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# Some comments about fatigue crack initiation in relation to cyclic slip irreversibility

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**Abstract**

In the present work, an overview of recent measurements of plastic strain irreversibility obtained with atomic force microscopy (AFM) is used to discuss the opportunity to define fatigue crack initiation in terms of a critical value of plastic strain irreversibility. We illustrate the fact that the critical value of height emergency associated with deformation band, necessary to crack initiation, is a decreasing function of the plastic strain localization in band. This phenomenon can be understood in terms of an excess of elastic energy associated with mobile dislocations and an interaction between vacancy mobility and oxygen diffusion.


*Keywords:* Crack initiation; Plastic strain irreversibility; AFM

## 1. Introduction

Improving the structural integrity of materials under cyclic loading can be achieved only with a sound understanding of the early stage of damage. The present paper is only focused on one of the origins of fatigue crack, namely slip band emergence but it is clear that other processes can occur such as initiation near inclusions or near grain boundaries. In pure metals and alloys hardened by solutes or coherent precipitates, fatigue damage evolution is controlled by surface step displacement. The sharp surface is drastically modified by the emergence of slip bands which induces only extrusions or extrusions and intrusions [1–6]. These irreversible surface markings arise from surface steps which are partially reversible during the different sequences of one cycle [7,8]. It is now well established that the presence of slip bands is the origin of fatigue crack initiation [1–9]. Consequently, the life-controlling mechanisms can be partially described in terms of the microstructurally irreversible fraction of cumulative plastic strain [9]. The irreversible motion of dislocations can occur as a localized plastic deformation mode. Under cyclic loading, two kinds of localization have been reported,

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**Nomenclature**

| | |
|---|---|
| $\gamma_{pl,loc}$ | mean local shear strain amplitude endured by a slip band |
| $\gamma_{irr,pl,loc}$ | critical value of the local irreversible plastic strain |
| $w$ | band thickness |
| $h$ | height of the extrusion |
| $h_c$ | critical height of the extrusion |
| $D$ | grain size |
| $\langle h \rangle$ | average value of the extrusion height |
| $P$ | probability density |
| $f(x)$ | gamma distribution |
| $\Gamma$ | gamma function |
| $\sigma$ | distribution variance |

namely shear band (SB) and persistent slip band (PSB) which results in quite different physical processes. Thus a universal microscopic law of crack initiation, formulated in terms of plastic strain irreversibility, remains seriously questionable. In the present contribution, an overview of recent measurements of plastic strain irreversibility (extrusion height) obtained with atomic force microscopy (AFM) is proposed in different single phase metals and underaged alloys [10–18]. These results are used to discuss the opportunity to define crack initiation in terms of a critical value of plastic strain irreversibility, as recently proposed in Waspaloy alloy [17]. For this purpose, the main aspects of the localization of plastic strain on intense slip bands during cyclic loading are discussed.

## 2. Plastic strain localization phenomenon

The origin of plastic strain localization in slip bands during cyclic loading has been extensively discussed in the past. These dislocations patterns can result from a minimization of stored elastic energy and/or from space and time fluctuations of different physical parameters like dislocation velocity and density, internal stresses, temperature... Both origins depend on metallurgical state. In single phase f.c.c. metals, the starting point of plastic strain localization in persistent slip bands (PSBs) is the formation of dipoles and multi-poles promoted by cross-slip and cyclic loading [4–6,19–21]. The sweeping of dipoles loops seems to contribute to the early stage formation of clusters [22]. The localization of plastic strain into PSBs, in relation to reorganization of edge dipoles in these clusters in order to form a ladder structure, is supposed to occur when the existing dislocations structures (tangles and veins) are not able to accommodate further plastic deformation [23]. In metal with a more planar slip character (low stacking fault energy, high friction stress, solid solution hardening,...) the ladder organization in the band is often not well established [2,23–28]. The dislocations structure in the band consists generally of dense slab of dipoles and multi-poles. The common point of these bands is the presence of different kinds of defects (point defects, prismatic loops,...) which reduce the mobility of the dislocations and consequently reduce the slip reversibility [19,24–26,29]. The edge defect is mainly caused by mutual annihilation of screw dislocations produced by loops emitted from the walls [30]. Prismatic loops result from the interaction between edge dipole of primary slip system and cross-slip system [25,29]. The annihilation of edge dislocations by climb produces different kinds of point defects [19]. It is important to point out that the annihilation processes depend on stacking fault energy (SFE) and then that the density of the defects decreases when SFE decreases. In other words, the strain reversibility in bands is higher in low stacking fault energy alloys than in high SFE alloys. Moreover, we can state that the slip bands are much thinner when SFE is low, with reference to aluminum ($w = 1.5$ µm, $\gamma_{SFE}/\mu b = 18.9 \times 10^{-3}$) [14] nickel ($w = 1$ µm, $\gamma_{SFE}/\mu b = 6.3 \times 10^{-3}$) [52], copper ($w = 1$ µm, $\gamma_{SFE}/\mu b = 3.8 \times 10^{-3}$) [2] and 316L ($w = 0.7$ µm, $\gamma_{SFE}/\mu b = 1.1 \times 10^{-3}$) [28].

The occurrence of strain localization within underaged alloys results from a shearing process of precipitates [31] and depends on the space distribution and the size distribution of these precipitates. Not only these bands (namely shear bands, SBs) have a more complex structure than the structure related to classical PSBs, but they