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On the nature of acoustic emission and internal friction during cyclic deformation of metals

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Abstract

A strong correlation between acoustic emission (AE) and internal friction (IF) has been established experimentally during rapid hardening of model copper polycrystals and single crystals deformed cyclically at constant plastic strain amplitudes. The difference between these two interrelated phenomena becomes pronounced when strain localization occurs in persistent slip bands or deformation bands. We demonstrate that the extension of the Kocks–Mecking–Estrin constitutive modelling approach to the cyclic deformation mode allows calculation of the major characteristics of both IF and AE in the same universal dislocation-based phenomenological framework, highlighting the fundamentally similar nature of both phenomena originating from elastic energy dissipation during plastic deformation.

Keywords: Acoustic emission, Internal friction; Single crystals; Dislocation damping; Dislocation kinetics

1. Introduction: fundamentals of plastic hysteresis during cyclic deformation

Plastic flow in a deforming crystal is a dissipative, inhomogeneous and non-equilibrium process driven by external stress as a function of time. This process gives rise to self-organization of dislocation ensembles into distinct patterns at different length scales with considerable spatial and temporal variation in the dislocation density, depending on the loading conditions. When the driven stress (or strain) is periodic in time, i.e. during cyclic plastic deformation, the dislocation patterning is particularly pronounced and is of particular interest. The modern acoustic emission (AE) technique paves a way to monitor the temporal evolution of dislocation structures in situ, thereby providing access to fine detail of the dynamic and statistical properties of the sound emission events arising from elementary dislocation reactions during fatigue of materials.

The phenomenology of cyclic plastic deformation is traditionally and most comprehensively described by the shape of the hysteresis loop such as that shown in Fig. 1 and its evolution during cycling. As a result of cyclic stress–strain analysis in model single crystals coupled with detailed microstructural investigations it has been established that at moderate imposed strain amplitudes an extended stress plateau follows the rapid cyclic hardening stage; the microstructure evolves from a network of loose dislocation loop patches to a cell or vein pattern with high dislocation density in the walls and then to development of persistent slip bands (PSBs) or deformation bands (DBs) emerging on a free surface during the plateau section of cycling [1–3].

Several parameters have been introduced to characterize the hysteresis loop shape during cyclic deformation with

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constant plastic strain amplitude ε_{pl_a}. The simplest and most widely used parameter of the hysteresis loop is the stress amplitude σ_a during a cycle. The progressive increase in σ_a in response to cyclic loading with a constant strain amplitude signifies cyclic hardening, whereas a reduction in σ_a is indicative of cyclic softening. Abel and Muir [4] have proposed that the hysteresis loop shape can be evaluated by the so-called energy parameter β_E in association with the Bauschinger effect, which plays a central role in the concept of fatigue damage and fatigue tolerance: β_E is defined as:

$$\beta_E = \left[4\sigma_a\varepsilon_{pl\_a} - \oint_{loop}\sigma d\varepsilon\right] \Big/ \oint_{loop}\sigma d\varepsilon \qquad (1)$$

and is aimed at relating, though implicitly, the plastic work ΔW dissipated during a cycle $\Delta W = \oint_{loop}\sigma d\varepsilon$ with the amount of the "reversibility" of slip due to the Bauschinger effect: a larger β_E value corresponds to a "pointer" hysteresis loop and to a larger Bauschinger effect. The most prominent feature of the β_E parameter is that it peaks as the strain localization in the first persistent slip band sets in. Similarly, Mughrabi [2] has proposed an energy-based parameter V_H to identify the formation of PSBs as $V_H = \oint_{loop}\sigma d\varepsilon / 4\sigma_a\varepsilon_{pl\_a}$. Hence, V_H is defined as the area enclosed by the loop divided by the area of the circumscribing parallelogram. Clearly, V_H and β_E are interrelated, i.e. $V_H = 1/(1 + \beta_E)$, so that when β_E increases, V_H decreases and maximum of β_E corresponds to the minimum of V_H at the onset of PSB formation and vice versa. The characteristic behaviour of β_E and V_H is illustrated in Fig. 2d as a function of the number cycles in [1 2 3]-oriented copper single crystal.

Although both V_H and β_E represent fatigue-specific parameters that depend on the amount of plastic work ΔW, and although both are highly sensitive to the hysteresis loop shape and to the onset of strain localization, neither of them has a simple physical meaning. In contrast, the internal friction (IF), which is defined using the same area ΔW of the hysteresis loop [5], can be clearly interpreted as a measure of the "efficiency" of an open mechanical system in the process of elastic energy dissipation. Of course, all transformations in the hysteresis loop shape are reflected in the behaviour of Q^{-1} in the same way as in β_E or V_H. Nevertheless, the amplitude-dependent IF, which is commonly associated with elementary dislocation reactions and dislocation–impurity interactions, has not been used widely to characterize the cyclic hysteresis in fatigue studies.

In this paper we are going to highlight the synergistic parallelism between AE and IF on one hand and, on the other, to delineate the difference between these two phenomena which are intimately related to energy dissipation in solids. AE is associated with the production of elastic waves by sudden local stress relaxation in the materials. IF (or damping) is known as an integral measure of the ability of a material to absorb and dissipate elastic energy imposed on the sample. Mechanical damping has been shown in many instances to be sensitive to deformation history, thermal treatments, phase transformations, impurity concentrations, microstructural changes, etc. AE is sensitive to the same issues too. However, no interrelation between these two evidently similar phenomena has been quantitatively established to date. This is probably because IF measurements are traditionally performed at very small elastic strains (far below the yield stress) where AE is hardly observable. However, both AE and IF can be concurrently measured in materials under intermediate plastic strains during cyclic deformation [6]. In essence, all IF techniques rely on the amount of mechanical energy dissipated in response to the strain imposed. The ratio

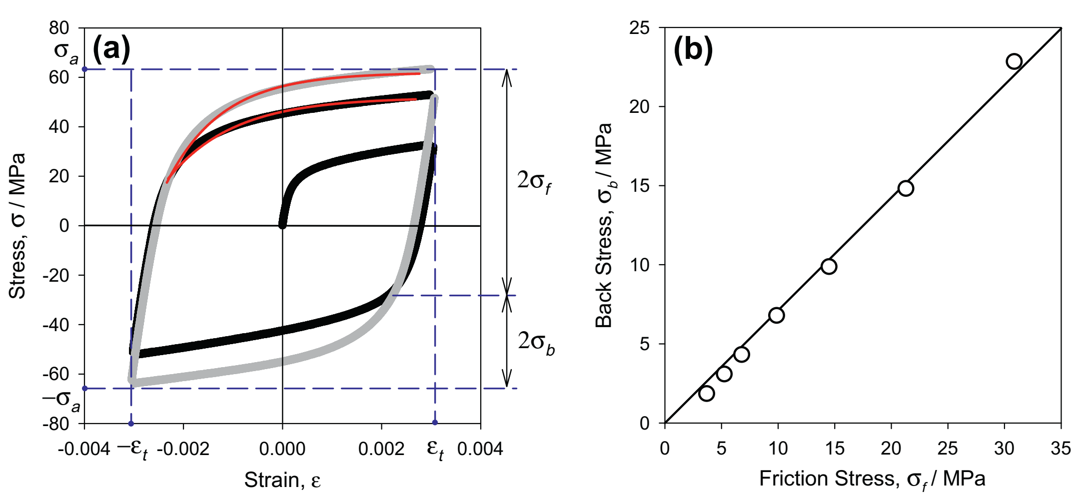

Fig. 1. Schematic illustration of the cyclic hysteresis loop plotted as a function of the plastic strain (*a*): σ_a is the stress amplitude and ε_t is the total strain amplitude; experimental data adopted from Ref. [47], showing proportionality between σ_b and σ_f in cyclically deforming copper single crystal (see Ref. [47] for experimental details and procedures used to derive σ_b and σ_f).