Dynamics of Plastic Deformation Fronts in an Aluminum Alloy

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Forming aluminum alloys into desired shapes has long been hampered by undesired propagating fronts of plastic flow. We have performed experiments to investigate these fronts to find what causes their motion and what determines their velocity. A simple phenomenology quantitatively captures many experimental details, most importantly the propagation of the fronts at constant stress and the transition between hopping and continuous front motion. [S0031-9007(97)03401-7]

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At first it seems obvious that a piece of metal should smoothly lengthen the harder one pulls. However, as long ago as 1837 Savart [1] noticed in experiments on copper strips that sometimes small increases in applied force resulted in large changes in length, while other times large increases in force produced little, if any, extension. Portevin and Le Chatelier [2] were the first to study systematically these discontinuities. A plot of applied force versus length revealed serrations and steps which persisted until the sample broke, and the phenomenon now bears their names.

In the decades since, much has been learned about the Portevin–Le Chatelier effect. Each serration in the stress-strain curve corresponds to the initiation and propagation of a visible front that travels along the sample. The motion of these fronts has been investigated under a variety of loading conditions and geometries [3,4], and a transition has been observed [3] from hopping to continuous front motion as the extension rate is increased. Fronts begin only after an initial uniform plastic strain, as first discussed by Cottrell [5]. The dependence of this critical strain on temperature, loading conditions, and specimen geometry has been investigated [6–8]. The Portevin–Le Chatelier effect has been linked to the observation that samples deform more easily at higher strain rates [9–11]; models relating this fact to dislocation dynamics have been explored [4,12–14].

Only one piece of the puzzle has eluded explanation: the speed at which fronts travel. Progress was difficult, in part because of an inconsistency between two well-regarded experiments. One found that front velocity vanished as loading rate went to zero [15], while the other found that the velocity appeared to diverge [16].

In hopes of clarifying this situation we began experiments and modeling that focused on the behavior of a single front. We found it necessary to disassemble many of the conclusions that had previously been reached [17] and to reassemble them into a new phenomenology that captures the essential features of the experiments.

Experiments.—We isolate the first front to pass through the sample and focus on its behavior. Experiments are conducted with commercial polycrystalline aluminum-magnesium alloy samples (type 5052) with a nominal content of 2.5% magnesium and 0.25% chromium. The bone-shaped (see Fig. 1) samples have a gauge length of 102 mm, are 12.7 mm wide, and 1 mm thick. One end of the sample is fixed while the other is displaced at a constant speed. We measure the force needed to maintain this constant speed and acquire video images of the fronts. From the force measurements we can calculate a nominal stress (force/area), assuming a cross-sectional area of 12.7 mm² for all samples.

We visualize the fronts with the shadowgraph technique [18] common in hydrodynamics. The sample is polished, and parallel light is reflected from it. Any roughening of the surface creates divergences of the parallel light, which are then detected by a video camera focused slightly off of the sample surface. Profilometer measurements show that this technique detects deformations of less than 1 μm. A deformation front visualized in this way is shown in Fig. 1.

Obtaining a single front to study is not straightforward. Fronts usually form in pairs at a weak point in the sample
and then move in opposite directions, stopping when they reach the ends. If the fronts form close to one end of the sample, then one front hits an end and is pinned first. We wait for this to happen and then stop pulling, halting the remaining front in the middle of the sample. We then begin the experiment by pulling at the desired speed. The remaining front resumes motion in its original direction. By stopping and then restarting the experiment we are able to investigate the dynamics of single front initiation, as well as subsequent motion.

Results for three different pulling speeds are shown in Fig. 2. Each shows the elastic reloading of the sample until a yield point is reached. The initial motion of the front is accompanied by a sudden drop in stress. For the slowest pulling speed [Fig. 2(a)] this drop is sufficient to stop the front. Plastic deformation stops and the sample must again reload to the yield point, producing a sawtooth pattern. The video camera captures the hopping motion of the front; each hop covers a distance comparable to the front width (≈1 mm). For faster pulling speeds, the stress drop no longer stops the front. The front travels at a constant velocity, as can be seen from the smooth space-time plots in Figs. 2(b) and 2(c). The stress is roughly constant, becoming smoother at still faster pulling speeds. Once the pulling stops the stress decreases slightly while the front slows to a stop, as seen in Fig. 2(c).

Figures 2(b) and 2(c) show that deformation fronts travel with constant velocity at constant stress [19]. This fact may explain the inconsistencies between prior experiments [15,16], in which the stress slowly increased during the experiment. Figures 2(b) and 2(c) show that if the pulling speed is increased, front velocity changes proportionally. Figure 2 also shows that when the sample is pulled 50 μm the front moves 6 mm regardless of how fast the sample is pulled. The total distance the sample grows is just the distance the front moves multiplied by the strain jump across the front $\Delta \epsilon_p$ [see Eq. (5)]. Since the distance the front moves is independent of pulling speed, $\Delta \epsilon_p$ is also unchanged as one pulls faster.

In addition, Figs. 2(b) and 2(c) show that the steady state stress level changes little even when the pulling speed increases by an order of magnitude. We explored this phenomenon further in an experiment in which the pulling speed abruptly increases fivefold. Figure 3 shows that the stress increased only by about 1%.

Phenomenology.—Our phenomenology is based on three well accepted ideas: (i) As a sample deforms plastically the applied force is reduced. The observed magnitude of this effect depends on the stiffness of the machine pulling the sample. (ii) A sample begins to deform plastically when the stress exceeds a critical value, the yield stress. (iii) The yield stress can decrease as the sample deforms more quickly. This negative strain-rate sensitivity plays a crucial role in the Portevin–Le Chatelier effect and is believed to result from interactions of dislocations with impurities in the aluminum.

Our equations follow from these ideas. The stress on the sample $\sigma$ is related to machine stiffness $\mu$, end
displacement $X(t)$, and plastic strain $\varepsilon_p(x,t)$ through the machine condition

$$\sigma = \mu \left[ X(t) - \int_0^L dx' \varepsilon_p(x') \right]; \quad \mu = \frac{KE}{KL + EA}, \quad (1)$$

where $\mu$ depends on specimen geometry (original length $L$, and cross-sectional area $A$), Young’s elastic modulus $E$, and the spring constant of the machine $K$. We can measure $\mu$ directly from the elastic part of the force versus length curve.

The rate of deformation is proportional to the difference between the applied stress, $\sigma$, and the yield stress, $\sigma_y$. This gives (when $\sigma > \sigma_y$)

$$\dot{\varepsilon}_p = \frac{\sigma - \sigma_y}{\tau_1 E}, \quad (2)$$

where $E$ is Young’s modulus and $\tau_1$ is a time constant. We measure $\tau_1$ to be $\sim 50 \mu s$.

The phenomenology of the negative strain-rate sensitivity is contained in an expression for the yield stress, which is assumed to be the product of two terms. Rate-independent effects are described by a function $\sigma_y^0(\varepsilon_p)$ (approximately $\sqrt{\varepsilon_p}$ [20]). Rate-dependent effects are contained in the function $f(a)$ (see Fig. 4); its argument $a(x,t)$ describes a population of mobile, or active, dislocations. $f(a)$ decreases as $1 - a$ until $a = a_c$; for $a > a_c$, $f(a)$ is constant. We measure $a_c$ to be 0.12 (it is dimensionless), independent of pulling speed. The total yield stress $\sigma_y(x,t)$ is then

$$\sigma_y(x,t) = \sigma_y^0(\varepsilon_p) f(a). \quad (3)$$

Finally, we relate the production of the active dislocation field $a(x,t)$ to the strain rate $\dot{\varepsilon}_p$. Active dislocations are produced whenever the strain rate is nonzero, but their presence is not limited to the point where they are created; they fly off across a characteristic distance $l$. The active dislocations are then destroyed by some pinning process on a time scale $\tau_2$. The equation embodying these ideas is

$$\dot{a}(x,t) = \lambda \frac{1}{\tau_2} \int_{x-l}^{x+l} dx' \varepsilon_p(x') - \frac{a}{\tau_2}. \quad (4)$$

The emission of dislocations is the mechanism by which fronts propagate. As a point in the sample deforms, it sends out mobile dislocations which weaken the neighboring material. This weakened material begins to deform, sends out new dislocations, and the process spreads.

**Experiment and Theory.**—Equation (1) predicts that if fronts move at constant velocity, they must do so at constant stress. Our first experiments attempted to impose a constant, preset force on the sample and then measure the front velocity. These attempts failed since deformation fronts moved at whatever speed was necessary to produce their own desired stress level, rather than the stress aimed at by the testing machine controller.

For the sample to maintain a constant stress it must deform so that $\dot{\sigma} = 0$. Assuming all fields to be in steady state at velocity $\nu$ and differentiating (1) then gives

$$\dot{X} = \int_0^L dx' \varepsilon_p(x') = \int_0^L dx' \frac{\partial \varepsilon_p(x')}{\partial x'}\frac{\partial a(x')}{\partial x'} = \nu \Delta \varepsilon_p, \quad (5)$$

where $\Delta \varepsilon_p$ is the jump in strain across the moving front. $\Delta \varepsilon_p$ is measured to be roughly constant; therefore, front velocity $\nu$ is proportional to pulling speed. Figure 5 shows that the pulling speed, and hence front velocity, changes by orders of magnitude when the applied stress changes by just a few percent.

Minute changes in stress cause large changes in front velocity both in model and experiment. The smooth line in Fig. 5 is obtained from our model using the parameters given in Table I. Although our phenomenological equations have so far been applied only in a single spatial dimension, they give good quantitative agreement with almost all features of the experiment using a single set of parameters. Figure 2 shows that the theory also captures the stress drop which accompanies front initiation and the transition between smooth and hopping [21] front motion. Front widths and strain jumps across the front are also consistent between theory and experiment. Finally, the theory
predicts, in accord with experimental observation, that new fronts will propagate at a sequence of successively higher yield stresses, a phenomenon we do not have space to discuss here.

While many features of deformation fronts in aluminum alloys have previously been observed and explained, the experimental and theoretical picture we have painted is essentially different from those treatments. Our experiments are different, and we use different mathematical forms than have been customary. This perspective clarifies conflicting prior claims and captures the essential features of the fronts. One eventual goal of this line of research is to understand deformation fronts well enough to predict processing steps and alloy compositions that eliminate them in practical circumstances. To this end we have presented the first close quantitative comparison between experiment and phenomenology of a single deformation front.

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[19] Constantly increasing stress would clearly be needed in a sample where the work hardening increased along the length; however, such strain gradients appear only after many bands have propagated, and are not reproducible.
[21] In the hopping regime the deformation occurs along alternating planes, like a washboard, so we do not expect quantitative agreement in this regime with a one-dimensional theory.