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Strain-rate fluctuations during macroscopically uniform deformation of a solution-strengthened alloy

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Using a work-hardened aluminum alloy that exhibits dynamic strain aging, oscillations in strain rate transitioning into intermittent local plastic activity are observed through an extended elastoplastic transition, before onset of the Portevin–Le Chatelier effect. Fourier analysis confirms this intermittency spans multiple scales. Wavelet analysis provides a method of quantifying transitions in the deformation behavior in both the time and frequency domains, and reveals a period doubling transition in both the local strain rate and global load signals.
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The classical assumption of homogeneous plastic deformation has come under scrutiny, as a result of various experimental findings. Extreme cases of localized deformation leading to macroscopic serrations on deformation curves, such as the Portevin–Le Chatelier (PLC) effect in alloys, have been studied for decades [1]. However, at stress transients much lower than those responsible for the PLC effect, intermittency in plastic deformation has attracted less attention, although the first observations of this were made long ago [2,3]. Recent experiments using acoustic emission and various optical techniques reveal a power-law scaling of the deformation events during "smooth" deformation, which was attributed to avalanches in the dislocation ensemble—a nonlinear dynamic system with a large number of degrees of freedom [4–6]. Another type of plastic deformation response that suggests a reduction in dimension of the system lies in the synchronous motion of plastic domains, which appears as propagating or stationary waves at different work-hardening stages [7–10]. Such coordinated plastic activity has also been observed about the elastoplastic transition in Ref. [4] and the wave velocity appears to be related to the degree of work hardening [11]. As in the case of intermittent dislocation avalanches, these "autowaves" do not have the strain magnitude associated with a plastic burst developed in the PLC effect, and several regions of plastic activity—i.e. deforming at a higher strain rate relative to the bulk—may be developed. This form of synchronization at the scale of the specimen appears to be found in a variety of metals, and the development does not rely on the presence of a specific mechanism that leads to plastic instability (such as the PLC effect).

Characterization of the dynamics of the PLC effect has served to draw a connection between the PLC effect and the more general plastic response of metals through dislocation avalanches, fitting well into the picture of universality [5]. The classic tensile test presents a wealth of dynamics that are representative of stick–slip systems from a more general perspective, and are also accessible through models. It is documented that the onset of the PLC effect occurs after a critical strain value before which macroscopically smooth loading and plasticity is observed. It is generally agreed that the PLC effect is a manifestation of dynamic strain aging, due to solute atoms diffusing to temporarily pinned dislocations. When the stress level becomes high enough to unpin the dislocations in collective fashion, a localized region of the material deforms, forming a macroscopic band visible on the surface of the material. The behaviors

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observed have been characterized into several types including propagating and static deformation bands replacing each other with varying applied strain rates. Analysis of the dynamics for different types of PLC behavior yields scale invariance, which may show up in statistical distributions or be uncovered via more complex, e.g. multifractal, analysis [12–14].

In the analysis and interpretation of the PLC effect, emphasis is generally placed on the constitutive response, which may be considered to be a specialization of a velocity weakening stick–slip law. Quasi-static elastic response then serves to provide spatial coupling in the presence of localized plastic relaxation. Continuously propagating or hopping bands are routinely developed in such simulation procedures [13,15]. In the case of hopping bands, the analysis of deformation curves clearly demonstrates a tendency for a system with an intrinsic high dimensionality to organize in such a manner so as to present a low dimension [13].

More specifically, the present study attempts to answer the question of what the local deformation characteristics look like in a dynamically strain-aging material before the onset of macroscopic instability. We show that synchronous oscillations are developed in a solution-strengthened aluminum alloy during an extended elastoplastic transition. The evolution of the oscillations with straining is not continuous but displays several transitions despite the macroscopically smooth appearance of the average trend. Period doubling is demonstrated in both the load signal and spatiotemporal data derived from digital image correlation. During the plastic response, before the onset of macroscopic serrations, dynamics consistent with those observed for other metals are observed. The key offering that follows from the present work lies in a demonstration of both autowaves and power-law behavior of stress fluctuations in a single tension test, during microplasticity in the initial loading and upon yield, respectively.

The material used in this experiment was an Al–Mg alloy, Al5052-T0, which contains 2.5% wt. Mg. The specimens were cold rolled to a strain of approximately 200% and a thickness of 0.84 mm. X-ray diffraction patterns showed the material had a preferred crystallographic texture typical of a rolled face-centered cubic metal. Specimens with a gage length of 38.0 mm and width of 12.7 mm were pulled in tension at a constant crosshead displacement rate corresponding to an average applied strain rate of $3.2 \times 10^{-6}\,\mathrm{s}^{-1}$ in a compliant screw load frame. An extensometer was used on some samples to collect average strain data. These experimental conditions result in a high critical strain for the onset of PLC instability in this alloy. Prior to testing, the specimens were painted with a speckle pattern in order to perform digital image correlation (DIC). The 2-D local strain field was calculated from the DIC data and image correlation software, Vic-2D [16], and then differentiated with respect to time to obtain the local strain-rate field.

Data from the load vs. time signal, as well as temporal data extracted from the DIC, were analyzed using Fourier transform and wavelet analysis. To focus attention on the dynamics of the response signal, the average trend was removed before analysis by using either a polynomial fit or a running average. Additionally, the initial loading portion and the macroscopically smooth plastic portion of the signals were analyzed individually. The Fourier analysis was performed to isolate characteristic frequencies in the signal and to look for power-law behavior of multiple scales.

While the Fourier transform is a longstanding tool for signal analysis, its utility is limited to data sets that are stationary. Wavelet analysis is similar to Fourier analysis in that they are performed by taking the integral of the inner product between the signal and an analyzing function. However, wavelet analysis uses a finite function (called a wavelet) instead of the infinite trigonometric series used in Fourier analysis. Because the wavelets are finite, the analysis can reveal information in the temporal regime as well as frequency, which allows for the identification of transient behavior in the analyzed signal. In each level of the discrete wavelet analysis based on dyadic scales, the wavelets are stretched, or dilated, by a factor of 2, causing the period of the wavelet to double.

Attention is turned first towards the evidence of plasticity developed during an initial nominally elastic loading of the sample. The average modulus derived from the stress–strain curves for three samples is 68.3 GPa. The analysis was performed for stresses in the range of 100–250 MPa, less than the average 0.2% offset yield stress of 321 MPa. An example spatiotemporal plot of the strain rate (in the direction of elongation) vs. time is shown in Figure 1a. The plot shows local data collected from the DIC along the vertical centerline (y-axis) of the specimen as a function of time (x-axis). A similar approach to represent the spatiotemporal characteristics of type A PLC bands was taken by Zavattieri et al. [17]. Fluctuations in the local strain rate, or waves, are apparent in the spatiotemporal plot of the loading regime. The velocity of these waves, drawn from the plot, evolves from 3.8×10^{-4} to $2.9 \times 10^{-5}\,\mathrm{m\,s}^{-1}$.

The load vs. time curve was preprocessed to remove a roughly linear trend, and then wavelet analysis of local transients was performed (Fig. 1b). Due to the use of a dyadic scale for the wavelet analysis, the comparison of two consequent levels of the discrete wavelet decomposition (labeled Appx 4 and Appx 5) clearly reveals the period doubling behavior around 2500 s. Because of the intricacies and approximations involved in the DIC analysis, we sought to establish some relation between the force–time signal and the DIC result. Shown in Figure 1c is a wavelet analysis of the local strain rate of a single spatial position from the plot of Figure 1a. Again, there is a particular level of the wavelet analysis (Appx 4) that suggests a doubling of the period. The difference in time for the period doubling of the global and local signal is not a contradiction because we do not assume that the event occurs throughout the whole specimen at once. However, the fact that the global signal is representative of what is happening at a local scale gives us confidence in the analysis. The spatial plot of strain rate before and after the period doubling transition is shown in Figure 1d, suggesting that the period doubling event has an effect on the number of waves propagating throughout the specimen. Multiple propagating bands provide a mechanism of deformation, lacking the marked serrations generally associated with the PLC effect.