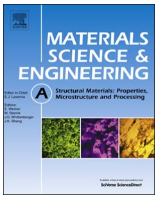
Materials Science & Engineering A 697 (2017) 248–258

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea



Micro- and mesomechanical aspects of deformation-induced surface roughening in polycrystalline titanium

V. Romanova[a,*], R. Balokhonov[a], A. Panin[a,b], M. Kazachenok[a], A. Kozelskaya[a]

[a] Institute of Strength Physics and Materials Science of the Russian Academy of Sciences, pr. Academicheskii 2/4, 634055 Tomsk, Russia
[b] National Research Tomsk Polytechnic University, pr. Lenina 30, 634050 Tomsk, Russia

ARTICLE INFO

Keywords:
Titanium alloys
Deformation-induced surface roughening
Micromechanics
Finite-element method
Crystal plasticity
Mesoscale

ABSTRACT

This article addresses the problem of multiscale surface roughening in commercial purity titanium subjected to uniaxial tension. *In situ* investigations of the evolution of grain- and mesoscale roughness in selected regions of titanium specimens were performed. Based on the experimental data obtained, 3D polycrystalline models with explicit consideration of grain structure were generated and implemented in finite-element calculations. Constitutive models of grains were constructed, using crystal plasticity theory to take into account the elastic-plastic anisotropy on the grain scale. The experimental and numerical results obtained have shown that a series of multiscale surface undulations are formed on the free surface of the specimen subjected to tension. The smallest out-of-plane surface displacements are attributed to intragrain dislocation glide. Larger displacements are associated with relative grain motion. The latter give rise to the formation of an orange peel pattern. The displacements of the two types are a microscale phenomenon. The largest surface displacements formed by the grain groups involved in out-of-plane and in-plane cooperative motion are referred to as the mesoscale roughness. The latter is found to correlate well with local strains of the specimen regions under examination. The main conclusion drawn from the experimental and numerical results is that it is the mesoscale that will furnish a clue to prediction of plastic strain localization and fracture of materials far in advance of the macroscale manifestation of these processes.

1. Introduction

Deformation-induced surface roughening is a common feature of polycrystalline metals. Extensive experimental and numerical studies [1–25] show that the free surface of the materials undergoes roughening under plastic deformation even in uniaxial tension where no external forces are applied to the surface. In the general case, surface morphological changes develop throughout all the length scales from micro to macro. A comprehensive classification of the mechanisms responsible for the surface roughening on different length scales was proposed by Raabe et al. [1].

Three distinct roughening scales are identified for the majority of polycrystalline metals. The smallest surface displacements attributed to dislocation steps in surface grains are referred to as the microscale roughness [1]. Individual grains, in turn, are displaced relative to each other to form an orange peel pattern. This phenomenon is classified as a microscale [1,2] or as a mesoscale process [3,4]. Specific roughening patterns develop on the mesoscale level in which case it is groups of grains rather than individual grains that demonstrate cooperative out-of-plane surface displacements to form surface undulations seen as ridges and valleys, cluster-like structures, etc. [1,6–14]. The mesoscale roughening patterns are affected by a number of factors, with the material microstructure, texture, and local loading conditions being of critical importance. Finally, surface macroscale waviness controlled by structural part geometry, external loading conditions, and macroscale plastic strain localization develops on the specimen length scale [2,15–17].

Roughening on the micro- and mesoscales is commonly considered to be an unwanted effect responsible both for cosmetic defects and for deterioration of the mechanical properties due to plastic strain localization, which places strong limitations on metal forming applications of the materials. For the most part, investigations along these lines aim at elaborating effective methods to suppress roughness at least within certain length scales. The majority of experimental and numerical studies on the micro- and mesoscale surface roughening are presented for fcc metals, i.e., aluminum alloys and steels widely used in forming processes. A large number of experimental and theoretical data about the influence of the grain size, texture, and loading conditions on the

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* Corresponding author.
E-mail address: varvara@ispms.tsc.ru (V. Romanova).

http://dx.doi.org/10.1016/j.msea.2017.05.029
Received 15 December 2016; Received in revised form 24 April 2017; Accepted 7 May 2017

development of the orange peel, ridging, and roping in these materials are available in the literature (see, for example, [1–7,9–14,18–26]. In our recent works [27–30], certain aspects of the mesoscale surface roughening in polycrystalline steels and surface-modified titanium and aluminum alloys have been analyzed numerically, using three-dimensional models. It has been deduced that grain structure is responsible for the free surface roughening under deformation. The stresses and strains acting across the free surface were shown to appear in the vicinity of grain boundaries and to give rise to out-of-plane surface displacements. The effects of the grain shape, texture, and boundary conditions on the qualitative and quantitative characteristics of the surface roughness were investigated as well. A review of the results obtained and of those known from the literature has led us to conclude that the deformation-induced surface morphological changes in the materials can serve as an indicator of the state of local strain of the specimens. A deep understanding of the roughening mechanisms operative on different scales is required to establish the interrelation between multiscale deformation-induced surface phenomena, plastic strain stages, and loading history.

The present study is focused on the micro- and mesoscale surface roughening in commercial purity (CP) titanium subjected to uniaxial tension. Titanium alloys are widely used in industry due to their high strength and relatively low weight. At present extensive experimental and numerical data about the deformation behavior of titanium alloys in a wide range of loading conditions have been accumulated (see, for example, [31–36]), with the microstructure, texture, and physical and mechanical properties being well understood. However, we are not aware of any efforts made to study the grain-scale surface roughening induced by plastic deformation. The mesoscale roughening effects attributed to cooperative displacements of surface grains have not received any attention either. In this work, we present experimental and numerical studies on the micro- and mesoscale evolution of roughness in CP titanium specimens. Summarizing the experimental and numerical results, an attempt is made to find a correlation between surface morphology and degree of local strain experienced by the material.

2. Experimental procedure

Dumb-bell test pieces with gage sections of 5×30 mm were cut from 1 mm-thick CP-titanium sheets. The chemical composition of the material under study is given in Table 1. Uniaxial tension tests were performed at room temperature, using an INSTRON 5582 testing machine at a loading velocity of 0.3 mm/min. The specimen surface was polished mechanically and electrolytically prior to mechanical loading. A LEO EVO 50 scanning electron microscope equipped with an electron backscatter diffraction (EBSD) detector was employed to investigate the material microstructure. The EBSD analysis has shown that the material under study is characterized by an equaxed grain structure (Fig. 1a), with the average grain size being 70 µm. No predominant texture was revealed in the material either in the prestrained state (Figs. 1a and 2a) or upon uniaxial tensile testing (Fig. 2b, c).

The evolution of the surface roughening patterns was studied in the specimens subjected to tension, using a stop-and-study technique. As that took place, the specimen undergoing a certain elongation was unloaded and removed from the testing machine. The specimen surface morphology was then investigated, using a Zeiss Axiovert 40 MAT optical microscope, a New View 6200 3D optical profiler, and an Alpha-Step IQ surface profiler. Thereafter the specimen was placed in the testing machine again and its stretching was continued. In this way, the surface morphology was investigated for degrees of specimen elongation of 2.5%, 5%, 10%, 15%, 20%, 25%, and 30%, with spatial resolution being varied from 200 to 5000 µm.

Table 1
Chemical composition.

Element	Al	Zr	Mn	Cr	Si	Fe	Cu	Ti
wt%	0.2	0.4	0.3	0.01	0.06	0.2	0.02	Balance

Macroscopically, an isotropic material is assumed to undergo uniform strain up to the neck formation. On lower scales, however, the regions of the material located at different points of the specimen are found to experience different degrees of strain far in advance of the macroscopic strain localization. Given this fact, we have examined two regions: that located in the central part of the specimen and the one lying at a distance from the center, which is represented schematically in Fig. 1b. A set of control points was drawn on the surface to trace the strain observed in the regions of interest. In what follows, the strains experienced by the regions under study and by the whole of the specimen will be referred to as the local and macroscopic strains, respectively.

In summation, more than 50 optical images and surface profiles were analyzed with different resolution. In what follows we give only some representative illustrations, with the conclusions being drawn from the analysis of the whole package of the experimental data.

3. Experimental results

3.1. Grain-scale roughening

The grain-scale roughening in the material under study is strongly pronounced due to a limited number of slip systems that can be activated in CP titanium at room temperature. Becker [5] suggested that it was a common feature of hcp metals with a limited ability of dislocations to glide. Fig. 2 shows EBSD maps and optical images obtained in a selected region (marked by red line in Fig. 1a) for different degrees of strain. Two characteristic roughening patterns are seen on the grain scale. The smallest out-of-plane surface displacements are attributed to the formation of dislocation steps in surface grains (Fig. 3). Individual grains demonstrate well-developed slip band patterns that cover entire grains (see, for example, grain 1 in Figs. 2 and 3). Other grains exhibit less pronounced dislocation bands originating at and localized near grain boundaries. Notably, early in the plastic deformation, there are grains where no dislocation slip bands are seen at all (for example, grain 2 in Fig. 2d).

Along with the intragrain slip bands, larger grain-scale roughening known as the orange peel pattern develops on the specimen surface. This is caused by relative out-of-plane displacements of neighboring grains. As a result, grain boundaries become clearly visible on the polished surface in an early plastic deformation stage (Fig. 2d). On further loading, the orange peel pattern becomes more pronounced (Fig. 2e).

Compared to the intragrain dislocation steps, the intergrain displacements do make a major contribution to the grain-scale roughening as early as the initial plastic deformation stage. In tension, the intragrain dislocation steps grow but only slightly, while the contribution of the orange peel pattern to surface roughening increases. This conclusion is supported by the experimental data presented in Fig. 3c and d, where the surface profiles along the A-B line passing through grains 1 and 2 are illustrated for two degrees of tensile strain. Three sets of oscillations characterized by different frequencies and amplitudes are clearly visible. The highest frequency and amplitude oscillations that do not exceed a few nanometers are associated with the finest slip bands faintly visible in the optical images presented in Figs. 2d-e and 3a-b. Larger oscillations are attributed to rougher slip bands clearly seen on the grain surface (cf. optical images and surface profiles in Fig. 3). The oscillation height is several tens of nanometers and the period correlates well with spacing between the rough slip bands. The largest surface undulations related to the grain scale are responsible for the orange peel pattern. In the case at hand, the undulations are shaped as a