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Fatigue crack initiation – The role of point defects

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ABSTRACT

The role of point defects in the formation of surface relief and in the initiation of a fatigue crack in crystalline materials is analyzed. The dislocation interactions in the bands of intensive cyclic slip (persistent slip bands – PSBs) are specified and relations describing the formation and annihilation of interstitial and vacancy type defects in the channels of the ladder-like PSB are derived.

The continuous formation, annihilation and primarily the migration of point defects are proposed to be responsible for the mass redistribution within PSB and between PSB and the PSB/matrix boundary. The redistribution of the matter results in local tensile and compressive stresses that are the sources of the principal irreversibility of slip within PSB. Local tensile and compressive stresses are relaxed by dislocation movement within PSB in the direction of the active Burgers vector and lead to the formation of characteristic surface relief in the form of extrusions and intrusions. The intrusions represent crack-like defects and fatigue cracks initiate in the tip of intrusions.

1. Introduction

Fatigue crack initiation in crystalline materials is closely connected with the localization of the cyclic plastic strain. Cyclic strain localization results in the formation of the surface relief and represents the early fatigue damage [1–3]. Cyclic strain is localized into thin bands running parallel to low index crystallographic planes called persistent slip bands (PSBs). Local cyclic plastic strain amplitude in PSBs is considerably higher than the average applied plastic strain amplitude and can reach several percents up to tens of percents [4,5]. Moreover, plastic strain is not distributed homogeneously even within an individual PSB [5,6]. PSBs in polycrystals have typical thickness around 1 μm while in single crystals macro-PSBs are produced with considerably larger thicknesses, 10–50 μm [2]. The localized cyclic plastic strain results in the formation of the specific surface relief in the form of persistent slip markings (PSMs) at locations where PSBs egress from the material. PSMs generally consist of extrusions and intrusions, locally they can be formed by extrusion, intrusion or extrusion–intrusion pairs.

Cyclic straining within PSBs proceeds by shear, usually in parallel primary slip planes. Specific dislocation arrangement of PSBs in single crystals of copper fatigued at room temperature was for the first time observed in transmission electron microscope by Laufer and Roberts [7] and Lukáš et al. [8]. Later it was referred to as a ladder dislocation structure though in reality in three dimensions it is an alternation of thin dislocation-rich walls and thick dislocation-poor channels. Similar ladder-like structure of PSBs at temperatures down to liquid helium temperature have found Basinski et al. [9] and Buchinger et al. [10]. The knowledge of dislocation arrangement of PSBs allowed proposing the early models of dislocation movement and their interaction [11]. It has been recognized that steady state dislocation pattern of PSB is possible only due to both dislocation production and annihilation. Only dislocations were considered to play the dominant role in cyclic plastic straining in spite of the fact that it was difficult to explain the formation of a very specific surface relief in the form of extrusions and intrusions observed already at the onset of last century [12] and documented in many papers (for review see e.g. [2]).

The measurement of the resistivity of cyclically deformed copper polycrystals [13,14] and later also of copper single crystals [15,16] revealed high production rates of point defects in cyclic straining and documented also their mobility [13,16,17] at temperatures starting from temperature of liquid helium. Ladder-like dislocation structures were observed also in polycrystals cycled at room [18] and at liquid nitrogen temperatures [9,10,19]. The knowledge of the dislocation arrangement of PSBs and the experimental findings of the high production rates of point defects in cyclic straining stimulated Essmann et al. [20,21] to formulate the well known EGM model explaining the growth of extrusions emerging from PSBs in cyclically deformed metals. According to the EGM model the vacancies produced by annihilation of dislocations in the thin dislocation walls of the PSB structure increase the volume of the PSB lamella and the extra volume egresses from the material as a static extrusion. The height of the extrusion is

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proportional to the extra vacancy concentration and to the depth of the PSB under the surface. The extrusion profile is later modified by random slip [22] and the notches at the extrusion/matrix interface or within extrusion stimulate the initiation of the fatigue cracks (see also [3]). Similar model has been proposed by Brown [11,23] which is based on the formation of vacancy and interstitial dipoles in PSBs and ejection of interstitial dipoles to the surface. The tensile fiber strain and produced extrusion in the PSB stimulate the initiation of a crack at PSB/matrix interface.

The EGM model has been modified by Polák [24,25]. In both these models only vacancies are considered since interstitial production was believed to be very low due to high energy of formation of an interstitial. Three premises substantially distinct from the premises of EGM model were adopted in Polák's model [24,25]: (i) vacancies are produced during localized cyclic straining of a PSB not only in the dislocation walls but also in the channels; (ii) vacancies in the channels play the dominant role since they can migrate also to the matrix where they annihilate at dislocations and (iii) vacancies that left PSB migrating to the matrix are substituted by newly produced point defects.

These modifications completely changed the mechanisms of PSM formation. Only the first phase consisting in the formation of a static extrusion is similar to both models. According to Polák's model the steady production of vacancies and their migration from the channels to the matrix results in the reciprocal movement of atoms. This leads to continuous redistribution of the matter between PSB and the matrix and finally to steady growth of extrusions and production and deepening of intrusions during cyclic straining. The intrusions are crack-like defects and fatigue cracks soon initiate in the tip of intrusions.

In the present contribution we shall elaborate original Polák's model by analyzing the relevant interactions of dislocations in localized slip bands (PSBs) resulting in the production of both interstitials and vacancies. Two types of point defects namely interstitials and vacancies are considered throughout the paper though some other configurations as unit vacancy dipoles or unit interstitial dipoles, divacancies, di-interstitials or crowdions are in reality created, annihilated and migrate in the crystal. The production and annihilation rates of point defects in a regular wall structure of a PSB are derived. The importance of the dislocation arrangement of the PSB and the mobility of a particular type of migrating point defect at a given temperature for the shape of PSMs (extrusions and intrusions) is demonstrated. The predictions are compared with the observed relief at emerging PSBs produced in polycrystalline materials by cyclic straining at two temperatures.

2. Dislocation interactions in a regular wall structure of a PSB

Ladder-like (or wall-and-channel) dislocation structure of a PSB has been found in several simple metals (both in single- and in polycrystals) like copper, nickel etc. strain cycled to the saturation of stress amplitude [2,7–10,18,19,26]. Fig. 1 shows schematically three-dimensional arrangement of dislocations in the lamella of PSB with a ladder-like structure. The lamella is composed of alternating thin dislocation rich walls (consisting of edge dipoles and multipoles) and thick dislocation poor channels. High plastic strain within a cycle is accommodated by the formation of the dislocation loops starting from the edge dislocation segments in the walls and their expansion into the channels. The majority of the loops reach the neighbor wall without interaction with other dislocations within the channel and the edge sections become integrated in the dipolar structure of the wall. Two nearly straight screw dislocation segments are left from each loop and under the action of shear stress start moving in the opposite directions in the channel carrying the major part of the plastic strain. Moving screw dislocations can be annihilated by cross-slip with opposite screw dislocations provided annihilation distance is below a critical distance y_s [20,21].

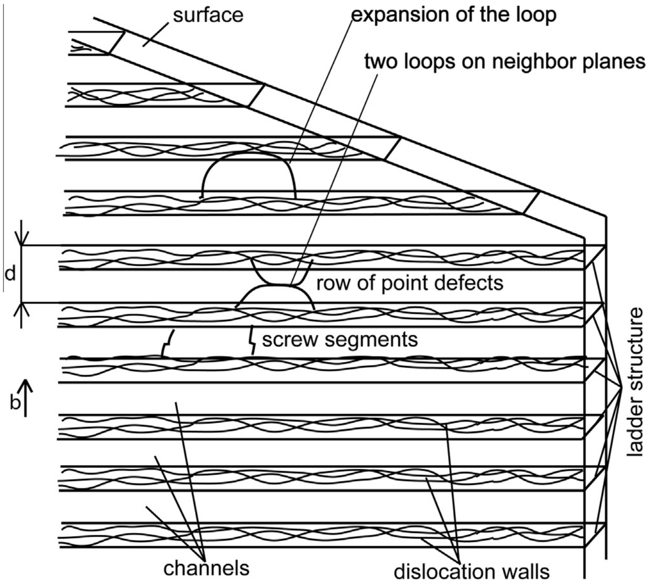

Fig. 1. Dislocation ladder structure in PSB showing dislocation bowing and interactions (schematics).

Fig. 2 shows schematically the distribution of dislocations in PSB, their interactions during cyclic straining and formation of unit dipoles (rows of vacancies or interstitials) in the channels. The largest number of dislocation interactions takes place in the walls.

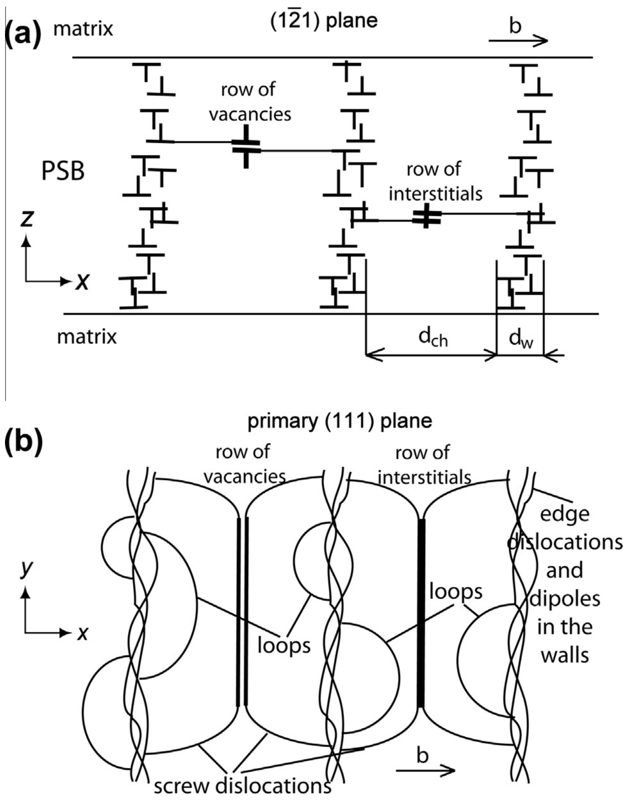

Fig. 2. Schematics of dislocation interactions and formation of point defects in a PSB, (a) projection in $(1\bar{2}1)$ plane and (b) projection in primary (111) slip plane.