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High-Voltage Transmission Electron Microscopy of Shear Bands in Titanium and 4340 Steel

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Microstructures of adiabatic shear bands in commercially pure titanium and tempered AISI 4340 steel were investigated by high voltage transmission electron microscopy. The structure of shear bands in titanium consists of small (0.05-0.3 μm) grains with well-defined grain boundaries, while regions near the shear bands show a high density of dislocations. In the tempered 4340 steel, both the shear band and the surrounding regions consist of highly dislocated α'-martensite with a low density of {112} microtwins. χ(Fe_5C_2) carbides are found to occur along such microtwins in the shear bands. The martensite lath boundaries inside the 4340 steel shear band are not well defined.

I. INTRODUCTION

Adiabatic shear bands are formed in many metals and alloys subjected to high-strain-rate deformation. These shear bands are of concern in ballistic impact, fragmentation, metal forming, and machining processes because they usually lead to failure. The formation of these shear bands has been attributed to a plastic shear instability created by thermal softening due to localized deformation. This plastic shear instability was first studied in high-strain-rate tests by Zener and Hollomon [1] and termed "adiabatic shear". Since then, to further understand the formation mechanisms, a number of investigations have been made to determine the theoretical criterion for this plastic instability [2-7]. However, our understanding of the formation mechanisms is still limited, partly because the structure of these bands has not been satisfactorily established, to this date. A few studies have reported microstructural observations of shear bands in an aluminum alloy [8], medium and high carbon quenched and tempered steels [9-13], 70-30 brass [14], titanium and titanium alloys [15-17], and a precipitation-hardened austenitic stainless steel [18,19]. In order to achieve a better understanding of the deformation associated with adiabatic shear bands such detailed structural observations are essential. With this in mind, a high-voltage electron microscope was used, for greater foil penetration (>1μm), to observe adiabatic shear bands in commercially pure titanium and quenched and tempered AISI 4340 steel.

II. EXPERIMENTAL TECHNIQUES

The commercially pure titanium plate used in this study (0.02 C, 0.4 Fe, 0.012 N, 0.131 O, and the balance Ti in weight percent) was annealed at 700°C for 1 hour. The grain size, measured by the linear intercept technique, was 61 μm. The 12.5 mm thick titanium plate was impacted at a velocity of 600 m/s by a stepped projectile (10.5 mm diameter with a 3 mm diameter step, 3 mm in length) to produce shear bands. Greater details of the experimental conditions and results are given in [19].

The AISI 4340 steel specimen employed in this study was kindly provided by Mr. D. Erlich, SRI International. It was oil-quenched from 695°C, tempered at 230°C for 2 hours, then air cooled. The hardness obtained was HRC 52. The heat treated steel was deformed in an exploding cylinder by Stanford Research Institute, as part of comprehensive shear-band investigation project. Greater details of the experimental conditions for the contained fragmenting cylinders are given by Shockey and Erlich [20] and Erlich, Curran, and Seaman [21].

Microstructures of the shear bands were observed with a Kratos EM-1500 (operated at 1.5 MeV) at the National Center for Electron Microscopy, Lawrence Berkeley Laboratory, CA. Thin foils were made with a Fishione twin-jet electropolisher, from 3 mm discs containing shear bands passing through the center. One side of the disc was masked with "stop-off", to expose only the band area, so as to ensure preferential thinning of the shear band area. The electropolishing conditions employed were: for the

FIG. 1 *Shear band in titanium. The interface between the band and the matrix is very distinct.*

titanium a solution of 0.5 vol % HF, 3 vol % H_2SO_4, and 96.5 vol % CH_3OH, cooled to below -40°C; for the 4340 steel 30 vol % Nital cooled to below -20°C. The 4340 steel samples then were ion milled using a cold stage.

III. RESULTS AND DISCUSSION

A. *COMMERCIALLY PURE TITANIUM*

Approximately 15 shear bands were optically observed in the section of the target made along the axis of the projectile [19]. The band widths varied between 1 and 20 µm, and the bands traversed the original grains. Figure 1 shows one of these shear bands formed in the titanium target. The band and the matrix are clearly divided by a rather smooth and distinct interface. Detailed features of a shear band are seen in Fig. 2, showing a high-voltage electron micrograph (bright field). The shear band and the adjoining matrix are clearly divided by this distinct interface (arrowed), similar to the observation of Fig. 1. The shear band consists of very small grains, where sizes range between 0.05 and 0.3 µm. The electron diffraction pattern of this band area shows a ring pattern (upper left of

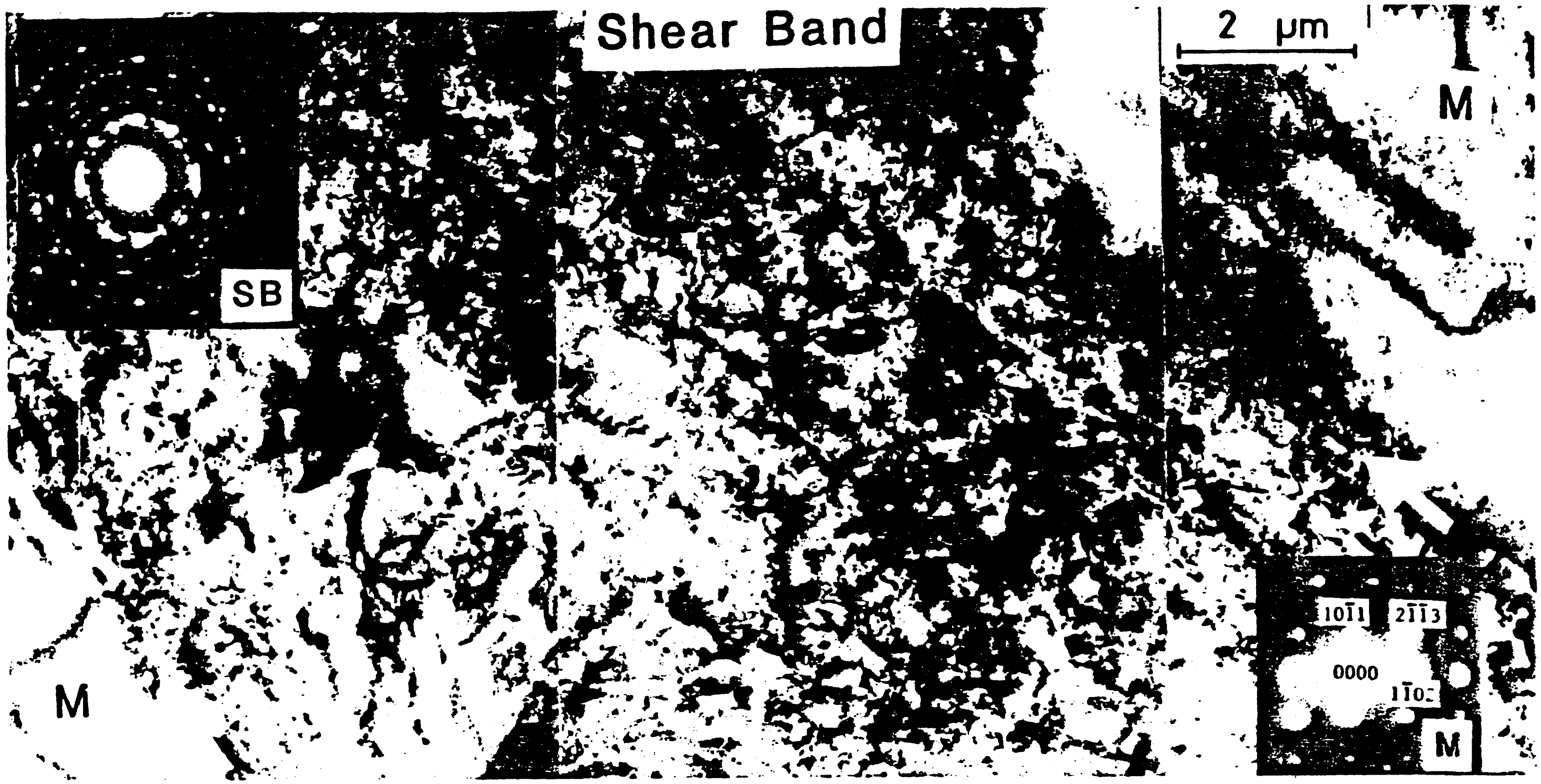

FIG. 2 *High-voltage electron micrograph of the shear band (SB) bounded by the matrix (M). Arrows indicate the boundary between the two.*

Fig. 2), indicating that uniformly oriented small grains constitute the shear band. This is in contrast to the α-hcp single crystal diffraction pattern of the matrix area (right-hand side of Fig. 2). As the band is traversed towards the interface from the center, the morphology of the small grains, constituting the shear band, does not change. The matrix areas are seen to contain a large number of dislocations.

High magnification dark-field micrographs of the shear band clearly showed that the density of dislocations was rather low at the grain boundaries. No evidence of melting in the shear band was obtained, nor was there any trace of a high-temperature phase (β). These observations indicate that the small grains in the shear band were formed, in part, by a dynamic recrystallization process.

B. AISI 4340 STEEL.

Shear bands in the 4340 steel were generally narrow and their widths varied from submicron to 6 μm, unlike the titanium. A typical example is shown in Fig. 3, a scanning electron micrograph of a shear band formed

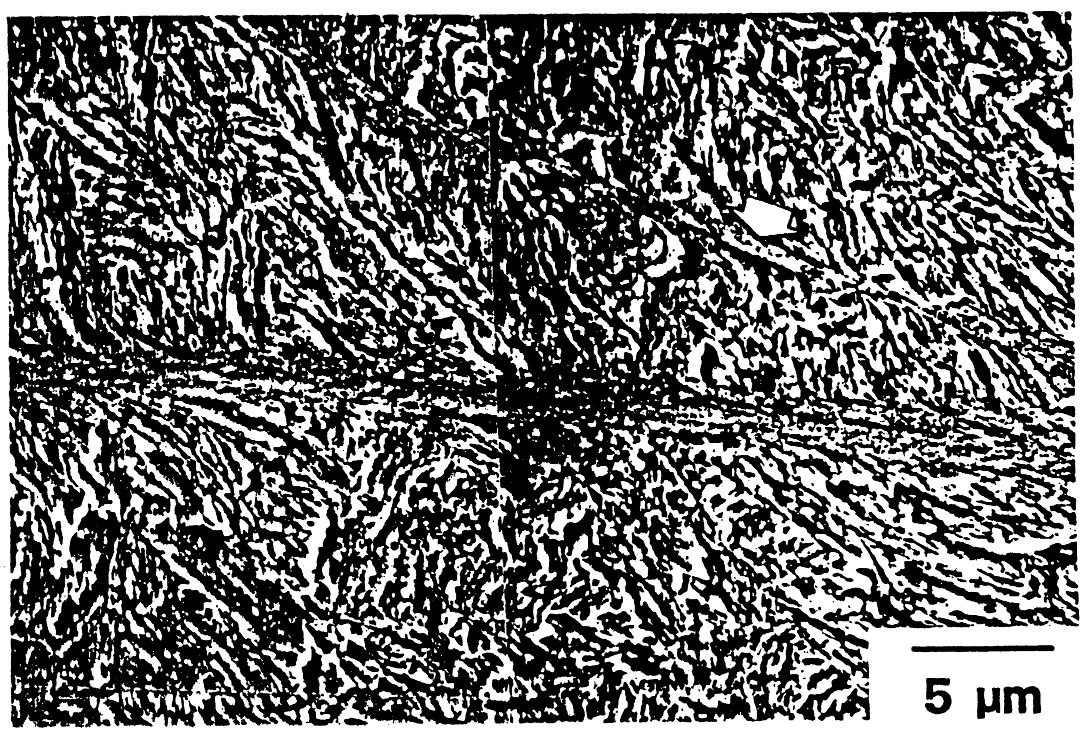

FIG. 3 *Scanning electron micrograph of shear band in quenched and tempered AISI 4340 steel. Interface between the matrix and the shear band is not well defined.*

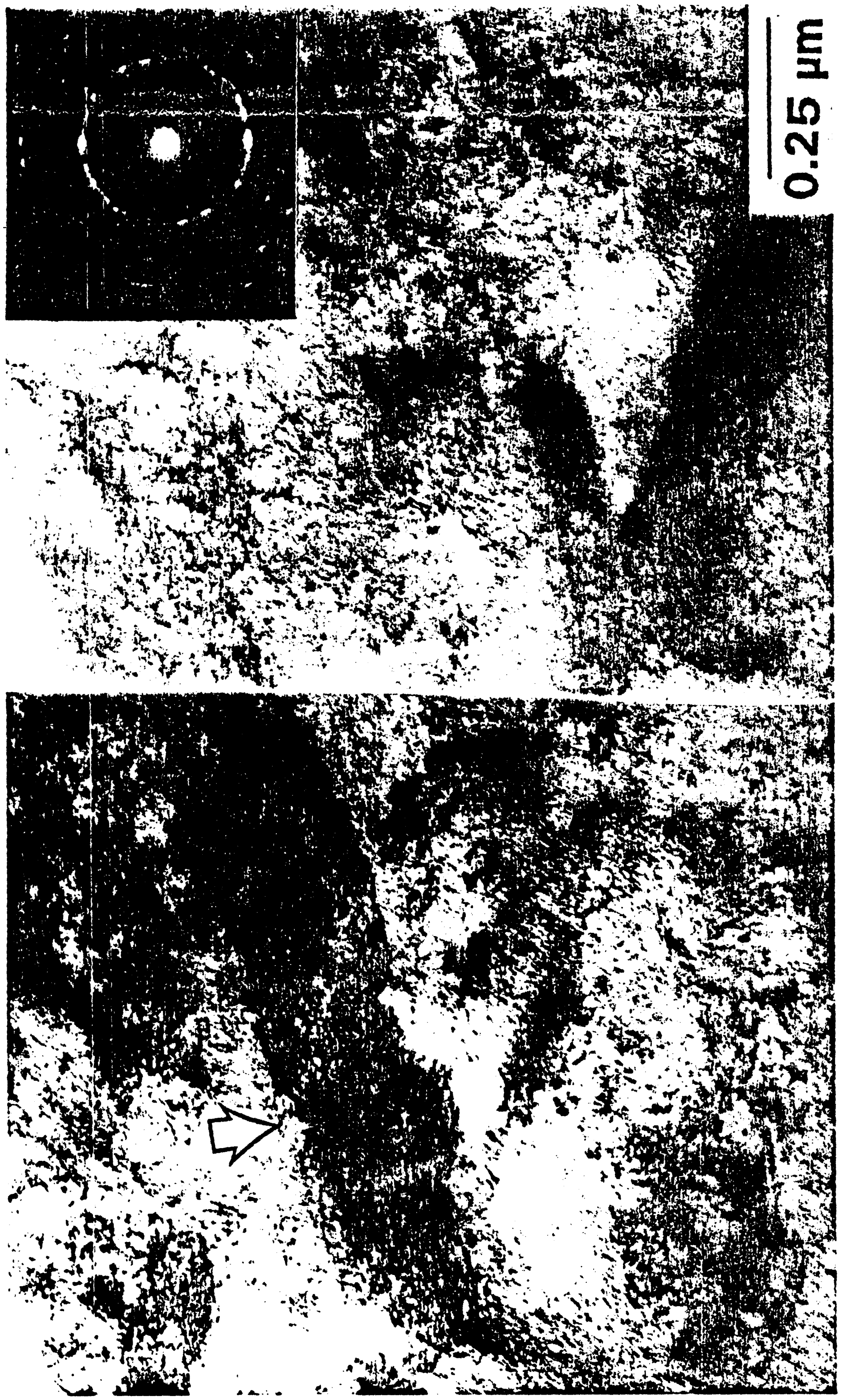

FIG. 4 *High-voltage electron micrograph of matrix area near a shear band in 4340 steel. Boundaries between α' martensite laths are clearly seen. An arrow indicates the direction of the interface between the shear band and the matrix.*

FIG. 5 *High-voltage electron micrograph of a shear band near the area of Fig. 4. (a) χ-carbides formed on (112) internal twin boundaries; (b) diffraction pattern showing a structure identical to the matrix α' martensite and χ-carbides.*

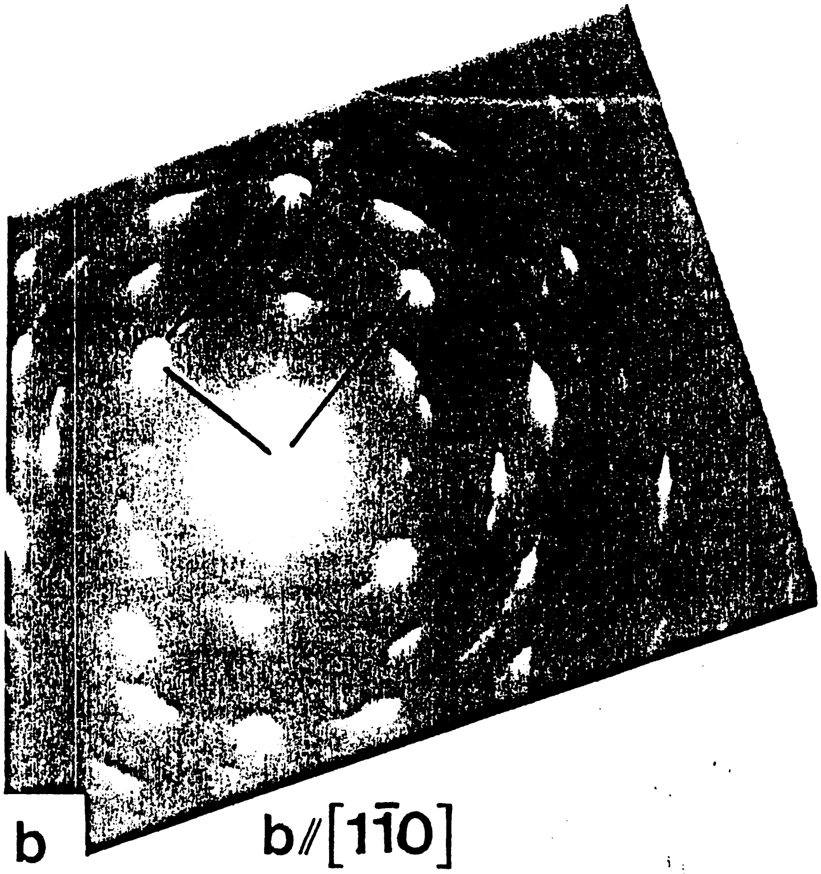

FIG. 5 *Continued.*

in the 4340 steel. This figure shows bifurcation of the shear band (indicated by the arrow); bifurcation was often observed. A distinct interface between the shear band and the matrix is not observed in this micrograph, unlike the observations of the titanium shear band. This diffuse interface was also observed on a much finer scale in the transmission electron micrographs.

Figure 4 is a bright field micrograph of the matrix area near a shear band, showing α' martensite laths which have well defined boundaries. Although this area is considered to be subjected to a considerable amount of deformation due to the shear band formation, no specific alignment of the α' martensites has taken place.

Shear bands in the 4340 steel showed a somewhat different microstructure from that of the matrix area. Inspection of the electron diffraction patterns taken from the shear band showed that the structure was the same as that of the matrix α'martensite, with the addition of $\chi(Fe_5C_2)$ carbides. Figure 5(a) is a typical example of a shear-band area microstructure. No boundaries of α' martensites may be observed. A dark field micrograph, using the 111 reflection of the χ-carbide, revealed that the dark bands of Fig. 5(b) consist of χ-carbides (50-300 Å), formed on (112) internal twin boundaries. The precipitation of χ-carbides on such boundaries is charac-

FIG. 6 *Another microstructure of the shear band in 4340 steel. Note the tweed structure.*

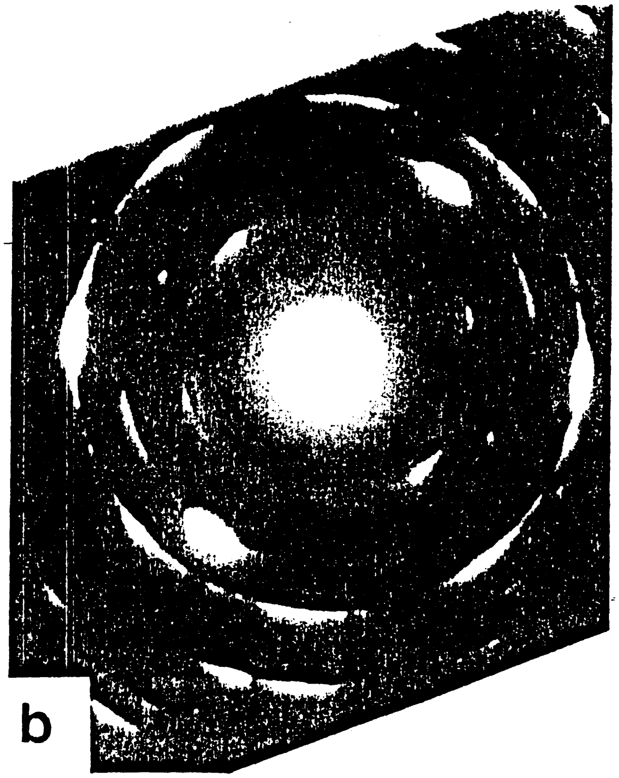

FIG. 6 *Continued.*

teristic of the third stage carbide formation in tempered medium and high carbon steels [22,23].

Figure 6(a) shows another microstructural feature of a shear band formed in the 4340 steel, identified as a tweed microstructure. Boundaries of the α' martensite laths are also not observed in this micrograph. By inspecting the image contrast of the tweed microstructure and the ring diffraction pattern (Fig. 6(b)), taken from the area of Fig. 6(a), one can propose that the α' martensite laths of the matrix were fragmented by the large shear deformation, destroying the lath boundaries. No evidence for the formation of an austenite phase was obtained.

IV. SUMMARY

Microstructures of shear bands in commercially pure titanium and quenched and tempered AISI 4340 steel were investigated by high voltage transmission electron microscopy. The observations can be summarized as follows: (1) Shear bands in the titanium consisted of small (0.05-0.3 μm) grains with well-defined boundaries. These small grains were thought to be formed by a dynamic recrystallization process. Matrix regions of the titanium were highly dislocated. The interface between the shear band the matrix in the titanium was very clear.

(2) Shear bands in the 4340 steel had the same structure as the matrix α' martensite with the addition of χ-carbides, which were found on (112) internal twin boundaries. Matrix regions of the 4340 steel showed rather well-defined martensite boundaries, while no clear boundaries were observed in the shear bands.

(3) For both cases, titanium and 4340 steel, no evidence of a transformation to their high temperature phases was observed.

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