity of mechanical twin formation in titanium does not depend on the rate of indenter penetration into the parent plane of a specimen, but it depends on the structural state of a crystal and the depth of pyramid penetration, that is apparently connected with capture of new dislocation layers, on the basis of which there is formation of elastic twins.

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