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Motion of screw segments in the early stage of fatigue testing

Yichao Zhu [a,*], Stephen Jonathan Chapman [b]

[a] Department of Mathematics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong
[b] Mathematical Institute, Andrew Wiles Building, Radcliffe Observatory Quarter, Woodstock Road, Oxford, OX2 6GG, United Kingdom

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ABSTRACT

The motion of gliding screw dislocation segments in channel-veins and persistent slip band structure is analysed mathematically and the shape of these segments is determined. The model provides a possible explanation of the "length effect" of such dislocation segments observed in magnesium. Finally, the possible implications for the cross-slip of screw segments in fatigue testing are discussed.

1. Introduction

Dislocation structures in the early stage of cyclic fatigue tests under a constant strain amplitude have been well studied experimentally [2,4,12,14,19]. According to these experimental observations, the stress amplitude rises with the number of cycles typically for the first few thousand cycles. The microstructure at this stage comprises an assembly of veins (matrices) of long edge dislocations in multipolar configuration as shown in Fig. 1(a).

The veins are isolated by relatively dislocation-free channels, where some gliding dislocation segments connecting edges from different veins are observed. These segments are sometimes termed "screw segments" due to their predominantly screw characteristic. As the cyclic deformation proceeds, the stress amplitude reaches a constant value known as the saturation stress and a more regular "ladder" structure known as persistent slip bands (PSBs) starts to form. As shown in Fig. 1(b), these bands are characterised by regularly spaced high-density walls of edge dislocations. It is known that PSBs play an important role in the nucleation of cracks, which eventually gives rise to fatigue failure. The mechanism behind the transition from dislocation veins to PSBs is still unclear. Two factors seem to be essential for the formation of PSBs. The first is the behaviour of screw segments in the channels. How they respond to the cyclic load and in particular how they cross-slip is of great interest, since cross-slip of the screw segments is widely believed to be the mechanism for generating edge dipoles in the veins. The second factor seemingly responsible for the formation of PSBs is the self-arrangement of a large number of these multipoles into a regular ladder structure. We considered this second question by examining the equilibrium states of uniformly distributed dipoles [21]. Here we will focus on the role of the screw segments moving in the channels. We note that cross-slip mechanisms are also elementary in other plastic deformation processes [11,16].

In the literature there exist a number of models attempting to quantitatively reveal the elementary processes of the cross-slip mechanism (reviewed in [16], for example). Dislocations are usually split into Shockley partials with a stacking fault in between. Thus the cross-slip mechanism is effectively a result of many factors in aggregate, including the compression of the stacking fault ribbon, the strength of the stress component resolved in the cross-slip plane, the self-induced line tangent in the cross-slip plane, etc. For screw segments of curved dislocations (not pure screw any more), the situation is more complicated. This is because the geometry of dislocations at the mesoscopic scale, in which dislocations are treated as line singularities embedded in an elastic media, also plays a critical role. Computationally, cross slip of screw segments has been studied by using 3-d dislocation dynamical (DD) simulation (e.g. [6,7]) or molecular dynamical (MD) simulation (e.g. [18]).

The aim of this paper is to provide an explicit formulation of the sliding screw segment curves given various experimental conditions (stress, strain rate, etc.). With these analytical results one may explore the role of the screw segments in fatigue testing. The paper is arranged as follows. First, a travelling wave formulation of the screw segments is presented, followed by analysis to relate the

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[*] Corresponding author. Tel.: +852 235 87417; fax: +852 235 81643.
E-mail address: mayczhu@ust.hk (Y. Zhu).

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Nomenclature

$\boldsymbol{x}=(x_1,x_2,x_3)$	Cartesian coordinates
t	time
$\mathbf{b}; b$	Burgers vector; its magnitude
$\mathbf{e}_1,\mathbf{e}_2,\mathbf{e}_3$	orthogonal basis vectors corresponding to (x_1,x_2,x_3)
$\mathbf{q}$	parametrisation of the dislocation curve
$\mathbf{l}$	dislocation tangent
$\mathbf{m}$	normal to slip plane
$\mathbf{n}$	normal to dislocation within its slip plane
b_n, b_l	edge and screw components of the Burgers vector
θ	angle between the dislocation tangent and its edge component
κ	dislocation curvature
$\mathbf{v}$	dislocation velocity
u_0	translating speed of the screw segment
m_g	dislocation mobility
$\mathbf{M}$	mobility tensor
μ, ν	shear modulus and Poisson's ratio
$\boldsymbol{\sigma}$	stress tensor
σ^e	resolved stress
σ^{sat}	saturation stress
$\mathbf{f}$	Peach–Koehler force
$\mathbf{f}_{loc}$	self-force of a curved dislocation
L	typical radius of curvature of the dislocation
d	width of the screw segment
d_0	width of a screw segment when it has no motion
d_c	width of the cross-slip portion from a screw segment
d^v	measured average spacing between two centres of neighbouring veins
w^v	measured average width of veins
a	dislocation core radius
K_s	Schmid factor
ρ_s	number density of screw segments
$\dot{\mathcal{E}}_p$	plastic strain rate
ξ	critical angle for cross-slip to take place
	A hat on a variable indicates its non-dimensional equivalent

inputs of the model to the parameters characterising the experimental conditions. Then we use the results to provide a possible explanation of the experimental observation of the "length effect" of screw segments. Finally, the model is integrated with the experimental data to interpret the role of screw segments in fatigue testing.

2. Model formulation for the screw segments

If we look on the slip plane of a screw segment in Fig. 1(a), we can produce a schematic diagram showing the screw segment migrating in this plane, as shown in Fig. 2. We choose orthogonal Cartesian coordinates $\mathbf{x}=(x_1,x_2,x_3)$ in which x_1 is in the direction of the channel, x_2 across the channel, and x_3 normal to the slip plane, with corresponding orthogonal vectors $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$. The Burgers vector is then $\mathbf{b}=(0,b,0)^T$. We denote the position of the screw segment by $\boldsymbol{x}=\mathbf{q}(\theta,t)$, where the curve is parameterised by θ, the angle between $\mathbf{e}_1$ and the dislocation tangent $\mathbf{l}$ (see Fig. 2). The value of θ indicates the dislocation character at that point; it takes values from 0 to π, since the screw segment joins tangentially at its two ends with the edge segments from different veins. The width of the channel is denoted by d; we denote by $\mathbf{v}(\theta,t)$ the normal velocity of the screw segment, which may vary from point to point. Throughout we assume linear isotropic elasticity with shear modulus μ and Poisson's ratio ν.

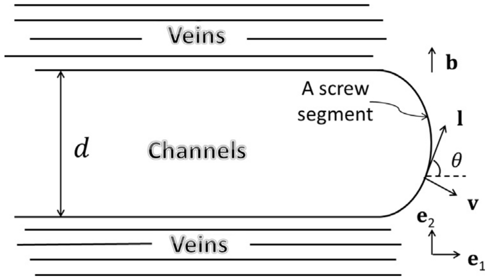

Fig. 2. Schematic diagram showing parameters needed to model the screw segments in this paper: a screw segment denoted by $\mathbf{q}$ of width d can be spatially parameterised by θ, the angle between $\mathbf{e}_1$ and the dislocation tangent $\mathbf{l}$. The screw segment moves in speed u_0, which may vary from point to point on the segment.

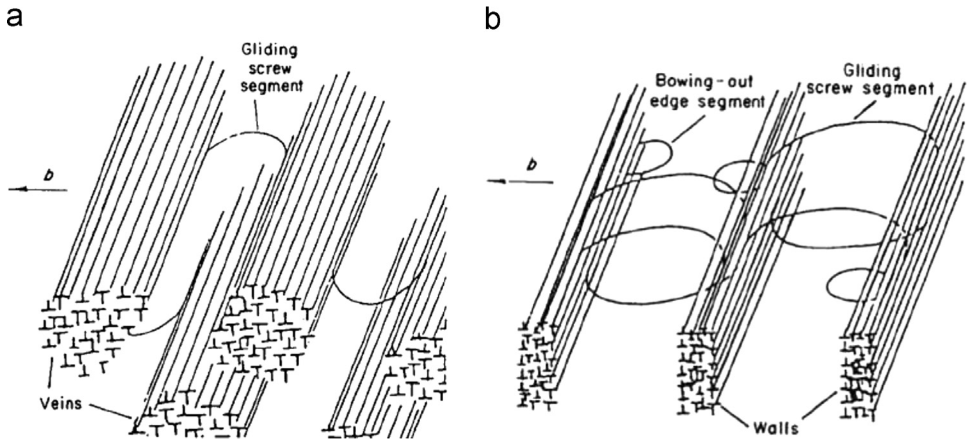

Fig. 1. Schematic diagram of the channel-vein structure and persistent slip bands (PSB): (a) before reaching the saturation point, the dislocation structure comprises an assembly of veins (matrices) of long edge dislocations in multipolar configuration; the veins are isolated by relatively dislocation-free channels, where gliding screw segments connecting edges from different veins are observed; (b) as the stress amplitude reaches the saturation point, a more regular "ladder" structure known as PSBs starts to form. (These illustrative figures are abstracted from [12].)