The formation of a quasi-periodic surface profile by means of dislocation slip

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Abstract. This work presents the experimental results concerning the research of the morphology of the face-centered cubic (FCC) single crystals surface after compression deformation. Our aim is to identify the method of forming a quasiperiodic profile of single crystals with different crystal geometrical orientation. A set of modern methods as optical and confocal microscopy is applied. It is done to determine the morphology of surface parameters.
The results show that the octahedral slip is an integral part of the formation of quasiperiodic profile surface and is starting with the initial strain. We present values of shear quantity directly in shear traces, meso- and macrobands and in shear tracks shift within them. The similarity of the process of surface profile forming at different levels of scale is given.
Finally, we suppose that octahedral slip is the main way to form quasiperiodic deformation relief. We compare our results to published data and identify common regularities for various metal FCC single crystals with different deformation methods. The experimental results presented can be used for mathematical modeling of plastic deformation.

1. Introduction

Changes in topology of solid surface after deformation are of interest to researchers from various branches of science for many years. The experimental data and results of mathematical models indicate that folding, wrinkling, extrusion and intrusion, checkerboard distribution regions, etc. are frequent and appear in a variety of load conditions. This process is typical for the poly- and single crystals, the folds can be observed in geology and metal forming. Folding being manifested in different ways of deformation, it has various manifestations and can be initiated as a slip and twinning.

The results of finite element modeling of the emergence of roughness during plastic deformation of polycrystalline aluminum are given in article [1]. Results showed that texture samples and the direction of strain influence the formation of roughness. There are “ribbed ridging profiles” and the surface of the “orange peel shape”. The paper also indicates that the Taylor factor affects the type of roughness. Article [2] represents the experimental data which show that the size and orientation of the grain influence roughness during plastic deformation. The results were obtained by the example of polycrystalline aluminum alloys. In all cases, there is a quasi-periodic surface profile after the deformation.

The series of works by Gubernatorov V.V. with colleagues had called the reason for corrugating surface distortion of the material layers. They also show that the corrugation may be formed in a structurally homogeneous material (single crystal), that is, availability of basic stress concentrators is not a prerequisite [3]. This fact is explained by the loss of stability of the material layers, which occurs due to the presence of alternating stresses in the meso-level deformation under shear constrained. The paper notes that the wrinkling is a consequence of the gradient of the stress-strain state of the cross section of the sample and the constraint of deformation of the material layers in the hearth.

The process of forming folds, staggered distribution areas of extrusion and intrusion was considered from the point of view of physical mesomechanics [4]. Within the framework of this approach there is an unsubstantiated multiscale process, carried out in the connection with interfaces of various nature, and the surface layer is regarded as an independent structural level. The multiscale of the deformation process, the connection with interfaces of various nature were explained in the framework of this approach. The surface layer was considered as an independent structural level.

Thus, considering the accumulated experimental and theoretical material, we can conclude that the formation of a quasi-periodic profile of initially a flat surface is characteristic of the process during the deformation of materials in various ways. The reasons for this process may be different. As of today in literature the various circumstances of its origin are discussed.

In earlier studies, the authors have repeatedly pointed to the quasi-periodic surface profile of single crystals after plastic deformation and on the periodicity of distribution of the deformation values (including alternation of local places of tension and compression) [5-6]. Moreover a distinctive morphology characteristic of structural elements of different types of strain relief was described.

Thus, the study of the morphological characteristics of the surface after different types of loads is relevant in the fundamental and applied sciences.

The problem of this paper is the analysis of structure formation in the face centered cubic (FCC) single crystals with the use of a complex of modern methods. This study was carried out using the model material and can be seen as basics of engineering sciences.

The purpose of this study is establishment of the relationship of the surface topology with morphological types of deformation relief depending on the crystallographic orientation of the single crystals.

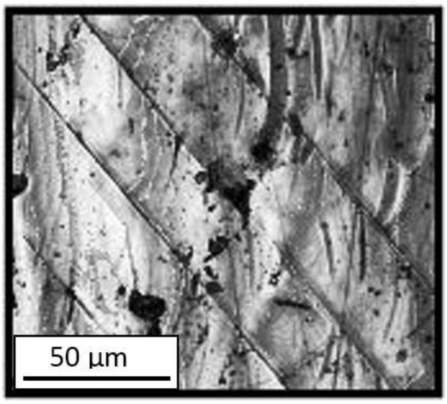
2. Materials and methods

This paper represents experimental results carried out by the example of single crystals of nickel. Nickel is an appropriate material for studying the folded structure generation under deformation by slip planes. Possessing a high level stacking fault energy (200 mJ/m^2) and being mechanically loaded at room temperature and medium strain rates, the nickel single crystal is deformed by slip systems {111} <110>. Single crystalline samples have been grown according to the Bridgeman method from molten nickel. Then electro-discharge was machined in the shape of 3 × 3 × 6 ± 0.1 mm samples having their compression axis orientations coinciding with [111]. The single crystals' orientations have been controlled using backscattering patterns up to the accuracy of ±0.02◦ obtained from a DRON-3 diffractometer. The samples' surfaces have been mechanically and then electrolytically polished in the saturated solution of chromic anhydride in phosphoric acid at a voltage of 20 V to a mirror-like finish. Such a sample preparation technique has been used to exclude introducing any subsurface defects. Compression tests have been carried out using an Instron ElektroPuls E10000 machine operated at a strainrate of $1.4 \times 10^{-3} s^{-1}$ at ambient temperatures. To minimize the friction between the sample ends and tensile machine platens, we used graphite lubrication. Shear traces on the single crystal faces were obtained and then examined using optical microscope Leica DM2500P, SEM instrument Tescan Vega II LMU, a NewView 7200 interferometer and confocal laser scanning microscopy Olympus LEXT OLS4100.

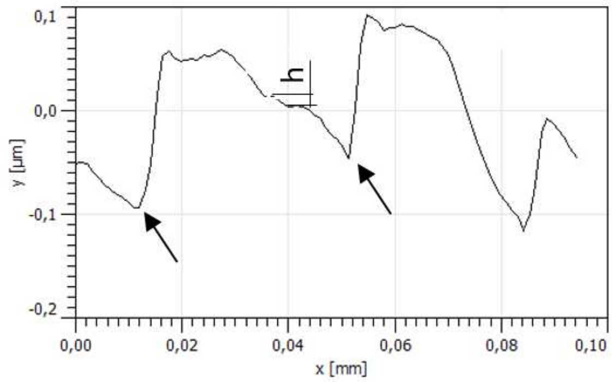
3. The organization of the surface profile

Structural levels of deformation relief is the minimum scale structural level "shear zone". This level is appeared in all crystalline solids, when deformation occurs due to motion of dislocations in the slip plane. The appearance of slip tracks on the crystal surface because of shear in the slip planes is observed in single-crystals and in grains of polycrystalline.

Each crystal geometrical orientation single crystal has its own surface structures. It is repeated, and it has common laws for single crystals of various FCC-metals. However, each individual case has its own individual characteristics. Since the beginning of the loading on the surface of single crystals, any orientation are being formed shear traces. In fact, a quasi-periodic surface profile has already been formed. At the same time, each area of extrusion is accompanied by intrusion areas (indicated by arrows in Figure 1), which can be considered as local stress concentrators.



a



b

Figure 1. The [001] nickel single crystal (110) face: surface structures – a, the surface profile – b, e=3%.

Moreover shear stages are being seen (indicated by h in Figure 1, b) on the surface profile. The value of the shear amount in the tracks is about 200 ... 1400 nm. The difference in the magnitude of shear is due to the degree of development tracks and dialed a different number of shear planes.

With the increasing degree of deformation, we can observe an increase in the density of tracks with a tendency to organization of the shear tracks in the pack, which is reflected on the surface of the profile. The quasi-periodic profile is being provided with packs of trace shear at a larger scale level, while a similar profile having a decreasing scale is being observed also (Figure 2) and is being provided in separate shifts in shear tracks.

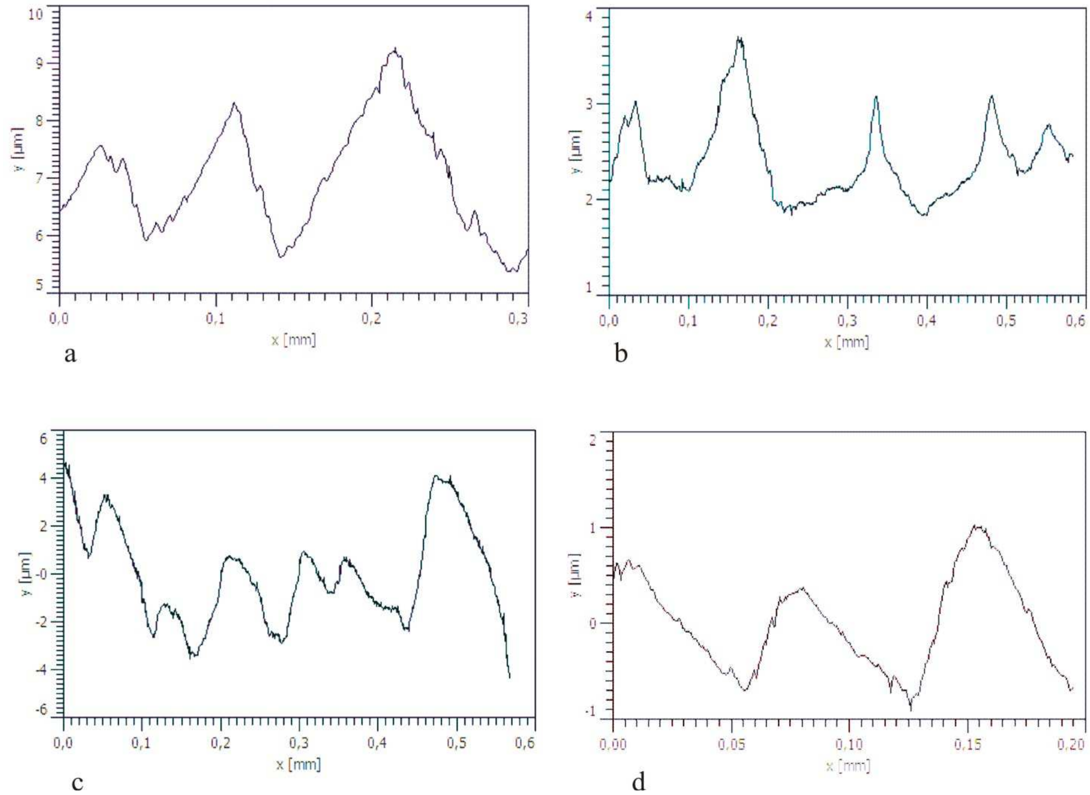


Figure 2. The surface profil of the nickel single crystal: [001] {001}, e=5% – a, [110] (110), e=8% – b, [111] (111), e=31% – c, [111] (110), e=29% – d.

The tendency of the organization shift tracks in bundles is characteristic for [001] single crystals with lateral faces {001}(Figure 2, a). A similar way of organizing the surface structures can be observed for single crystals with compression axis [110] (Figure 2, b). There are forming mesobands of deformation. The shear is about 1900 ... 3800 nm in them, while the magnitude of the shear in the tracks that are forming the mesobands is about 80 ... 300 nm. The macrobands and folds are being formed in the [111]-single crystal (Figure 2, c-d). The magnitude of shear in macrobands is about 1700 ... 11200 nm, in traces, which are forming macrobands, is about 100 ... 1300 nm.

In addition, we note that the folding process is most evident in the [111]-single crystal. Depending on the location of the folded structures, they have different morphology. They may be formed by one or more slip systems, or slip traces can not be distinguished visually. Detailed classification of folded structures are given in [8] for the case of single crystals of nickel.

We have got interesting results analysing an L0 parameter – the length of the stretched profile (the length which is obtained when all projections and depressions of the profile are stretched in a straight line within a base length). The value of L0 in the local region under consideration exceeds the length of the measuring section by 2...16%. The minimum value corresponds to the shear traces packs maximum of the folded structures. It depends on the type and location of the structure. This fact depends of the method of organization of surface morphology (and thus crystallographic orientation).

At the same time, it is known that the greater the total energy, the larger the area of body surface. Accordingly, the process of forming a quasi-periodic surface profile can be considered as a method of increasing crystal face surface. Quasiperiodic surface relief as an additional way to reduce (relaxation) the elastic energy of the crystal with a loaded strain is considered.

An important feature of the organization of quasi-periodic structures is formation of intrusion areas on the surface of single crystals. It is in straitened geometric conditions, and it is stress concentrators. At the same time, extrusion areas are locations of stress relaxation because they are under less crowded conditions. As a result of the stress gradient carry occurs of material from the valleys to the peaks by using octahedral slip.

A similar mechanism of deformation has been described in [7] in the study of cyclic deformation. Bands formed during fatigue testing of materials are called persistent slip bands (PSB). In this paper, it is also noted that the PSBs are formed from a plurality of parallel lines slip, and intrusions grow in the direction of the active slip plane. There are reports that at an early stage an extrusion has a triangular profile and a smooth surface [7-8]. With further loading, the triangular shape is lost and an extrusion profile acquires a more complex shape. It is becoming more or less rounded, and, at the top, there are some roughness [9]. Bands of intrusion are considered as a special case of shear tracks with active plastic deformation [7]. In this paper, the authors described the similar nature of the formation of structural elements of the strain relief of various types. There are the results of studies of copper single crystals oriented to a single slip in the system (111) [101] uniaxial compression up to 10% along the [2.9.20], paper [10]. The paper describes the quasi-periodic irregular primary strips parallel (111) with a period of about 30 μm. The paper provides information that alternation of areas allows unloading crystal and preserving its integrity during deformation.

Previously, the authors have shown that the [111] quasi-single crystal copper surface profile in the formation of folded structures is characteristic too. It has also been pointed out that the folds are formed with the assistance of the octahedral slip.

4. Conclusion

Our studies showed that the nature of the development of surface structures after compression deformation of FCC single crystals with the same crystallographic installations is qualitatively similar. On the surface, from the onset of plastic deformation, a quasi-periodic surface profile is formed, i.e. alternation of areas of intrusion and extrusion material. This process is typical for different scale levels.

A significant feature of a quasi-periodic surface profile is an alternation of areas of intrusion and extrusion material. In this case the extrusion zones are places of stress relaxation because they are less crowded conditions. While the intrusion zones are more limited geometrically, they are stress concentrators. They contribute to the movement of material on the surface of the crystal. As a result, a quasi-periodic surface morphology can be considered as an additional way to reduce (relax) elastic energy of the loaded crystal during deformation.

The formation of the quasi-periodic surface profile is carried out by the main deformation mechanism. This is dislocation slip.

The experimental results presented can be used for mathematical modeling of plastic deformation of the polycrystal's individual grains.

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