Comment on "Portevin–Le Chatelier effect"

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Instabilities of plastic flow in alloys and the associated deformation patterns are currently attracting a lot of attention. We comment on a recent investigation by Franklin *et al*. [Phys. Rev. E **62**, 8195 (2000)] on one such type of instability, the Portevin–Le Chatelier effect, attempting to clarify a few points about the instability mechanism as well as the reported experimental results.

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In a recent paper by Franklin *et al*. [1], a phenomenological model for the Portevin–Le Chatelier (PLC) effect, i.e., for repeated plastic instabilities and the propagation of bands of localized deformation in aluminum (actually a commercial alloy) is discussed. The experimental data reported can also be found in [2].

The motivation for commenting on this work is as follows. First, we believe that the present understanding and level of modeling of the PLC effect is more sophisticated than suggested in [1], particularly regarding the nonlinear and spatiotemporal aspects. To illustrate this point, we provide an account of the present state of the art and the way it suggests guidelines for incorporating basic physical mechanisms into phenomenological modeling. Second, the proposed model contains assumptions that are quite at variance with current views upon the nature of the instability, as described in the existing literature. Finally, we wish to make a few observations regarding the experimental results themselves. In what follows, an attempt is made to list and discuss these points. To this effect, some basics of the PLC instabilities are first recalled.

In dilute alloys deformed at medium temperatures, the mobile dislocations interact with solute atoms that diffuse towards their cores while they are temporarily arrested at obstacles. This induces an increase of the glide resistance with increasing dislocation waiting time at the obstacles and decreasing average dislocation velocity. This dynamic aging is maximum when the two defect populations have comparable mobilities. Therefore, the effect occurs only within a finite range of temperatures and applied strain rates, the former essentially governing the solute diffusivity and the latter the average dislocation velocity. Within this range, the dislocations exhibit a portion of negative stress versus velocity dependence, which corresponds to an unstable state.

At a macroscopic scale this mechanism translates into a spatially correlated behavior of the dislocations and a nonuniform plastic deformation. The unstable behavior is bistable, with dislocations collectively jumping between two states outside the unstable range, one with slow dislocations dragging solute atoms, the other with fast unpinned dislocations. This state corresponds to the PLC bands. Sometimes visible to the naked eye, these bands have been extensively described in the past (cf., e.g., Ref. [22] of [1]). The reasons for the strong correlated behavior of the dislocations and the origin of their spatial coupling are the object of ongoing theoretical and experimental studies [4–7].

Since the model [1] is not based on defect properties, it cannot, in our opinion, capture important characteristic features of the PLC effect like its occurrence within a finite range of applied strain rates and temperatures, or the influence of solute concentration on jerky flow. For instance, the relation between stress and nonlocal strain rate, which is sketched as a uniformly decreasing one in Fig. 4 of [1] implies that there is no upper bound to the instability domain. The related constitutive equation (17) of [1] incorporates a central nonlinearity represented by a negative step function having no *extended* range of negative strain rate sensitivity. In such conditions, the ability of the model to predict experimental features is not assured at high strain rates, precisely in the range of interest in [1], where the PLC bands propagate in a continuous manner along the specimen gauge length.

The conclusion (7) of [1] reads: "homogeneously deforming samples show negative strain rate sensitivity at large strains." Similar statements can be found in the text, for instance "experimental observations of negative strain rate sensitivity have involved homogeneously deforming samples" and "negative strain rate sensitivity can only be observed in a homogeneously deforming sample." Unless we have misunderstood them, these statements, which are central to the discussion of the model, are not in agreement with known theories of plastic instabilities. The strain rate sensitivity (i.e., the local derivative of stress with respect to strain rate) is positive under normal conditions. It is intuitive that when this quantity locally takes on negative values, homogeneous plastic flow is unstable with respect to any fluctuation in strain rate, since the latter can increase under decreasing stress [3]. We assume that these generally agreed facts are not questioned in [1], but only aspects connected to propagating fronts. Based on a previous study (Ref. [17] of [1]), they are considered as unable to explain the occurrence of propagating fronts. As this is not the appropriate place for discussing this earlier study, we only wish to emphasize that other models are not subject to this limitation. A possible source for the absence of moving fronts is that the analysis should include, in addition to gradient forms, a condition expressing that the elastic plus plastic strain, which is the total strain, is controlled by the deformation machine (cf., e.g., [4]). For instance the model presented in [5,6] (see also [7]) does predict the properties of all the types of bands, including the continuously propagating ones.

Since the early work of Penning (cf., Ref. [13] of [1]), who discussed its mathematical aspects, the negative strain rate sensitivity is incorporated in virtually all physically based or phenomenological models for the PLC effect. Its macroscopic aspect, viz. the occurrence of a domain of negative strain rate sensitivity has also extensively been checked by highly accurate experiments, including in the domain of propagating PLC bands [8]. Some confusion arose in early studies due to inaccurate measurements of the strain rate sensitivity (cf., Ref. [15] of [1], where the strain is erroneously considered as a state parameter). Thus, the statement that ''the rate dependence of the flow stress is not known with certainty because interpretation of experiment .. is difficult'' is perhaps no longer representative of the present situation. Indeed, this issue has been definitely settled in a seminal paper [3]. The domain of occurrence of the PLC effect and that of the global (measured) negative strain rate sensitivity are found to approximately coincide. Actually, with increasing strain, PLC instabilities start when the strain rate sensitivity becomes slightly negative. The reason for this small shift is also well understood in terms of transient behavior of the solute concentration on dislocations as the microstructure evolves during straining (cf. [4] and Ref. [16] of [1]). As is made fully clear in Ref. [16] of [1], PLC instabilities never set in when the measured strain rate sensitivity is positive.

We now turn to some aspects of the experimental results that also deserve comment. Considering the data shown in Fig. 10 of [1], it appears that the strain rate sensitivity associated with the regime of continuously propagating bands is positive and tends towards zero for pulling velocities of the order of 1000 μm/s. After a transient (cf. Fig. 13 of [1]), it also shifts from positive at small strains to negative at large strains. These results are not easy to understand since band propagation occurs and deformation is heterogeneous. Furthermore, as mentioned above, the bulk of existing experiments (cf. Ref. [22] of [1] and the reviews [3,4,7]) indicate that the average stress level always decreases with increasing pulling velocity. The physical reason is simply that less solute concentration is able to diffuse to and pin the dislocations when they move faster, i.e., with smaller waiting times. This contrasts with what is shown in Figs. 7 and 10 of [1] where band propagation is associated with increasing stress levels as a function of pulling and front velocity (these two quantities are proportional to each other, see Fig. 8 of [1]). Finally, some data seem to be mutually not consistent. For instance, the load level at the velocity of 1300 μm/s is not the same in Figs. 10 and 11 of [1]. Further, it seems difficult to make a correspondence between the stress levels for front propagation deduced from Figs. 2(a) and 2(b) and 3 in [2] and those indicated in Fig. 5 of [2] or Fig. 10 of [1]. In these last two figures, some data points are indicated, that would correspond to a negative (i.e., compressive) ''pulling'' velocity.

The types of PLC bands (cf. Ref. [3] of [1]) can be understood in terms of a competition between two time scales. One is the reloading time between two jerks, which decreases with increasing strain rate. The other is a characteristic time associated with the relaxation of the amplitude of the spatial correlations. With increasing pulling velocity or strain rate, one observes successively random band nucleation, as the spatial correlations are fully relaxed during reloading, spatially correlated nucleation events occurring one after the other (the so-called ''hopping bands'') and more continuous propagation at the highest strain rates when relaxation of the spatial correlations has no time to occur. The random type of bands are not investigated in [1,2], probably because sufficiently low strain rates were not tested. For the same reason, the domain of occurrence of the hopping bands that should extend over at least two orders of magnitude in strain rate is not examined. Further, the band shown in Fig. 1 of [1] and Fig. 1 of [2] could as well be interpreted as a hopping one, considering the observed pseudoperiodic roughness of the surface behind the front.

In summary, we wish to show that on the basis of a large body of careful experimental results and theoretical modeling, the understanding of the PLC effect has substantially progressed in the past 20 years. The relations between solute diffusion on dislocations, negative strain rate sensitivity, onset of plastic instabilities, and types of PLC bands or fronts are now well documented in many alloys. They have been incorporated with some success into present models. Thus, the absence of a physical basis for the constitutive behavior of the model [1] is at variance with the present state of the art of the PLC effect.

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[1] S. V. Franklin, F. Martens, and M. Marder, Phys. Rev. E **62**, 8195 (2000).
[2] F. Martens, S. V. Franklin, and M. Marder, Phys. Rev. Lett. **78**, 4502 (1997).
[3] U. F. Kocks, Prog. Mater. Sci. **19**, 185 (1981).
[4] M. Zaiser and P. Haehner, Phys. Status Solidi B **199**, 267 (1997).
[5] M. A. Lebyodkin, Y. Bréchet, Y. Estrin, and L. P. Kubin, Phys. Rev. Lett. **74**, 4758 (1995).
[6] M. Lebyodkin, L. Dunin-Barkowskii, Y. Bréchet, Y. Estrin, and L. P. Kubin, Acta Mater. **48**, 2529 (2000).
[7] L. Kubin, C. Fressengeas, and G. Ananthakrishna, *Dislocations in Solids*, edited by F. R. N. Nabarro (North-Holland, Amsterdam, in press).
[8] Ch. Schwink and A. Nortmann, Mater. Sci. Eng. A **234–236**, 1 (1997).