Mechanics of Materials 117 (2018) 202–213

Contents lists available at ScienceDirect

Mechanics of Materials

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

Research paper

Self-organization of plastic deformation and deformation relief in FCC single crystals

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A R T I C L E I N F O

Keywords:
Deformation relief
Deformation inhomogeneity
Grinfeld instability
Stress relaxation
Crystal plasticity
Self-organization

A B S T R A C T

The purpose of this article is to present patterns for various types of deformation relief formed by octahedral slip, ways of its self-organization and its ability for stress relaxation. The article shows quantitatively that with the scale-up of the structural element of the deformation relief in the sequence of “shear traces, mesobands, macrobands, folds”, the deformation becomes more inhomogeneous at their joints. At the same time, self-organization of deformation within the area occupied by one type of relief occurs in such a way that inhomogeneity of deformation within the occupied area decreases, and deformation in any local area tends to the average deformation on the face. The research shows that deformation relief formed on the crystal surface by octahedral slip releases stress at the meso and macro levels. It is shown that self-organization of shear traces into pack slip band, meso and macro bands reduces local stresses at the place of their formation as compared to the zone occupied by the shear traces. Estimated calculations showed that the difference in the rate of local strain between different types of structural elements of relief increased by about 40%. It is shown that the development of the quasiperiodic profile of the crystal surface upon plastic deformation occurs in terms of the Asaro-Tiller-Grinfeld instability. The critical wavelengths of surface perturbations λc are calculated for structural elements of the various relief types.

Qualitative similarities of the deformation relief which forms in FCC single crystals suggests possible similarities in the results provided.

1. Introduction

The deformation relief that is formed on free surfaces of various types of materials definitely reflects the processes taking place inside. The relief is analysed for various types of stress on poly- and single crystals using theoretical and experimental methods.

If the surface of a metallic sample is polished and then subjected to loading, then the systems of parallel lines known as fine slip lines can be found on the surface (Hirt and Lothe, 1968; Honeycombe, 1984). As far back as in the early 20th century, Rosenhain and Ewing, as well as Hirt and Lothe (Hirt and Lothe, 1968), showed that these lines appear as surface steps resulting from microscopic shear displacements (dislocation motion). A separate slip line may be identified using a replica method (with a magnification range of 5000–25,000). Observing the deformation relief through an optical microscope makes it possible to resolve individual shear traces that are formed by a stack of slip lines.

When studying the deformation relief formed by shear traces, closer attention must be paid to such parameters as the amount of shift, the distance between traces, and the length of trace. In the early works of Mader, Cronmuller, Pfaff and Mitchell, among others, slip lines in FCC metals were measured, and the shift amount in traces was found to be independent of deformation and almost constant within the second stage. The findings of the above studies were further summarized in the paper by Honeycombe (1984). Until now, these parameters have been used in studies of relief (Cai et al., 2008; Chan et al., 2009; Charrier et al., 2012; Franciosi et al., 2015; Ho et al., 2011; Kahloun et al., 2016; Teplyakova et al., 2003).

Based on works (Teplyakova et al., 2003) using single crystals of aluminium in different orientations for measuring the distances between shear traces and the dimensions of the relief elements, a conclusion was drawn of primary and secondary macrofragmentation as well as of symmetry or asymmetry of the shift extension. In Kramer et al. (2005), it is reported that when single crystals of aluminium are stretched near axis [001], a 2% plastic deformation in the slip band reveals a 250 nm growth in height, further followed by a standstill. In the case of [112] orientation, the slip bands are observed and grow continuously. Work (Kahloun et al., 2016) reveals the evolution of the relief in tensile testing though the example of single crystals of

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https://doi.org/10.1016/j.mechmat.2017.11.011
Received 24 August 2017; Received in revised form 15 November 2017; Accepted 28 November 2017

copper with stretching axis [2,4,21] and α-iron with stretching axis [5,26,37]. For copper, at the early stage of plastic deformation, slip bands were rare with a constant amount of shift. With the increase of deformation, the number of active slip bands grows in a linear fashion. Copper is characterized by slip bands 1.7 mm wide. α-iron is characterized by a dense and homogeneous network of fine slip bands at the beginning of plastic deformation. Besides, the increase of deformation is followed by an increase of the slipping motion within the bands. However, the number of active slip bands is saturated in the early stages of deformation. The bands have a width of 0.9 mm. In both cases, as deformation progressed, a deviation of the slip lines was observed with respect to the expected orientation of active slip. This fact is associated with the activity of transverse slip and, consequently, with the presence of screw dislocations in the microstructure. A similar comparison of the slip pattern for copper and iron is featured in Franciosi et al. (2015). For iron, the shear traces are spaced more evenly and denser as compared to copper. In Mecif et al. (1997), the slip pattern is observed for single crystals of copper and aluminium. At room temperature, the traces demonstrate a uniform distribution and do not tend to form coarse bands. In Cai et al. (2008), as in the case of single crystals of aluminium stretched along axis [112], the in-stack trace density (100 mm^{-1}), the inter-stack distances and the pack widths were identified. Generally, when considering the morphology of shear traces for FCC single crystals with different values of the stacking fault energy (SFE), it can be noted that with decreasing SFE, the traces become longer and the slip step smaller.

Formation of various types of shear traces is also observed in BCC materials. In Charrier et al. (2012), three types of elements were observed in the deformation structure under compression [001] of single crystals of niobium. Long straight traces (type A) that are characterized by a constant height along the trace. For short straight traces (type B) that are characterized by the same height all along the trace at the initial stage of deformation, but with deformation being increased, the height in the centre of the trace exceeds that at the edges. Short curved traces (type C), also known as boomerangs, which are observed at the beginning of plastic deformation. Formation of A traces is explained by the sources of dislocations which pass fairly long distances within the material. Formation of B traces is due to the activation of dislocation sources just below the surface, somewhere in the middle of the slip line. In this case, dislocations are emitted continuously, but in geometrically restricted conditions. The curved shape of B traces is a result of dislocation clusters. The curved traces (type C), or boomerangs, are formed by one subsurface source of dislocations that is located under the curve. Curved traces are formed in consequence of successive transverse slip.

Using cyclic loading on polycrystals of nickel, it was demonstrated that trace systems have different stages of development in different grains (Chan et al., 2009). With the increasing number of cycles, there is almost no increase in the width of trace packs, but the distance between them decreases due to constant generation of new slipbands among the existing ones.

As a basic structural element of the deformation relief (SEDR), shear traces are formed starting from the initial degrees of deformation in poly- and single crystals. At the same time, with the increasing degree of deformation, they restructure into an upper scale model (meso- and macrobands, different types of corrugations, persistent slip band, etc.). This restructurization is due to internal factors only, without any specific impact from the outside. Thus, we may speak of self-organization of the deformation relief.

Attempts to classify elements of the deformation relief have long been undertaken (Dillamore, 1980; Hatherly, 1982; Honeycombe, 1984; Jasienski and Piatkowski, 1980; Laird, 1996; Mecking, 1978). In these works, the main types of structural elements of the deformation relief include the so-called kink bands and secondary shear bands. The two mechanisms of plastic deformation are established in accordance: kinking and rotational shear. In Cotrell's works, the kink strips are sometimes referred to as flexure bands or inflection bands. Another element of relief is represented by localized shear bands. In a number of works (Buck and Essmann, 1964; Laird, 1996), it is noted that formation of such bands is due to mechanical instability. On the surface, the localized shear banks appear as wavy, intertwined, split traces of slip, which is associated with the process of double lateral slip. The wavy slip bands in single crystals of aluminium are also referred to in Kramer et al. (2005). They are observed when the crystals are stretched in the vicinity of the direction [111] and include several active slip systems. In Ha and Kim (2011), it is reported that shear traces appear in [132]-single crystals of aluminium under compression by means of discrete slip bands. Therefore, “deformation band” seems a very broad term for describing the deformation relief. Whenever it is possible to identify the mechanism of deformation (shear, reorientation of inner regions of the crystal, kinking, etc), deformation bands can be identified more specifically too. However, the issue of what mechanisms form particular deformation bands remains open, and attempts to classify elements of the deformation relief are still underway.

In Lychagin et al. (2006), a classification of structural elements of the deformation relief was provided for FCC single crystals with different space lattices and their hierarchical subordination was established. It was shown that the relief elements are formed by means of translational and rotational mechanisms. At the same time, this work did not reflect such an element of the deformation relief as corrugations (folds). This is why the authors repeatedly turned to the classification of corrugated (folded) structures in their subsequent works (Alferova and Lychagin, 2013; Lychagin et al., 2016, 2011; Lychagin and Alfyorova, 2015; Lychagin et al., 2015).

In addition, there are a number of works which describe the formation of various types of deformation relief elements but do not consider their classification. In Magid et al. (2009), under the uniaxial compression of single crystals of copper, primary shear bands are formed on the macrolevel along the direction (111). Secondary conjugated bands which begin and end near primary shear bands develop perpendicular to them. The heterogeneous distribution of shear traces on the surface of single crystals of nickel as well as the shear clustering within the third stage of the loading curve are reported in Girardin et al. (2015). Formation of shear traces organized in various ways depending on the crystallographic orientation of the extension axis and the lateral faces of aluminium monocrystals deformed in vacuum are described in Cai et al. (2008). Depending on the orientation, shear traces may come in packs with wavy structures between them ([112] (110)), two systems of intersecting shear traces ([215] (130)) or evenly distributed fine slip bands ([233] (412)). For [110] single crystals of aluminium under compression, development of deformation bands is noted (Okada et al., 2009). The tension of single crystals of copper for orientation [001] is characterized by formation of thin shear traces and the absence of large relief elements or transverse slip. For [110]-monocrystals of copper, in contrast to aluminium, no development of deformation bands was observed (Okada et al., 2005).

Self-organization of shear traces into structural elements of the deformation relief is observed not only with active deformation of FCC single crystals, but also in other cases. Interesting effects of the deformation relief on steel are described in works (Man et al., 2009a,b). In this case, the deformation relief evolves from fine slip lines and develops to well-defined areas of extrusion which are accompanied by thin areas of material intrusion. Known as PSBs (persistent slip bands), these deformations are a characteristic element of the deformation relief under cyclic loading. Work (Man et al., 2015) investigated the early stages of the surface relief evolution in polycrystal stainless steel under cyclic loading. Persistent slip markings (PSMs) originate in all cases as surface extrusions which are subsequently accompanied by the formation of intrusion areas. It was shown that the localization of deformation takes place in PSBs which are formed by PSMs which in turn consist of intrusion and extrusion of the material. Restructuring of traces into shear bands accompanied by extrusion areas is also