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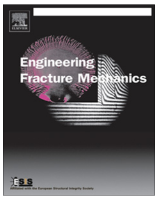

The role of extrusions and intrusions in fatigue crack initiation

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ABSTRACT

The profiles of persistent slip markings produced by uniaxial and biaxial cyclic straining in four different polycrystalline materials with f.c.c. structure were investigated using focused ion beam (FIB) cutting and TEM observation of oriented surface foils. Typical shapes of persistent slip markings are extrusions accompanied by parallel intrusions. In some cases only extrusions were developed and intrusions were produced later in fatigue life. In polycrystalline copper extrusions and intrusions appear on the surface of the grain where persistent slip band characterized by ladder-like dislocation structure egress on the surface. Similar features were observed in fatigued austenitic 316L and Sanicro 25 steels but the extrusion and intrusion shapes were more complicated. Crack-like intrusion shapes produce high stress and strain concentration and primary stage I crack starts to grow from the tip of intrusions. The experimental observations were compared with the predictions of the existing crack initiation models.

1. Introduction

Fatigue life of materials and structures consist of two important periods, fatigue crack initiation and growth of fatigue cracks. In majority of cases the crack growth occupies the larger fraction of fatigue life and application of general yield or linear fracture mechanics can quantitatively describe this period [1]. Fracture mechanics approach has been applied to the description of the growth of both long and short cracks [2]. Nevertheless the initiation of fatigue cracks also represents an important stage since without crack initiation there is no crack growth and no fracture. Therefore the initiation of fatigue cracks attracted significant attention of scientists and engineers shortly after the fatigue phenomenon was first identified [3]. Two basic types of fatigue crack initiation in materials cyclically strained at ambient temperatures have been recognized: (i) fatigue crack initiation in heterogeneous materials where the crack can start from cracked or debonded second phase particles (e.g. inclusions) or from pre-existing crack-like defects, (ii) fatigue crack initiation in homogeneous materials which contain only natural elementary defects like point defects, dislocations, stacking faults, twins and grain boundaries. This paper is focused on the experimental study of crack initiation in the case of homogeneous materials and aims to contribute to the clarification of the mechanisms related to how cyclic straining results in the appearance of fatigue cracks. The main interest is devoted to the localization of cyclic plastic straining and its contribution to the formation of surface relief in the form of extrusions and intrusions and ultimately to crack initiation.

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This subject has been studied for years in a great number of papers (see the recent review papers on this subject [4–11]). The fundamental source of information allowing for an understanding of the mechanisms leading to the initiation of fatigue cracks is the dislocation structure of the bands of localized cyclic slip called persistent slip bands (PSBs). The experimental TEM (transmission electron microscopy) and ECCI (electron channeling contrast imaging) studies of the dislocation arrangement in fatigued simple metals like copper, silver and nickel [12–23] and solid solution alloys like stainless steels [24,25] revealed characteristic ladder-like dislocation arrangements within the PSBs. High resolution studies of the surface relief using SEM (scanning electron microscopy) and AFM (atomic force microscopy) revealed the profiles of surface markings, called persistent slip markings (PSMs), at locations where PSBs emerge on the surface [22,26–32]. Nevertheless the relationship between surface relief and dislocation structure below the surface is still not thoroughly documented, particularly for polycrystals.

Experimental studies have motivated the theoretical models proposing the mechanisms leading to cyclic slip localization, formation of the surface relief, and crack initiation. Most of the recent models and simulations are based on the dislocation interactions in the ladder-like dislocation structure observed in homogeneous simple metals, and an assumption that PSBs observed in the bulk are also typical for surface grains. The ladder-like dislocation structure in PSBs observed in the foils represents in three dimensions a plate consisting of thin dislocation-rich walls alternating with thick dislocation-poor channels. The first treatment of dislocation interactions in PSBs appeared in the work by Essmann and Mughrabi [33]. They considered the expansion of dislocation loops from the walls across the channels, interactions with dislocations in neighboring walls, and their annihilation. Simultaneous formation and annihilation of dislocations lead to the achievement of a saturated dislocation density in cyclic straining. Moreover, the production and annihilation of dislocations result in point defect production in the walls and their annihilation by sweeping dislocations. Relatively high saturated point defect density was estimated ($\sim 10^{-3}$ for copper) [33].

The production of point defects in cyclic straining, documented also experimentally [34,35], motivated Essmann et al. [36] to propose the first physically-based model (EGM model) which was able to explain the formation of extrusions and intrusions in fatigued metals. The EGM model is based on the production of vacancies due to dislocation interactions in the walls of PSBs. Vacancies represent extra volume and cause internal compressive stresses within PSBs. These stresses are relaxed in the direction of active Burgers vector and an extrusion starts to grow where the PSB emerges on the surface. Mughrabi [5,9] considers the source of crack initiation to be the stress concentration from extrusion and notch effects due to random slip within PSBs.

Coinciding with the work by Essmann et al. [36], Tanaka and Mura [37] modelled PSBs by the line of dislocation dipoles impinging on the grain boundary. They proposed the formation of embryonic cracks in dislocation pile ups accumulated under cyclic stress. The layers of dislocation dipoles can be transformed into a free surface (crack) when the stored energy accumulated after N cycles becomes equal to the surface energy. They derived a simple equation relating the number of cycles to crack initiation with the specific fracture energy of the material and applied strain or stress amplitude. The Tanaka and Mura model has been revised and modified many times (see e.g. [6,38]) and used for the prediction of the fatigue life curves for a number of materials. In spite of some success in fatigue life prediction, the modelling of PSBs by the line of dislocation dipoles is not in good agreement with real dislocation structures of PSBs in simple f.c.c. and b.c.c. metals. A more realistic dislocation structure of PSBs has recently been considered by Sauzay et al. [39,40] in calculation of the internal stresses produced at PSB impinging grain boundaries. Due to the finite thickness of PSBs and observed dislocation arrangement, these stresses are substantially lower than calculated by the pile up model.

The EGM model was further developed by Polák [41]. Since point defects in copper are highly mobile at room temperature [34,42,43], they readily anneal out during cyclic loading and static extrusions considered in the EGM model [5,36] cannot accumulate in room temperature cyclic loading. Consequently, the mechanism of extrusion formation proposed in the EGM model has been substantially modified [41]. Polák's model considers the production of point defects not only in the dislocation walls but also in channels of the PSBs. Moreover, point defects, predominantly vacancies which are steadily produced in the channels, migrate (during cycling) to the dislocation walls and to the matrix where they are absorbed at edge dislocations. Migration of vacancies from PSBs to the matrix results in systematic transfer of atoms in the opposite direction (i.e. toward PSBs). The matter is thus steadily accumulated at PSBs and internal compressive stresses arise within. Compressive stress is relaxed plastically in the direction of the primary Burgers vector and the steady growth of an extrusion is envisaged. The growth of extrusions has been described quantitatively, provided vacancies are absorbed at PSB/matrix interface, by Polák and Sauzay [44]. Due to the matter conservation law, intrusions arise on the PSB/matrix boundary. The kinetics and the shape of the intrusions have been calculated using the data on vacancy production and migration corresponding to polycrystalline copper [45,46]. The intrusions represent crack-like defects and fatigue cracks start to grow from the tips of intrusions.

Another basic approach to trace the fatigue initiation mechanism is the three-dimensional DDD (discrete dislocation dynamics) simulation of dislocation motion in a grain of model polycrystal. Déprés et al. [47–50] started with a surface grain containing a single dislocation segment serving as a source under alternating stress. They considered the cross-slip probability and after several initial cycles obtained growth of the dislocation density in an inhomogeneous arrangement consisting of dipolar walls and channels. Dislocations running out of the grain produce steps on the surface which in some cases could be classified as extrusions and intrusions. Unfortunately, 3D simulations are time consuming and it is not possible to run enough cycles to obtain an appreciable size of PSMs. Nevertheless the simulation approach seems to be promising provided