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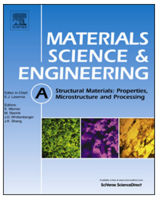

Mechanisms of extrusion and intrusion formation in fatigued crystalline materials

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ABSTRACT

Experimental data on the formation of persistent slip markings (PSMs) at the egressing persistent slip bands (PSBs) and physically based models of surface relief formation and fatigue crack initiation are surveyed. The original Polák's model of fatigue crack initiation based on the formation, migration and annihilation of vacancy-type defects in PSBs is further refined and extended by taking into consideration the annihilation of vacancies in the matrix and the formation of internal stresses. The proposed mechanisms of surface relief formation are based on the plastic relaxation of internal compression stresses in PSBs and internal tensile stresses in the matrix. By solving the migration of vacancies from the PSB and their annihilation in the matrix, the shapes of extrusion and parallel intrusions are derived analytically under some simplifying assumptions.

1. Introduction

Fatigue crack initiation in crystalline materials is closely connected with the localization of cyclic strain. Early experimental observations of Ewing and Humfrey [1] and numerous further studies (for review see e.g. Man et al. [2]) revealed the localization of the cyclic strain in thin bands of the material embedded in the matrix, which run parallel to highly stressed crystallographic planes. Since the cyclic slip in these bands is intensive for a long fraction of the fatigue life they were called "persistent slip bands" (PSBs). While the matrix is cyclically strained elastically, plastic strain is concentrated on PSBs and plastic strain amplitude in PSBs can reach up to several percent. The high cyclic plastic strain in PSBs results in the formation of the pronounced surface relief in locations where PSBs egress on the surface and produce specific slip pattern, or markings called "persistent slip markings" (PSMs).

In early studies [1,3] the shape of PSMs was observed using optical microscopy. Extrusions and intrusions are the main features of PSMs. Taper sectioning [4] and the use of replicas [5] allowed distinguishing several details of the extrusions and intrusions. Modern metallographic techniques, namely transmission electron microscopy (TEM), high resolution scanning electron microscopy (FEG-SEM), atomic force microscopy (AFM) and focused ion beam (FIB) technique [6–12], achieve high resolution and thus allow one to study the details of the surface relief topography. Despite numerous experimental observations, agreement on the role of surface relief in the formation of fatigue cracks has not been attained [13]. The disagreement on the mechanisms leading to the initiation of the early stage I cracks is closely related to different models of surface relief formation and fatigue crack initiation.

The first physically based model explaining the growth of extrusions is the model proposed by Essmann et al. (EGM model) [14]. The EGM model envisages the formation of high density of vacancy-type point defects in the walls of ladder-like dislocation structure of PSBs due to dislocation interactions. According to the EGM model vacancies generated in the dislocation walls expand the volume of the PSB. The volume expansion gives rise to interface dislocations and their slipping out of the PSB results in the elongation of the PSB lamella and in the formation of static extrusion. Similar arguments are used in the Brown model [15] where the fiber stress in the PSB is supposed to arise due to dislocation dipoles. Continued cyclic deformation leads to a gradual roughening of the extruded material. Stage I shear cracks are initiated at the PSB–matrix interfaces on both sides of the extrusion emerging on the surface and/or in locations of stress enhancements in the roughened extrusion [13] due to notch effect of the extrusion. Repetto and Ortiz [16] attempted to calculate the profile of extrusions and intrusions in copper single crystals relying on the vacancy diffusion to the surface.

Polák [17,18] proposed the substantial extension and modification of the EGM model. In his model vacancies are produced by dislocation

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interactions in PSB both in the dislocation walls and in the channels. This leads to the higher predicted height of the static extrusion, in agreement with experiments [19]. A more important feature of the model is the migration of steadily produced point defects at temperatures at which they are mobile. Continuously produced vacancies or divacancies at temperature close to room temperature migrate from the channels to the matrix and annihilate there at edge dislocations. It leads to the steady mass redistribution between PSB and the matrix. This mass redistribution is the source of internal compression stress in the PSB and internal tensile stress in a thin sheet of the matrix adjacent to PSB. Plastic relaxation of these stresses leads to the dynamic extrusion growth and to the production and deepening of intrusions at the PSB/matrix boundary. The intrusions are crack-like defects from which fatigue cracks start to initiate.

The main objections against Polák's model were raised recently by Mughrabi [13] stating that at the very beginning of cycling only bulgy extrusions form. Only later, “intrusion-like” deepenings, described as “very fine and thin in comparison with extrusions”, are observed to develop. Moreover, they are not formed on both sides of the extrusion but more often at the side of the extrusion where the emerging active slip plane is inclined to the surface at an acute angle. Mughrabi [13] reasons that comparison with experimental facts suggest strongly that the “intrusions” are much less dominant than the extrusions and that they do not develop by a mechanism comparable to that of extrusion formation, as proposed in Polák's model. The conclusion was that much of the experimental evidence suggests that “intrusions” develop as a consequence of the previously formed extrusions as proposed in the EGM model [14] and are in fact embryonic stage I shear cracks.

In this contribution we would like to present some experimental results showing the presence of intrusions and primarily propose a mechanism which elaborates the formation of extrusions and especially intrusions. This mechanism can predict the shape of intrusions in agreement with experiments and it also explains why intrusions start to be formed after some delay after the formation of extrusions and why intrusions arise parallel to an extrusion often only locally, as found experimentally. By solving the diffusion and annihilation of point defects produced in PSBs the shape of extrusion and parallel intrusion is derived analytically. The proposed mechanisms thus represents refining and quantitative presentation of Polák's model [17,18] of fatigue crack initiation.

2. Summary of experimental observations of the shapes of extrusions and intrusions

There are numerous studies on the shapes of PSMs produced in single and polycrystalline materials in cyclic loading at different conditions. Temperature, strain amplitude and grain size are the principal factors that affect the shapes of PSMs. The shapes of PSMs in fatigued metal yield great variability even if experiments are performed on one material at constant temperature and plastic strain amplitude. In different locations on the surface of fatigued material either only extrusions, or extrusions accompanied by thin intrusions on one side, or extrusions accompanied by thin intrusions on both sides of an extrusion appear. Rarely even individual intrusions are observed, e.g. in single crystals [20].

There are several experimental methods which can image the shape of extrusions and intrusions. Some methods have certain limitations. SEM images lack the true information in three dimensions [21]. Direct observations of the crystal surface using AFM can detect the height of extrusions but not their exact shape [6,19]. AFM observations of the plastic replica taken from the fatigued crystal can detect the height of the intrusions but not its real shape [22]. As a consequence AFM images of plastic replica cannot distinguish reliably between the intrusion and the crack. The only method allowing one to see the true shape of PSMs is the use of FIB cuts observed in high-resolution SEM [11,12] or the production of thin foils using FIB cutting that could be observed in TEM [11].

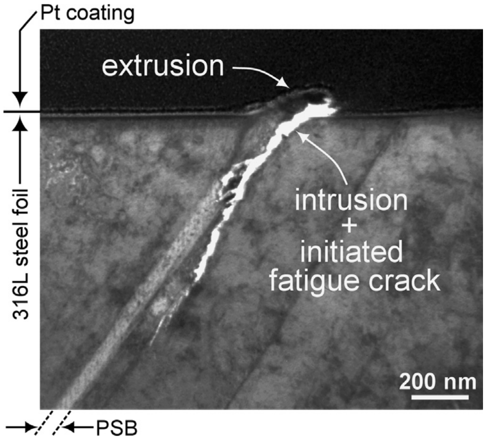

Fig. 1. TEM of a foil covered by Pt coating with initiated fatigue crack. Foil was produced by FIB cutting from the surface of 316L steel fatigued with $\varepsilon_{ap}=1\times10^{-3}$ for 3800 cycles (8.3% N_f) (after [11]).

In Fig. 1 we can see the detail of the foil prepared using FIB cutting which shows the extrusion slightly bent to the crystal surface accompanied on one side by an intrusion and a crack that started from this intrusion. The foil was prepared from the surface grain of 316L stainless steel cycled with constant plastic strain amplitude to 8.3% of the fatigue life. The surface was first covered by platinum to prevent damaging of the surface during ion bombarding. The area under the extrusion not covered by platinum, the area of the intrusion and the area of the crack are transparent for electrons.

Fig. 2a shows the AFM image of the surface of 316L steel cycled at depressed temperature to a low number of cycles. Already at this early stage of cycling two PSMs consist of thick extrusions accompanied by thin parallel intrusions. The PSM to the left already has a well-developed intrusion, in the PSM to the right the intrusion is just starting. At a later stage the intrusions start to develop parallel to the extrusion on several locations as shown by the AFM image of plastic replica in Fig. 2b. Man et al. [23] studied systematically the evolution of extrusions and intrusions in 316L steel and displayed a summary of *typical shapes of extrusions and intrusions* and kinetics of their height evolution in specimens cycled at room temperature with plastic strain amplitude 1×10^{-3} up to 15% of fatigue life (see Fig. 3). PSMs start as thin extrusions that are widened early in the fatigue life. At around 1% of the fatigue life thin intrusions start developing in some locations parallel to the central extrusion. The number of PSMs accompanied by one or two parallel intrusions increases with the number of cycles. The depth of intrusions increases even more rapidly than the height of the central extrusion. At 15% of the fatigue life 87% of PSMs consist of a central thick extrusion accompanied by two thin parallel intrusions, some of them presumably extended by initiated cracks. Similar experimental results based on AFM observations were recently reported in polycrystalline copper cyclically strained at ambient and depressed temperatures [24].

Since AFM cannot reliably distinguish between the intrusion and the crack we recently studied the profile of the PSM developed very early in cycling of 316L steel using multiple FIB cuts (see [12]). Fig. 4 shows the SEM image of four PSMs and also the profiles of two well-developed PSMs. Two short and thin PSMs to the right from large PSMs A and B developed only thin extrusions. Two central PSMs were wide, consisted predominantly of extrusions,