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Correlation between band propagation property and the nature of serrations in the Portevin–Le Chatelier effect

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Abstract—We investigate the correlation between the band propagation property and the nature and amplitude of serrations in the Portevin–Le Chatelier effect within the framework of the Ananthakrishna model. Several significant results emerge. First, we find that spatial and temporal correlations continuously increase with strain rate from type C to type A bands. Consequently, the nature of the bands also changes continuously from type C to A bands, and so do the changes in the associated serrations. Second, even the smallest extent of propagation induces small amplitude serrations. The spatial extent of band propagation is directly correlated with the duration of small amplitude serrations, a result that is consistent with recent experiments. This correspondence allows one to estimate the spatial extent of band propagation by just measuring the temporal stretch of small amplitude serrations. Therefore, this should be of practical value when only stress versus strain is recorded. Third, the average stress drop magnitude of the small amplitude serrations induced by the propagating bands remains small and nearly constant with strain rate. As a consequence, the fully propagating type A bands are in a state of criticality. We rationalize the increasing levels of spatial and temporal correlations found with increasing strain rates. Lastly, the model also predicts several band morphologies seen in experiments including the Lüders-like propagating band.

Keywords: Portevin–Le Chatelier effect; Plastic instability; Band types; Small amplitude serrations; Dynamical approach

1. Introduction

The Portevin–Le Chatelier (PLC) effect is one of the most intriguing spatio-temporal instabilities in metallurgy that has continuously attracted the attention of scientists for over half a century due to its technological and scientific importance [1]. The PLC instability is found when dilute metallic alloys are deformed under constant strain rate conditions [1]. The instability manifests itself as irregular stress serrations in a window of strain rates $\dot{\varepsilon}_a$ and temperatures T [2–5]. Conventionally, three types of plastic deformation bands have been identified [2–12]. For a range of low strain rates, randomly nucleated static type *C* bands are seen along with large amplitude nearly regular serrations. At intermediate strain rates, bands are formed sequentially one ahead of the other identified as the 'hopping' type B band. The serrations are smaller and more irregular. At high $\dot{\varepsilon}_a$ the continuously propagating type A bands are seen and the associated stress drops are even smaller. The instability domain typically spans two to three orders of magnitude in strain rate. Despite the enormous attention, there is a lack of clarity regarding several aspects relating to the band types, their propagation property and its influence on the nature of serrations. The purpose of this paper is to identify these issues and answer them within the context of the Ananthakrishna (AK) model for the PLC effect.

The original model due to Cottrell [13,14] has been revisited by several authors [15–17]. The basic mechanism of the instability is attributed to the interplay of two time scales, one corresponding to the waiting time of dislocations temporarily arrested by forest dislocations and the other to the diffusivity of solute atoms. When the two time scales are very different, either the dislocations are immobilized by solute atoms (low $\dot{\varepsilon}_a$ or high T) or they see solute atoms as immobile obstacles (high $\dot{\varepsilon}_a$ or low T). In the region where these two time scales differ less, a competition between the two mechanisms sets-in. Lower strain rates or longer waiting times allow higher solute concentrations at the dislocations leading to a higher unpinning stress. This in turn induces negative strain rate sensitivity. This phenomenon is called dynamics strain aging (DSA). When the stress reaches the critical unpinning value, the unpinned dislocations move at high velocities only to be arrested by obstacles. From a dynamic point of view, the slow pinning of dislocations and their abrupt unpinning induces negative strain rate sensitivity [2,3,16–20]. However, as dislocation interactions have their own positive strain rate sensitivity, no instability can occur as long as the total strain rate sensitivity is positive. The PLC instability sets-in when

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the orders of magnitudes of the two mobilities are similar inducing a negative total strain rate sensitivity (SRS) of the flow stress [2,3,16–20]. Indeed, the negative SRS feature, in one form or the other, is used in most models of the PLC effect [6,7,21–23].

Early PLC studies attempted classifying different types of serrations based on their geometric waveforms alone. The first study that correlates the band types with their waveforms using the band propagation property is due to Chihab et al. [8]. The study identifies type C, B and A along with features that are common to C–B and B–A. Even now, there are fewer studies that correlate the propagation property of the band types with the nature of serrations [6–12]. Indeed, recent advances in experimental techniques such as laser extensometer, laser speckle interferometry and infrared pyrometry have been instrumental in establishing correlation between band types and serrations [6,7,9,10,12].

While the above phenomenological classification is generally accepted [2–5], several conceptual questions remain unanswered. First, questions have been raised whether the transitions between the band types are smooth or abrupt, and what mechanisms cause these transitions (see for example Ref. [12]). While these questions may be difficult to answer in experiments since it would require experiments at fine intervals of strain rates, it can be clearly addressed in models, which however has not been addressed so far. Indeed, the very fact that the entire instability domain of three orders of magnitude in $\dot{\varepsilon}_a$ is classified into *just three regions* of type C, B and A bands, with no changes presumed to occur within each regime, may simply be an artifact of measurements at few values of strain rate. It is therefore conceivable that the changes could be continuous. Second, there is lack of clarity about the mechanisms that lead to increasing extent of band propagation accompanied by the decreasing trend of serration amplitude. Thirdly, based on an intuitive picture of band propagation that less stress would be required to keep the band in the propagating mode than to nucleate an isolated band, we conjuncture that a propagating band induces serrations whose magnitude is small relative to the stress drop for nucleating an isolated band (as in the type C band regime). This is equivalent to stating that considerable information about band propagation property is contained in the stress–strain curves. Early studies on the three different types of serrations were presumably directed at this. However, since stress is the spatial average of dislocation activity in the entire sample – a one to many correspondence – establishing this connection appears questionable. On the other hand, during propagation dislocation activity at any given time is localized and therefore stress is determined largely by the dislocation activity confined to this small spatial extent. This implies that there should be some correlation between the nature of serrations and band propagation. *It would therefore be interesting to examine whether the temporal extent of small amplitude serrations can be identified with the band propagation distance.* All these issues will be addressed in the context of the AK model for the PLC effect [24–30]. This also provides us an opportunity to carry-out a detailed study of the AK model that has not been reported so far.

Most models for band propagation use local strain, strain rate, negative SRS of the flow stress, activation enthalpy of dynamic strain aging, waiting time, etc. [6,7,21–23]. On the other hand, relating irregular stress signals to the collective pinning and unpinning of dislocations had remained a difficult task for a long time till the introduction of the AK model [3,24,25] due to lack of techniques for describing the cooperative behavior of dislocations and lack of dislocation based models. The natural ability of nonlinear dynamical approaches to describe collective effects is instrumental in the AK model *capturing most generic features of the PLC effect including the three types of bands* [24–30]. Therefore, the model is most appropriate for investigating the connection between the propagative nature of the bands and the consequent changes in the stress serrations.

2. The Ananthakrishna model

The basic premise of the AK model is that most generic features of the PLC effect such as the existence of the instability in a window of strain rates and temperatures, negative SRS of the flow stress, etc., emerge from the nonlinear interaction of a few collective degrees of freedom assumed to be represented by a few dislocation populations [20,24–27,31]. One prediction that is specific to the original bare model (which ignores the spatial degrees of freedom) is that stress drops could be chaotic at low strain rates [32]. This prediction has been subsequently verified using experimental signals from single and polycrystals [33–36]. Further analysis of experimental stress–strain curves at high $\dot{\varepsilon}_a$ (corresponding to type A bands) showed a scale free power law distribution for the stress drop magnitudes and durations [34–36]. The inclusion of spatial degrees of freedom not only predicts the different types of bands, but also recovers the power law distribution of stress drop magnitudes observed at high $\dot{\varepsilon}_a$ [2,3,26–28,37].

The AK model uses three types of dislocation populations, namely, the mobile ρ_m, the immobile ρ_{im}, and dislocations with solute atoms ρ_c. As we shall see ρ_{im} includes not just immobile dislocations arising from the formation of locks and junctions, it also includes dislocations immobilized by solute atoms. The conceptual framework of DSA is represented by dislocations with solute atoms ρ_c. The model equations have been written down in a number of previous publications, which, however, were mostly in the scaled form [2,3,26–30]. Here, we use unscaled equations with a view to explain the various dislocation mechanisms that have not been presented so far. We will also discuss how most of the theoretical parameters that go into the model equations can be estimated.

The evolution equations for the three densities and stress take the form

$$\frac{\partial \rho_m}{\partial t} = -\beta\rho_m^2 - p\beta\rho_m\rho_{im} + \gamma\rho_{im} - \alpha_m\rho_m + \theta v_0\left(\frac{\sigma_{eff}}{\sigma_y}\right)^m \rho_m + \frac{\Gamma\theta v_0}{\rho_{im}}\frac{\partial^2}{\partial x^2}\left(\frac{\sigma_{eff}}{\sigma_y}\right)^m \rho_m, \quad (1)$$

$$\frac{\partial \rho_{im}}{\partial t} = \beta\rho_m^2 - p\beta\rho_m\rho_{im} - \gamma\rho_{im} + \alpha_c\rho_c, \quad (2)$$

$$\frac{\partial \rho_c}{\partial t} = \alpha_m\rho_m - \alpha_c\rho_c, \quad (3)$$

$$\frac{d\sigma_a}{dt} = E^*\left[\dot{\varepsilon}_a - \frac{b}{L}\int_0^L v_0\left(\frac{\sigma_{eff}}{\sigma_y}\right)^m \rho_m dx\right] = E^*[\dot{\varepsilon}_a - \dot{\epsilon}_p(t)]. \quad (4)$$

The first term in Eq. (1) refers to the immobilization of two mobile dislocations due to the formation of locks and junctions. The second term refers to the annihilation of a