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Extrusion and intrusion in plastically deformed copper foils

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It was found experimentally that during the deformation of copper foil of thickness 200 microns, having only the through twin boundaries, which occur in extrusion and intrusion. Place of localization - twins boundary. This method of relaxation state of stress usually occurs when fatigue (cyclic) test specimens, which may cross slip of dislocations. Place localization of extrusions and intrusions - the region of stable slip bands (UPS). Thus, the formation of extrusions and intrusions during static deformation is not typical for copper samples in which because of the low stacking fault energy can not cross slip. It is shown that a possible cause of extrusions and intrusions in the copper foil is a specific orientation of the samples, their thickness (200 microns) and the presence of through twin boundaries through.
Keywords: color orientation maps, extrusion, intrusion, the copper sample, twin boundary.

Экспериментально обнаружено, что при деформировании фольг меди толщиной 200 мкм, содержащих только сквозные двойниковые границы, в них возникают экструзии и интрузии. Место их локализации – граница двойников. Такой способ релаксации напряженного состояния, как правило, имеет место при усталостных (циклических) испытаниях образцов, в которых возможно поперечное скольжение дислокаций. Место локализации таких экструзий и интрузий – область устойчивых полос скольжения (УПС). Таким образом, образование экструзий и интрузий, в процессе статической деформации не свойственно для медных образцов, в которых из-за низкой энергии дефекта упаковки невозможно поперечное скольжение. Показано, что возможной причиной возникновения экструзий и интрузий в медных фольгах является специфическая ориентация образцов, их толщина (200 мкм) и наличие сквозных двойниковых границ.
Ключевые слова: цветовые ориентационные карты, экструзия, интрузия, медный образец, двойниковая граница.

Експериментально виявлено, що при деформуванні фольг міді завтовшки 200 мкм, що містять тільки наскрізні двійникові межі, в них виникають екструзії та інтрузії. Місце їх локалізації - межа двійників. Такий спосіб релаксації напруженого стану, як правило, має місце при втомних (циклічних) випробуваннях зразків, в яких можливе поперечне ковзання дислокацій. Місце локалізації таких екструзій та інтрузій - область стійких смуг ковзання (ССК). Таким чином, утворення екструзій та інтрузій, у процесі статичної деформації не властиво для мідних зразків, в яких із-за низької енергії дефекту упаковки неможливе поперечне ковзання. Показано, що можливою причиною виникнення екструзій та інтрузій в мідній фользі є специфічна орієнтація зразків, їх товщина (200 мкм) і наявність наскрізних двійникових меж.
Ключові слова: колірні орієнтаційні мапи, екструзія, інтрузія, мідний зразок, двійникова межа.

Introduction

When loading crystalline samples due to their structure and orientation of heterogeneity in them there is difficult - the state of stress, relaxation is realized in different ways, leading to plastic deformation. The main methods of relaxation state of stress should include dislocation glide and the diversity of rotational changes. Ultimately, the state of stress relaxation processes determine the mechanical characteristics of the samples.

In [1, 2] in the study of relaxation processes occurring during plastic deformation of polycrystalline aluminum samples containing only through grain boundaries (two-dimensional polycrystalline), found the variety of specific rotation changes, many of which are not found in ordinary three-dimensional polycrystalline. As an example, the formation of the body arising from rotations rotations secondary crystallographic orientation favorable to the development therein of crystallographic slip. It is experimentally shown [3] that in the two-dimensional polycrystalline due to lack of constraint when they are deformed in the direction perpendicular to the sample surface all methods of relaxation state of stress are manifested most clearly.

Samples and investigations methods

Copper, as well as aluminum, is a bright representative of fcc - crystals, however, because of low value of defect packing energy in copper samples, unlike aluminum

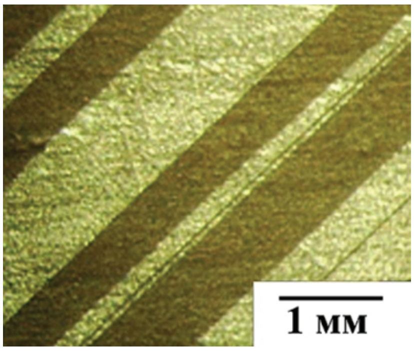

Fig. 1. Microphotograph of a typical structure of copper samples.

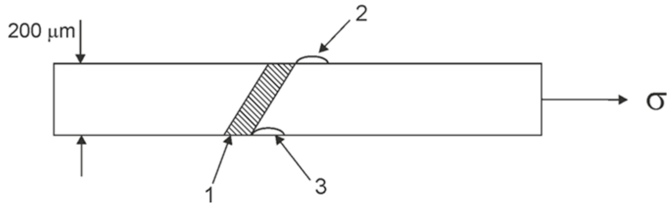

Fig. 2. Scheme of formation of extrusions and extrusions in copper foil: 1 – twin; 2 – extrusion; 3 – extrusion; σ – the direction of stretching of the sample.

samples, practically are always found twins of growth and, therefore, twinning boundaries the role of which isn't obvious in deformation processes. It can be argued that the choice as an object of study of two-dimensional polycrystalline copper, as well as two-dimensional polycrystalline aluminum, will reveal the features of the structural changes in their plastic deformation.

For polycrystalline copper samples with different grain size and containing only through twin boundaries and grain boundaries was chosen copper foil (99,98%) 200 microns thick was used. The samples, size 100×10 mm^2, were cut out from a sheet of foil, the average size of grains was ≈0,1 mm. Changing modes of thermomechanical processing, which consists in primary annealing at temperature of 500 °C, sample deformation value 2 – 7% subsequent recrystallization annealing vacuum (~10^{-2} Pa), polycrystalline samples were obtained, the average grain size of which varies in the range from 1 to 12 mm. Before recrystallization annealing both surfaces of the sample carefully ground and polished. Samples boundaries became apparent by means of spirit solution of concentrated nitric acid. The time of etching was of 1-15 sec. All the samples were deformed in conditions of monoaxial stretching with constant speed of deformation $\dot{\varepsilon} = 10^{-4}\ \text{sec}^{-1}$ with registration of the deformation curve. For all samples of *in situ* in the course of deformation the color orientation maps (COM) were registered [4].

Experimental results and discussion

As a result of the recrystallization annealing depending on the primary deformation ε the 3 types of samples were obtained. The samples of the first type contain fine-grained structure (ε = 2%). The average size of such grains makes ≈ 1 mm. Almost in each grain twinning structure are found. The samples of the second

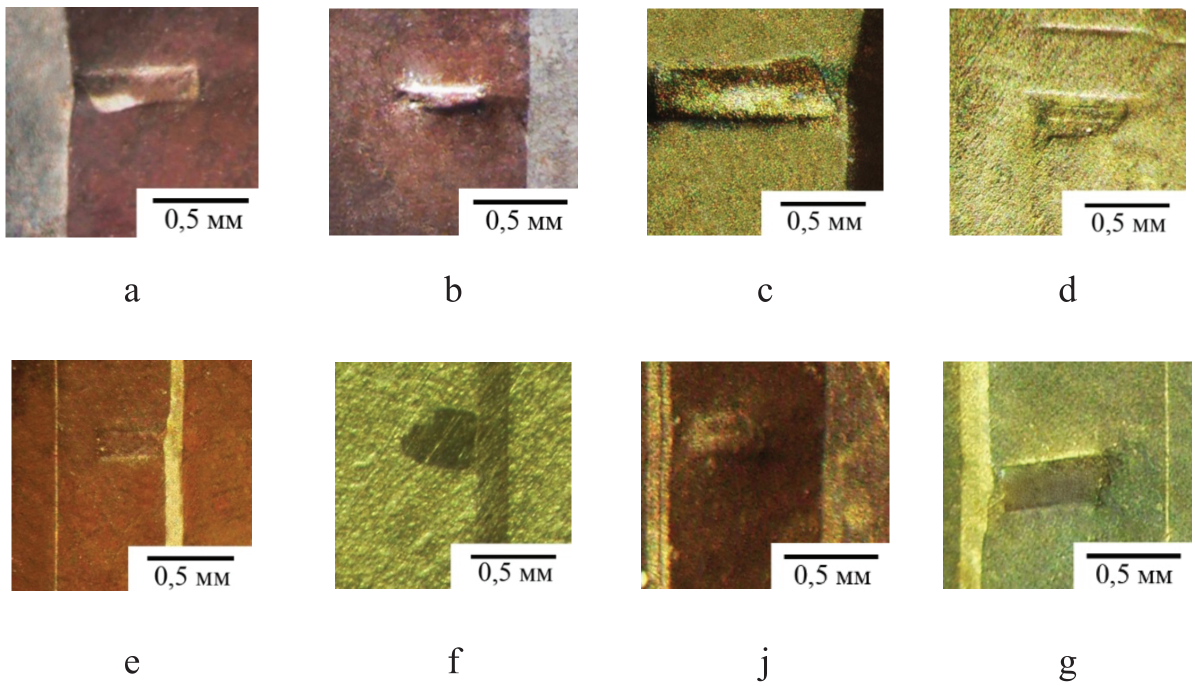

Fig. 3. Microphotographs (COM) of the various extrusions occur on the polished surface of the copper sample, after 12% deformation.

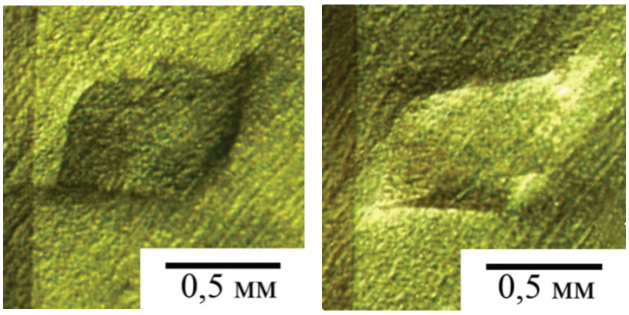

Fig. 4. Microphotos of extrusion occurred near twin boundary on one of the surfaces of the deformed sample and the intrusion occurred on the opposite surface.

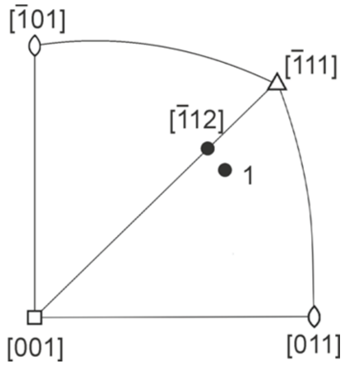

Fig. 5. The crystallographic orientation of the axis of the tensile specimen (1) with respect to possible slip systems.

type (ε = 7%) contain boundaries of grains and twinning boundaries. The average size of grains makes ≈ 10 mm. They contain twins differing in form, orientation and sizes. Finally, samples of the third type (ε = 4-5%), contain only twinning boundaries crossing all over the surface. It should be noted that all twins in the samples of the third type are oriented identically to the axis of stretching of the samples. Boundary certification according to X-raying data showed that all of the boundaries is coherent twinning boundaries ($\Sigma 3, 60^{\circ}, [111]$).

Research using the color orientation maps (COM) substructural and orientation changes *in situ* during the deformation of copper samples first and second type showed that the latter is fundamentally no different from similar studies found in the polycrystalline aluminum [5].

The third type of samples that are essentially "single crystals" are contained in the body, of identical orientation, through twin boundaries detected not typical samples of copper, structural relaxation as intrusions and extrusions. The observed effect is of particular interest for two reasons. Firstly, extrusion and intrusion usually found in fatigue tests [6,7], and secondly, they are the source of a transgranular fracture [8]. On Fig. 1 is a microphotograph of a typical structure of the samples of the third type, and Fig. 2 and Fig. 3 scheme of formation of extrusions and intrusions, and microphotograph of various extrusions occurring on the surface of the sample after deformation by 12%. Form and size of extrusion being various, but all of them are localized near the twins so that at least one of boundaries of extrusion was perpendicular to twinning boundary.

A feature of all extrusions that have arisen during plastic deformation of copper samples with twins is the appearance on the opposite side of the sample opposite extrusions intrusions. This is shown schematically in Figure 2.

The microphotographs of extrusion and intrusion occurred on opposite sides of the sample are shown in Fig. 4. The interferograms of the both surfaces testify to being of on one surface of the stamping material occurs (extrusion) and depression of another material (intrusion).

In [6,7] it was shown that the intrusion and extrusion occur in fatigue tests, and the main criterion for their occurrence is quite developed cross slip. Extrusion and intrusions occur on one of the surfaces of the sample in the stable slip bands.

Deformation of copper samples in the present study was carried out in a static test. Because of the low value of defect packing energy in copper samples indispensable for the development of cross slip. Thus, the experimentally observed effect of occurrence of pairs of "extrusion-intrusion" in the static tests of samples of copper requires explanation.

Studies have shown that the possible cause of a pair of "extrusion-intrusion" is the availability of pass-through twin boundary, a small thickness of the sample and the specific orientation of the axis of tension, close to $\left[\bar{1}12\right]$ (Fig. 5)

At what orientation in crystals with fcc - structure, along with the system $\left(\bar{1}11\right)\left[011\right]$ possible development of the secondary slip system $\left(111\right)\left[\bar{1}0\bar{1}\right]$. Given all the above, we can assume that the observed effect of occurrence of extrusion of copper samples at their specific structure deformation obliged samples containing through twin boundaries, the thickness of the sample and the specific orientation of the axis of the tensile specimen that is conducive to development in a sample of secondary slip.

Conclusion

1. It was found experimentally that the plastic deformation of copper samples with twin structure at room temperature under uniaxial tension at a constant rate of extrusion and intrusions occur.

2. It is shown that finding ways to relax the stress state that is not characteristic patterns of copper due to the impossibility of cross-slip (low stacking fault energy), can be explained by three factors - the small sample thickness (200 microns), the presence of only through the twin

boundaries and the specific crystallographic orientation the extension axis of the sample close to the $[\bar{1}12]$, leading to the emergence of dual-sliding systems $(\bar{1}11)[011]$ and $(111)[\bar{1}0\bar{1}]$.

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