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D. Lesuer, C. Syn, O. Sherby

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D.R. Lesuer[a*], C.K. Syn[a] and O.D. Sherby[b]

[a] Lawrence Livermore National Laboratory, Livermore, CA 94551, USA
[b] Stanford University, Stanford, CA 94305 USA

Abstract

Severe plastic deformation is observed within adiabatic shear bands in iron-carbon steels. These shear bands form under high strain rate conditions, in excess of 1000 s^{-1}, and strains in the order 5 or greater are commonly observed. Studies on shear band formation in a ultrahigh carbon steel (1.3%C) are described in the pearlitic condition. A hardness of 11.5 GPa (4600 MPa) is obtained within the band. A mechanism is described to explain the high strength based on phase transformation to austenite from adiabatic heating resulting from severe deformation. Rapid re-transformation leads to an ultra-fine ferrite grain size containing carbon principally in the form of nanosize carbides. It is proposed that the same mechanism explains the ultrahigh strength of iron-carbon steels observed in ball-milling, ball drop tests and in severely deformed wires.

Keywords: shear bands, steel, high rate deformation

* Corresponding author: Tel: 925-422-9633; Fax: 925-422-6434
E-mail address: lesuer1@llnl.gov

1. Introduction

Severe plastic deformation (SPD) has been extensively studied in metals and is generally recognized as an effective processing approach for producing nano-scale structures in bulk materials. Most studies of SPD have been done using equal channel angular pressing or torsion under high hydrostatic pressure. For these deformation conditions, several mechanisms of microstructure evolution and nano-scale microstructure formation have been proposed. SPD is also observed in adiabatic shear bands. These shear bands form under high strain rate conditions, in excess of 1000 s^{-1}, and strains in the order 5 or greater are commonly observed. In this paper, the formation of shear bands in an ultrahigh carbon steel (UHCS) has been examined for samples subjected to high rate compression testing. The microstructures produced in the shear band have been studied. Mechanisms of microstructure evolution and nano-structure formation during shear band development have been proposed. The results are believed to be generally applicable to other deformation modes of ultrahigh carbon steels including deformation during ball-milling, shot peening, ball drop tests and wire drawing.

2. Materials, Experiments and Results

The material for this study was a UHCS with composition 1.3%C, 3.0%Si, 0.5%Mn, 0.99%Cr and balance iron. After casting and forging, the plate was homogenized for one hour at 1125°C and air-cooled. This treatment produced a fully pearlitic structure with a hardness of VHN = 355 (R_c = 36). Dynamic compression tests of this material were performed using the split Hopkinson pressure bar technique. The steel sample was deformed between two long bars made of Ti-6Al-4V. The strain histories in these two elastic pressure bars were measured and analyzed to determine the engineering stress, engineering strain and engineering strain rate response of the sample. Further processing and testing details are contained in references 1-3.

An SEM micrograph of a typical shear band is shown in Fig. 1. The pearlite plates bordering the band are highly deformed and strongly oriented in the shear band direction. In the center of the band, a fine structure is observed with nanostructure features in the order of 70 nm. In agreement with other investigators [4-6] these features are the ferrite grain size. Adjacent to the adiabatic shear band, a mixture of two structures appears. Segmented, broken-up (ultrafine) regions are mixed with oriented pearlite regions. The lamellar spacing in the pearlite remains about the same throughout this unique region. Significantly, the spacing of the pearlite in the shear band is about the same as the pearlite spacing away from the ultra-fine structure region. This mixed structure results from the two thermal events during and after deformation - adiabatic heating resulting from the large shear strain followed by subsequent rapid cooling. The microstructure in the shear band suggests that the temperature rise exceeds the A_1 transformation temperature. Most of the pearlite will transform to face-centered-cubic austenite. If the increase in temperature is only about 100°C above the A_1 not all the pearlite will dissolve. This is the temperature range where three phases co-exist, fine-grained austenite, and ferrite-plus-cementite as undissolved pearlite. These three phases produce the two mixed structures observed in Fig. 1. Upon rapid quenching at the completion of the shear-banding step, retransformation will take place. The ferrite grain size in the shear band is approximately 50 to 100 nm and the carbide particle size is believed to be approximately 1.5 nm.

2. Severe Plastic Deformation and Resulting Strength

Hardness measurements were made across the shear bands produced in the UHCS with a nano-indenter. Figure 2 shows the result of a nano-hardness traverse. The indentation sizes were about 200 nm (0.2 μm). It can be seen that the hardness values recorded in the adiabatic shear zone gave an average value of 11 GPa with a maximum value of 11.5 GPa. The hardness of the pearlite adjoining the shear band is 6.5 GPa. The high hardness obtained in the shear band cannot be achieved by deformation under conditions of isothermal working. For example the tensile strength of severely cold-rolled pearlitic UHCSs is 2500 MPa [7]. This is equivalent to a nano-hardness of 6.3 GPa [8]. The result indicates that adiabatic shear, involving a temperature rise during deformation, is a requirement for ultra-high strength.

3. Severe Plastic Deformation and Microstructure Development

Xu, Umemoto and Tsuchiya [9] studied the changes in the structure of Fe-C powders as a function of ball-milling time. The authors noted the discontinous changes in structure and hardness during ball-milling. Figure 3 illustrates the change in Vickers Hardness of a hypereutectoid steel (0.89%C) as a function of ball-milling time. Two different heat treated conditions were evaluated, pearlitic powders and spheroidized powders. Two distinct hardness plateaus can be observed. A forbidden zone of hardness values exists. These two distinct hardness states indicate that the work-hardened material can only work harden to a certain state and then it must transform into another state. The authors propose that this transformation is "considered as dynamic recovery and dynamic continuous recrystallization". This model does not directly account for the role of deformation in the dynamic recrystallization process. Adiabatic shear banding followed by phase transformation was not considered as a mechanism for formation of the high hardness product. In the case of adiabatic shear banding, it is usually considered that the deformation in the band itself, accompanied by phase transformation, is the cause of achieving the high strength. It will be shown in the remainder of this section that there is a strong case for phase transformation in the present study of adiabatic shear banding in Fe-C steels.

Figure 4 illustrates a construction of the stress-strain-temperature history of the sample in the shear band. The initial strain region (to $\varepsilon = 0.9$) was obtained from Hopkinson bar test data [3]. The flow stress continues to decrease to a strain of $\varepsilon = 2.8$ where the flow stress is 500 MPa. This is the flow stress of UHCS deformed at 1000 s^{-1} at 730°C [10]. A slight increase in the flow is shown at 800°C when transformation begins and austenite forms [at $\varepsilon = 3.2$]. Austenite is known to be stronger than ferrite [11]. The flow stress continues to decrease with further deformation in the austenite matrix as pearlite and cementite dissolve with increasing temperature. The flow stress decreases to 200 MPa at the end of shear band development, where the strain is $\varepsilon = 7.2$ and the final temperature is 1180°C. Rapid quenching follows since the band is bonded to a much colder matrix (i.e. 300°C).

The hardness of the shear band is extraordinarily high, 11.5 GPa. This is equivalent to a yield strength of 4600 MPa (667 ksi). We propose that this high strength is a result of nano-size carbides distributed uniformly in the ultra-fine ferrite grains (70 μm) [1]. This microstructure arises from a divorced eutectoid transformation (DET) that takes place during SPD in the shear band. We define the divorced eutectoid transformation as a transformation that is divorced of all normal transformations including pearlite, bainite and martensite. The structural changes are best described in three stages: (1) deformation in the ferrite range, up to e = 3.2, (2) deformation in the austenite range, e = 3.2 to 7.2 and (3) quenching after deformation.

In the first stage, the pearlite spacing is decreased, with simultaneous decrease in the cementite plate thickness. The second stage has the ferrite transforming to austenite. This transformation is athermal, i.e. instantaneous. The austenite will contain the same amount of carbon in solution as in ferrite (0.02 wt. %), because there is no time for carbon diffusion into the austenite lattice. This is because of the high strain rate in the shear band

($6 \times 10^5\ s^{-1}$), which produces a time in austenite of 10^{-5} s. The highly deformed carbide plates further deform in austenite and ball-up to become individual carbide particles with sizes in the order of 1-2 nm. The third stage involves re-transformation of austenite containing nano-carbides to ferrite. The austenite to ferrite transformation is athermal, and the nano-carbides will remain fine. The ferrite may retain 0.02 wt % C. The grain size of the transformed ferrite is dependent on a number of factors. The variables that need consideration are the prior austenite grain size, the initial ferrite grain size and the amount of deformation in each phase.

Transformations and microstructure development during shear banding can be better understood by considering the time-temperature history during shear band development. Figure 5 is a proposed reconstruction of the temperature-time sequence experienced by the material. The total time for deformation and cooling of the adiabatically sheared sample took about one microsecond. Figure 5a shows the three stages during deformation and cooling of the sample, wherein each stage involves a different rate of heating or cooling of the UHCS specimen. The first stage represents the stage of uniform deformation at a strain rate of 4000 s^{-1} to a true strain of 0.9 with the sample temperature increasing to 300°C. This stage took 2.2×10^{-4} s. The sample strain hardened to a very high hardness (about 6.5 GPa) that is equal to the maximum hardness observed in severely cold-worked pearlite [12].

The second stage represents the beginning and the end of shear banding, which results in a total true strain of 6.3. The strain rate in the shear band was calculated at about $6 \times 10^5\ s^{-1}$ [1]. This is 150 times the strain rate in Stage 1. The time spent in Stage 2 is only 1.05×10^{-5} s but dramatic changes in structure take place. The temperature increases rapidly in Stage 2, beginning from 300°C and ending at about 1180°C. Above 800°C, at about a strain of 3.2, BCC iron transforms to FCC iron (Fig. 4). The third stage involves re-transformation of FCC iron containing nano-carbides to BCC iron (ferrite) with nano-carbides. The cooling rate is about 10^6 °C s^{-1} [13]. The time spent in this stage is 1.1×10^{-3} s. The grain size of the transformed ferrite is expected to be fine because it is dependent on the prior FCC iron grain size and that grain size will probably be fine from the SPD taking place in the shear band. Figure 5b shows the temperature-time curve with a continuous time scale. It shows that most of time is spent in Stage 3, with less time in Step 1. The formation of the adiabatic shear band occurs with a very fast heating rate. The temperature-time history depicted in Figs. 5a and 5b supports the microstructural history described in Fig. 4.

4. Conclusions

During high rate deformation, SPD is observed within adiabatic shear bands in Fe-C steels. The structure in the band is a result of deformation and phase transformations. Adiabatic heating leads to transformation to austenite and subsequent rapid cooling produces a DET. The resulting structure contains nano-sized carbides uniformly distributed in ferrite with ultra-fine grains (70 μm). An extremely high harness can be obtained within the band – 11.5 GPa (equivalent to a yield strength of 4600 MPa). The results suggest that the same mechanism for microstructural development and resulting ultrahigh strength applies to eutectoid composition Fe-C steels as observed in ball-milling, ball drop tests and in severely deformed wires.

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Figure Captions

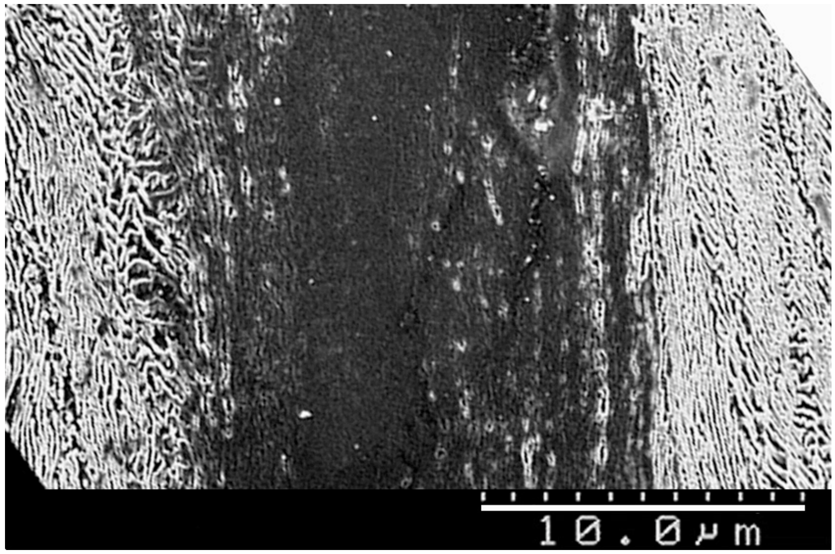
Figure 1. Photomicrograph of an adiabatic shear band in a pearlitic UHCS produced as a result of high rate testing.

Figure 2. Nano-indentation hardness across an adiabatic shear band in the UHCS-1.3C material.

Figure 3. Evolution of microhardness during ball milling for a Fe-C steel (0.89C) in the pearlitic and spheroidized conditions (after Xu, Umemoto and Tsuchiya).

Figure 4. Stress-strain response within the shear band during high rate deformation of the UHCS-1.3C material.

Figure 5. Temperature-time history in the shear band showing the phases present, (a) discontinuous time scale and (b) continuous time scale.



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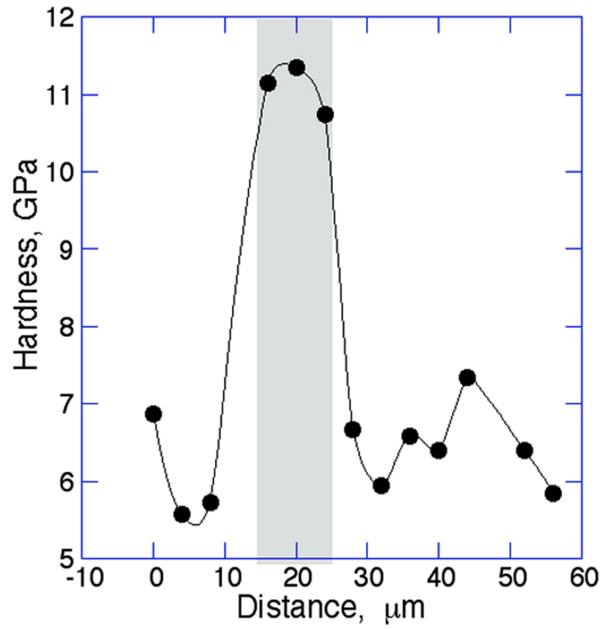

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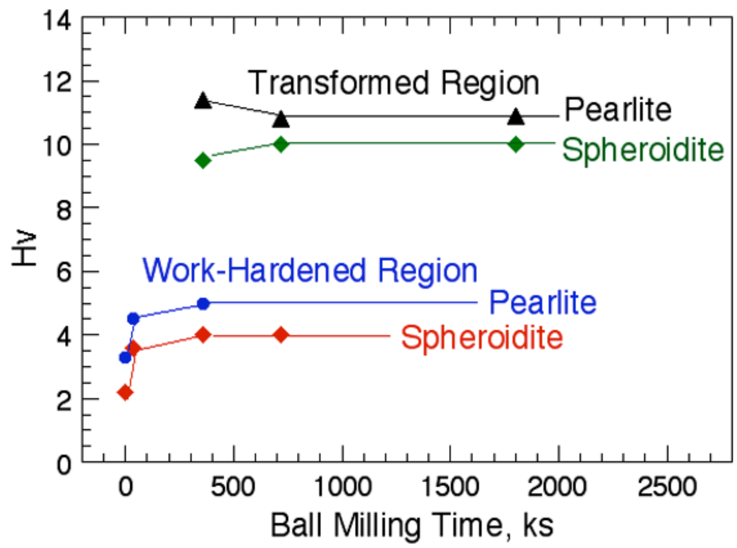

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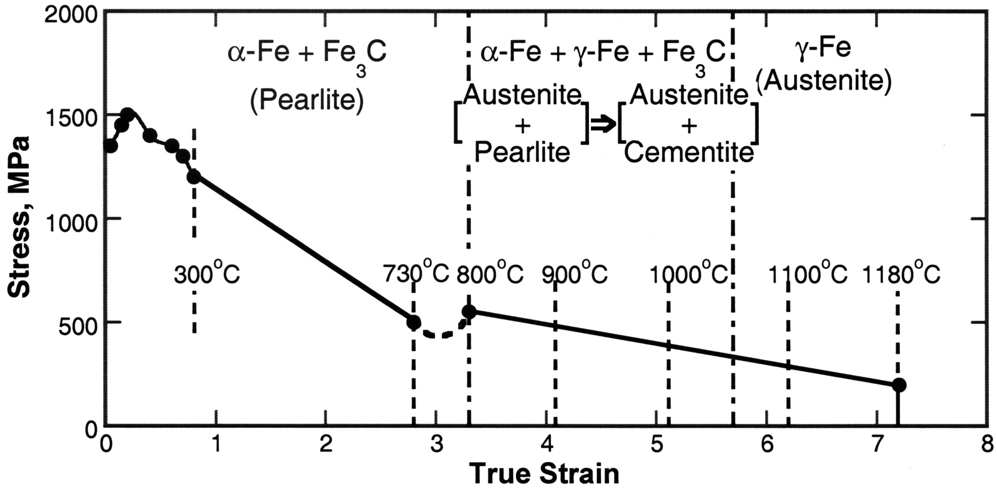

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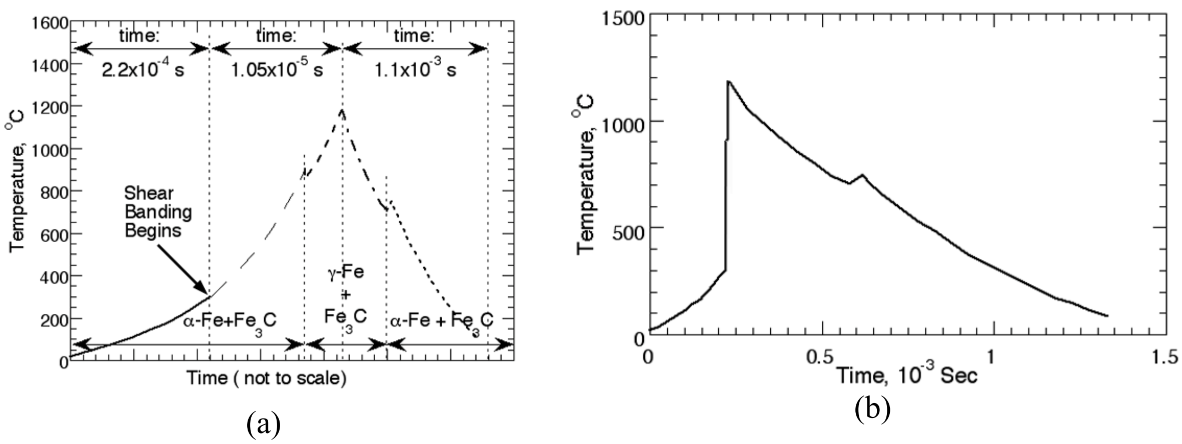

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