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Kinematics of deformation bands in an austenitic FeMnC TWIP steel

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Abstract. Tensile tests on a Fe22Mn0.6C steel at room temperature and different strain rates show serrations on the curves similar to Portevin-Le Chatelier (PLC) serrations of type A, associated with negative strain rate sensitivity. Propagation of deformation bands have been observed by high-rate extensometry over more than two orders of magnitude of the applied strain rate. This constitutes a remarkable difference with the PLC effect which shows a transition to static bands (type B or C) when the applied strain rate decreases. In this steel, bands moving as slow as a few tenth of mm/s are observed instead of static bands, which is two orders of magnitude lower than what is reported for type A PLC bands. This emphasises a strong correlation between plastic events, also confirmed by multifractal analysis of the tensile curves. Twinning which is responsible of the high strain hardening rate of this steel at room temperature is discussed as one of mechanisms of correlation between instabilities.

1. Introduction

The plastic deformation mechanisms of the Fe22Mn0.6C (wt%) steel depend on temperature and corresponding variation of the stacking fault energy [1,2]. Twinning occurs at room temperature and progressively disappears when the temperature increases. The tensile curves exhibit fluctuations characteristic of plastic instabilities and which morphology depends on temperature. The mechanisms of these instabilities are not known yet, with an exception above 423K/473K where dynamical strain aging of dislocations by carbon atoms may lead to the Portevin-Le Chatelier effect [3,4]. At lower temperatures, the bulk diffusion of carbon is too slow to account for this mechanism [5]. At room temperature, this steel displays negative strain rate sensitivity (SRS) at strain rates below 10⁻¹ s⁻¹. While this property is generally ascribed to the PLC effect, it is not a peculiar feature of this mechanism. Furthermore, at this temperature, twinning enters into competition with dislocation glide and promotes a high strain hardening rate, effect known as twinning-induced plasticity (TWIP), which leads to simultaneously high mechanical resistance and deformability [6,7]. Twins can also be at the origin of pronounced stress fluctuations [8]. To characterise these instabilities, we study the local strain distribution during tensile deformation using high-rate extensometer technique [9] and examine the correlation between instabilities by a multifractal analysis of the tensile curves [10].
2. Local strain measurement

Flat tensile specimens of a 3 µm grain size Fe22Mn0.6C steel with a gauge section of 60mm×12.6mm×1.25mm were tested in tension at room temperature with a constant crosshead speed. The nominal value of the imposed strain-rate $\dot{\varepsilon}_a$ varied from $2.08 \times 10^{-5} \text{ s}^{-1}$ up to $2.5 \times 10^{-2} \text{ s}^{-1}$. One side of the specimen is painted black and ten 1 mm wide white marks are painted normal to the longitudinal axis, distant by 1mm [11]. The sequence of pairs of black and white stripes forms a set of ten 2 mm wide extensometers in the centre of the gauge length. The positions of the black/white transitions are followed during the tensile test using a high resolution 1D CCD camera with a recording frequency of $10^3 \text{ Hz}$ and a pixel size of 1.3µm and fixed relative to the fixed crosshead.

The local strain is determined from the displacements measured by the CCD camera:

$$\varepsilon_i(t) = \ln \frac{x_{i+2}(t) - x_i(t)}{x_{i+2}(0) - x_i(0)}$$

where $x_i$ is the coordinate of the $i$th transition and $t$ is the time with reference taken at 0.

The macroscopic true stress-strain curves in Figure 1 show the typical behaviour of this steel: high fracture stress and strain, a high strain hardening rate due to TWIP effect, stress fluctuations and a negative SRS. The latter varies from a few MPa at the beginning of deformation to 30MPa at $\varepsilon = 0.5$, which corresponds to what was observed in C-Mn steels under PLC conditions [3,4].

Figure 2 illustrates the measurement of synchronised local displacements and strains with stress fluctuations: a stress drop (Figure 2.a) corresponds to an instantaneous acceleration of the displacements of the entire set of extensometers (Figure 2.b), as marked by the dotted lines. This shows that a strain localisation appears between the fixed crosshead and the set of extensometers. Then the displacements slow down one extensometer after another (inclined dotted line in Figure 2.b), which results in local strain jumps, marked by dashed lines in Figure 2.c. The occurrence of strain steps followed by intervals of slower deformation, plus the delay between the steps and the initial acceleration suggest the formation of a band moving through the set of extensometers. This is confirmed by the magnification of the local strain curve illustrated on Figure 3, which shows that the deformations of adjacent extensometers are delayed in time.

In the case of the PLC effect, moving bands (type A) are only observed at the highest applied strain rates, typically above $10^3 \text{ s}^{-1}$. When the strain rate is decreased, a transition to hopping of correlated static bands is observed (type B), associated with oscillations on the stress-strain curves. At the lowest strain rates, typically $10^2 \text{ s}^{-1}$, the correlations between the static bands disappear (type C). The main difference in the studied steel is the persistence of the propagation mode over the entire applied strain rate range, with an exception for $\dot{\varepsilon}_a = 5.56 \times 10^{-4} \text{ s}^{-1}$ where intermittent static bands superimposed to propagating bands were also observed and for $\dot{\varepsilon}_a = 2.08 \times 10^{-5} \text{ s}^{-1}$ where the recording time was too
short to access a full propagation sequence. The band propagation velocity \( V_b \) can be determined as it is presented in Figure 3 where one can see a linear dependence with \( \dot{\varepsilon}_a \) at a given applied strain, even at the lowest strain rates. This is consistent with the power law observed in the case of type A PLC bands, but with a higher exponent (1 instead of 0.8) \[12,13\]. However, bands moving as slow as a few tenths of mm/s are observed, what is far less than it is reported in the case of type A PLC bands (several mm/s).

3. Multifractal analysis
The transitions from type A to type C when \( \dot{\varepsilon}_a \) decreases is linked to correlations between the plastic deformation events, which generally lead to self-similar or fractal properties of deformation curves \[13\]. In order to test the self-similarity of the stress fluctuations, the tensile curve of a specimen tested at room temperature and at \( \dot{\varepsilon}_a = 7 \times 10^{-4} \text{s}^{-1} \) has been time differentiated numerically. The signal is then composed of successive peak values \( \psi_k \). By using a time scale of \( N \) intervals \( \delta t \), a local measure \( \mu_i(\delta t) \) of the signal in the \( i \)-th interval can be defined as the sum of all the \( \psi_k \) values in this interval, normalised by the sum of all the \( \psi_k \) values in the \( N \) intervals. Introducing the functions \( Z_q \):

\[
Z_q = \sum_{i=1}^{N} \mu_i^q
\]

where \( q \) is a real number, then \[10\]:

- in the case of a purely stochastic signal, \( Z_q \) is proportional to \( \delta t^{q/1} \),
- if the signal has a self-similar character, \( Z_q \) is proportional to \( \delta t^{q(1-D_q)} \), where the \( D_q \) depend on \( q \) and are called generalised fractal dimensions.

Figure 5.a shows that the signal has a strong self-similar character over 2 orders of magnitude of \( \delta t \), despite the small number of recorded points (<3000). At room temperature, the stacking fault energy is equal to 20 mJ/m\(^2\) and many microtwins are formed during plastic deformation \[2\]. As they are similar to dislocation pile-ups, they induce high stress concentrations at interfaces which are able to trigger
further plastic events in their vicinity. This can be at the origin of strong correlations. In comparison, the same analysis on a sample deformed at 673K, where no twinning occurs, shows a random signal of fluctuations due to noise (Figure 5.b). Tests performed at 423K show stress fluctuations on part of the tensile curves similar to type B PLC. Further multifractal analyses are needed to compare the results with previous studies in the case of the PLC effect [13].

Figure 5. Result of the multifractal analysis. Evolution of functions $Z_q$ with $\delta t$ (a) with TWIP effect at room temperature, showing straight lines with different slopes $D_q$ and (b) with no TWIP effect at 673 K, showing only one straight line with a slope equal to 1.

4. Conclusion
The propagation of localisation bands has been observed by high rate extensometry at room temperature in the Fe22Mn0.6C steel over more than two orders of magnitude of the applied strain rate. This is relevant with type A bands observed at high strain rate in the case of the PLC effect. Contrary to this effect, no transition to static bands occurs when the applied strain rate decreases: the band velocity simply decreases linearly down to very low values. The correlations between plastic events seem to be sufficient to extend the propagation mode to the lowest strain rates. Twinning induces a high strain hardening rate in this steel at room temperature. It may also play an important role in the complex mechanism producing the plastic instabilities and different from a classical dynamic strain aging.

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