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The development of titanium BT1-0 deformation twins under repeated exposure of concentrated load

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Abstract
The article examines the processes of the origin and development of tapered mechanical twins in titanium BT1-0, formed by pressing a diamond pyramid in the (0001) plane of the crystal. The staging of the tapered residual mechanical twins with increasing load was revealed, confirmed by electron microscopic observations and therefore the changing dependence of acoustic emission parameters.

Keywords: titanium, severe plastic deformation, slip, twin formation, mechanical twins, acoustic emission.

Introduction.
Titanium and its alloys with a unique combination of physical and mechanical properties are widely used as structural materials. To obtain the products made of titanium and its alloys with improved properties various methods of severe plastic deformation (SPD) are widely used, providing the necessary combination of properties due to significant dispersion of the structure, the changes of density and the configuration of structural defects. The degree of deformation and the temperature at which the process of severe plastic deformation occurs, play an essential role in the formation of the fine microstructure. An important feature of commercially pure titanium is the possibility to realize the plastic deformation without breaking the material density in a wide temperature range, including low temperatures [1]. The developed mechanical twins promoting the formation of bulk nanostructured titanium at room temperature, play a minor role and have a low density. This makes it possible to allocate a twin from the structure volume and to determine its characteristic data.
The development of plastic deformation in titanium occurs regardless the temperature and mechanical impact. The plastic deformation of titanium twins, where the process is carried out at simultaneous slip and twinning, can not be predicted, because the study of the plastic deformation by twinning, occurring within the conditions of the prior and concomitant slip is a difficult element in the actual mechanisms of this process. Within the deformed metal crystals depending on the orientation of the twin layer, this process may be a reinforcing factor or be the cause of a significant softening and in the vicinity of the twin boundaries an uneven distribution of the local mechanical stresses occurs forming the overvoltages which initiate further development of twinning.
The established dislocation theory of elastic twinning is based on the grounds that mechanical twinning is a fundamental property of crystalline systems conditioned by the anisotropy of the lattice elastic properties [2]. The theoretical study of twinning cooperation issues and slip is associated with insufficient knowledge of the twin adjustment processes in metals at various modes of deformation. The revealing of twin nucleation and growth patterns in metals is difficult because of their non-transparency and intense slip preceding and accompanying the twinning. The mechanical twinning is a regular reorientation of the crystal lattice under the influence of an external force and according to the scale of the crystal volume it occupies an intermediate position between micro- and macroscopic processes. The experimental studies of zinc, bismuth and other metals confirmed that the wedge-shaped deformation twins may be easily retrieved by a concentrated load at diamond pyramid indentation in the sample plane [3]. Their origin is initiated by stress concentrators, which are associated with geometric features of the indenter. At this way of deformation the mechanical twins occupy a limited volume at the voltage hub that allows you to use only the part of a crystal surface.
Microstructural analysis was performed using a transmission microscope «JEM-2100". The determination of the titanium grain structure, the grain boundary distribution, the phase composition and crystallographic orientation of the grains was conducted by the diffraction pattern analysis of backscattered electrons in a scanning microscope «Quanta 200 3D» using the program «OIM Analisis 5.2». During the indenter introduction in the sample surface of the signals of acoustic emission (AE) were recorded, which allow you to record the dynamics of the formation and the development of deformation defects.
The aim of this work is a comprehensive experimental study of the origin and development patterns of residual deformation twins obtained by the load on the diamond pyramid of the indenter into the titanium VT1-0 after the rolling with a total deformation value of 93% and annealing at 700 °C.
The experiment results and their discussion. After the hot rolling up to 93% and recrystallization annealing the titanium BT1-0 consists only of α-phase and the average grain size makes 76 microns respectively [4, 5]. The deformation by rolling facilitated the breakage and formation of grain structure on the basis of large internal stresses, depending on compression degree, as evidenced by radiographic studies and the subsequent annealing leads to the stabilization of the structure and at that the half-width of the peaks on the X-rays did not differ from reference ones [6]. The results of AE signals registration gave the opportunity to determine the mobility of dislocations [7].
The gradual load increase on the indenter and the increase of its immersion depth into the crystal were controlled by the

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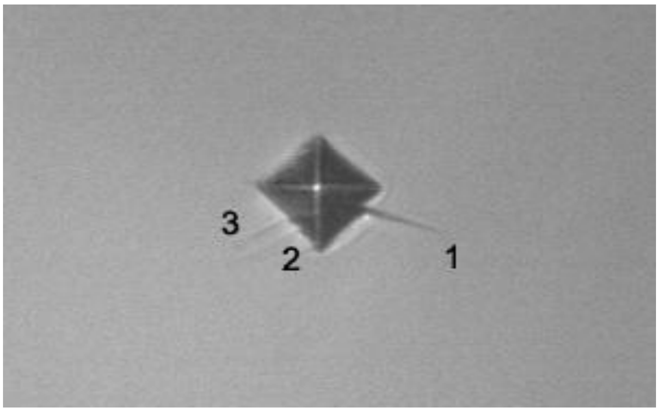
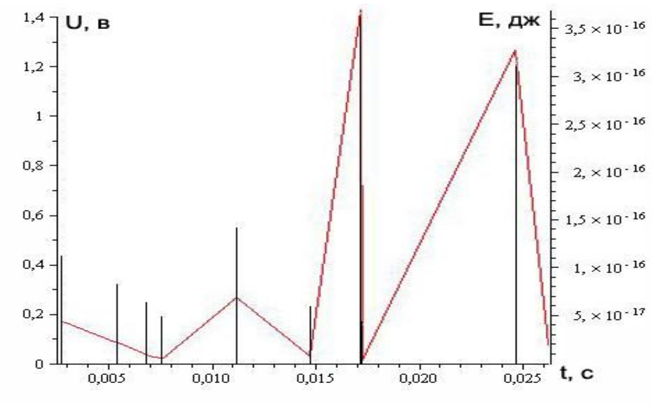
sequence of origins and the development of deformation twins along the footprint perimeter (Figure 1, b, c).

The indentation was carried out in grains, the orientation of the crystal lattice of which corresponds to the plane (0001) [8]. The indentation choice is caused by the fact that at this orientation most of the twinning layers reached the crystal surface, and the gradual increase of the indenter immersion depth allows us to trace the sequence of the origin and development of deformation wedge twins along the print perimeter.

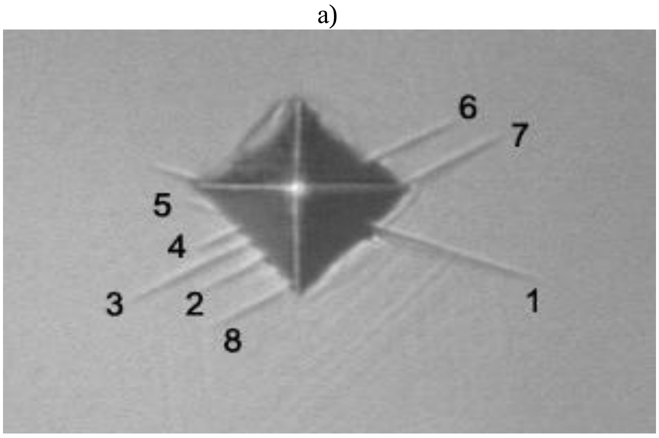
The primary load made 10 g, giving an imprint of the diamond indenter dive into the crystal with the diagonal of ~ 10mkm. However, the 10 g load on the indenter was not enough to save the majority of mechanical twins (Figure 1, a).

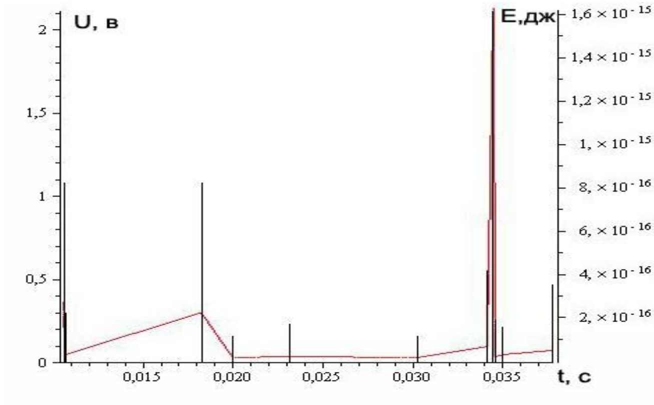
The appearance of acoustic emission during the indenter immersion into the sample body and the development of deformation is related to the active dislocation slip [7].





a)





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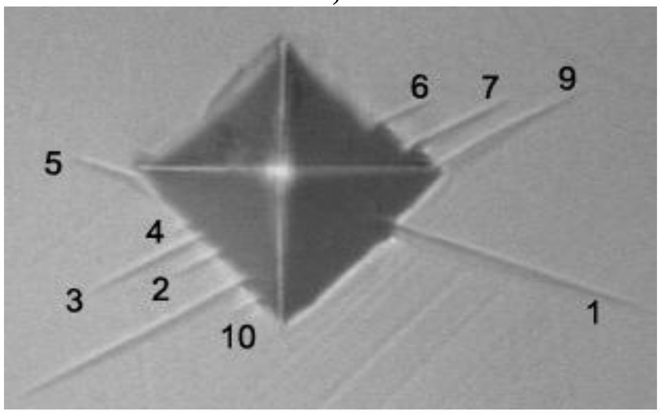

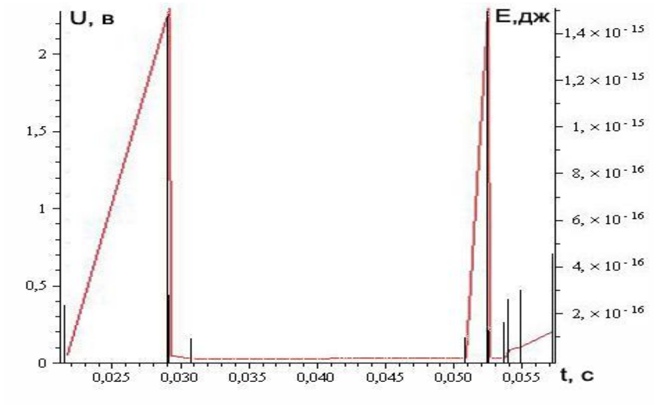

в)

Fig.1. Status of twins, the AE impulse (U) and energy (E) values, extracted by occurring processes at the indentation by the load of 10g - a, 25g - б and 50g - в. The numbers next to imprints perform the reference numbering of counterparts. x1500.

During the subsequent loading of the same indenter imprint with the load of 25g of the obtained imprint diagonal increased to 15-18 microns and the penetration depth of the indenter increased up to 3.5 microns. The load increase on the indenter led to the increase of the previously developed counterparts, and the development of new ones. The period of deformation processes in indentation volume increases, the relative values of AE pulses and gross energy compared to the load of 10g are increased (Figure 1,b).

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The change of the twin linear sizes with the increasing load on the indenter is uneven and unequal. There are twins, which significantly changed its sizes, at the same time the others remained in the same place, or disappeared. Especially, this process is enhanced and becomes more noticeable when at the loading in the same holes with the load of 50g on the indenter (Figure 1, в). The load increase affects the change of AE parameters, namely: the signal intensity increases at the simultaneous increase of the amplitude, indicating the increase in the number of defects formed during plastic deformation. This is confirmed by the growth of total AE energy. The observed sequence of residual wedge twins formation and development with the increasing load suggests that there is a multistage process that depends on the magnitude of the internal stress.

According to the above experimental data the imprints do not always keep residual deformation twins, the imprints are sometimes developed without twinning rays, which allows to suggest about the presence of residual internal stresses even after annealing at 700 °C. As for the restructuring of the lattice atomic layer a twinning dislocation is enough, the wedge twin is a set of crystallographic planes, where twinning was started but not completed. At that, each of the planes, partly covered by twinning is limited from non-twinning part of the crystal by plane inner tension resistance and emerging dislocation lines. Twins are born in the most deformed crystal sliding areas formed during plastic deformation [9]. In this experiment, the indentation of diamond pyramid samples in the same regions with the increasing load creates a stress state in the plastically deformed crystal, which contributes to the continuous distortion of an original structure. The inability to provide the local identity of twinning layer development conditions leads to the fact that their size will not be stable and reproducible deformation characteristics. The high sensitivity of twin boundaries to loading conditions, changing during the plastic deformation of the crystal lattice leads to the development of each twin, non-replicated in every detail, and the interaction of twins with the crystal lattice dislocation defects makes their distribution in the crystal volume not predictable in advance. The maximum thickness of a twin is observed on the sides or imprint tops that shows stimulating role of prior twinning slip in the origin of deformation twins. The change of twin linear sizes and shapes with the growth of concentrated load meets the criteria of the dislocation theory [2].

Conclusions:

1. The effect of a concentrated load is studied. This load allows to establish that at the minimum possible value of loading on the diamond pyramid and the same orientation of the crystal lattice the residual mechanical twins have different dimensions and the position along the imprint perimeter.
2. The repeated loading into the same indenter holes with a gradual load increase (10g, 25g and 50g) contributes to the earlier formed mechanical twins, the formation of new ones and the disappearance of old ones. The load increase affects the change of AE parameters. The diamond pyramid immersion depth in all three loadings differs, which suggests the presence of crystal lattice elastic properties anisotropy in different locations of the sample.
3. During the stepwise increase of the load on the indenter, along with the imprint size increase the zone was expanded, where twinning dislocations were generated. However, the uptake of the twin body with an increased imprint did not affect the activity of twinning dislocation source. This allows to suggest that the activity of twinning dislocation source may be inhibited by stresses from the concentrations of twinning dislocations at the crystal boundaries.

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