JMEPEG (1996) 5:23-26

A TEM Study of Deformation Substructure in High Strain Rate and Explosively Shock-Loaded Polycrystalline Iron

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Residual microstructures developed in polycrystalline iron after deformation at high rates of strain were characterized using transmission electron microscopy (TEM). Long, screw-type dislocations were observed in Hopkinson bar and impacted specimens compared to deformation twinning and dislocation cell structures found in shocked specimens. Localized deformation bands were observed in the impacted specimen. No evidence for deformation twinning was found in the Hopkinson bar and impacted specimens. The effect of substructure produced in the specimens on the hardness of these specimens is also observed.

Keywords

deformation, dislocation, high strain rate, iron, polycrystalline, substructure, TEM, twinning

1. Introduction

CONSTITUTIVE equations being developed to describe high strain rate plastic flow and shock must be correlated with deformation substructure for accurate design of material that will be subjected to dynamic loading. Thus attempts (Ref 1-4) were made to examine the deformation behavior of Armco iron and other materials under high strains and at high strain rates and temperature, for hydrocode modelling. Recent work (Ref 5, 6) showed formation of substructure in different materials tested at high strain rates. Many investigations (Ref 7-10) were conducted on the characterization of residual microstructure in fcc materials subjected to high strain rates; however, the response to high strain rate deformation in bcc materials, particularly iron, is not fully understood. This work examines the deformation substructure developed in single-phase polycrystalline iron specimens after three different high strain rate tests. The tests were Hopkinson bar test, impact by flyer plate, and explosively shock loading. The nature and speed of the shock front subjects the material locally to infinite high strain rates. The contribution of deformed substructure on the hardness is also considered.

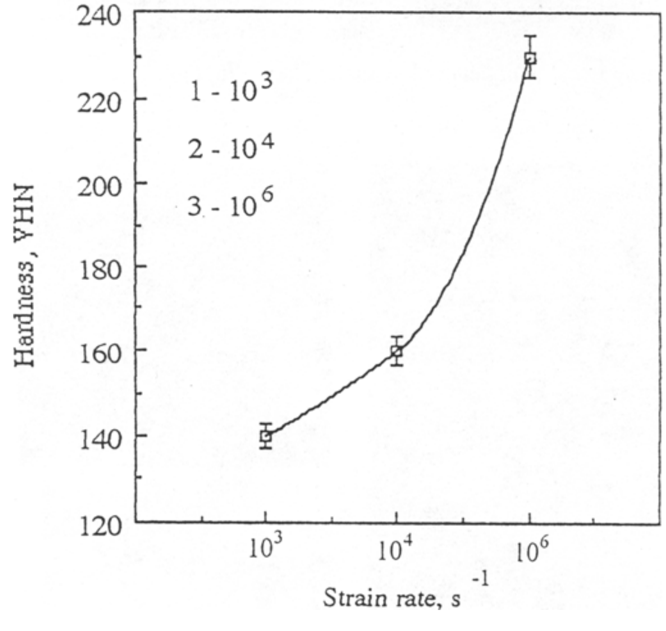

Fig. 1 Hardness versus strain rate

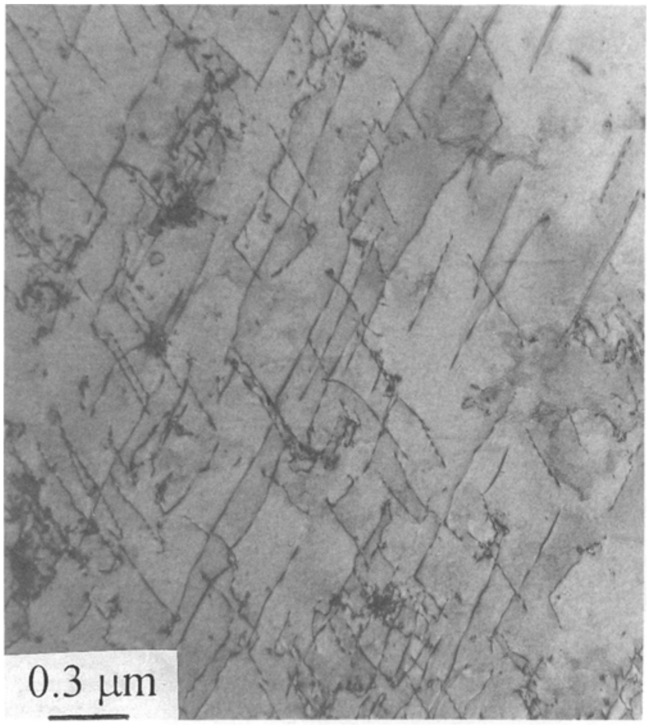

Fig. 2 Long, screw-type dislocations observed in the Hopkinson bar tensile test specimen (strain rate ~10^3 s^{-1}), bright field

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2. Experimental

High-purity iron samples that had been subjected to high strain rate Hopkinson bar, impact, and shock-loading tests were examined in this investigation. These tests were performed at strain rates of about 10^3 s^{-1}, 10^4 s^{-1}, and 10^6 s^{-1}, respectively. Further details of the tests performed are described in Ref 3. Hardness of the specimens was measured using a Vickers hardness tester. The specimens were examined in a Hitachi S-530 scanning electron microscope (Hitachi Seiki U.S.A., Inc., Congers, NY) operated at 25 kV. TEM foils were prepared from the

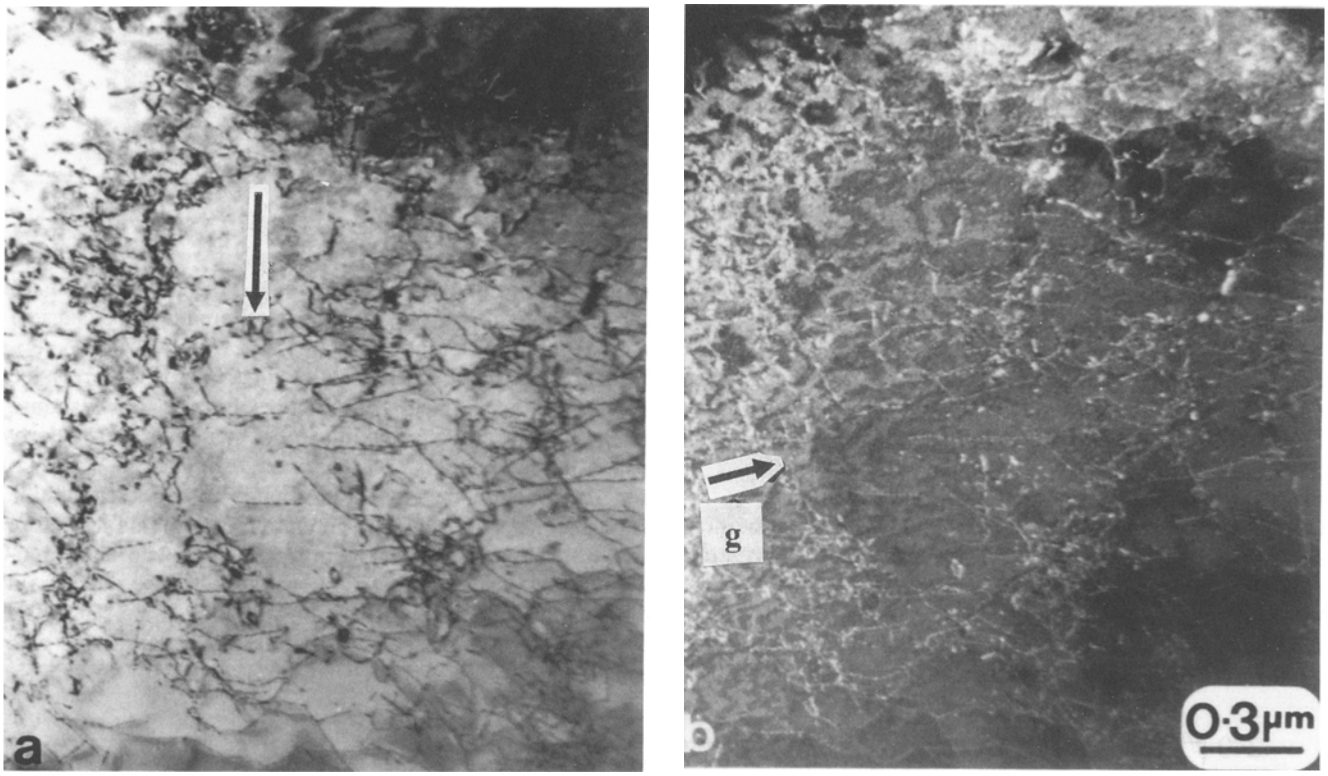

Fig. 3 Evidence of dislocation loop in the Hopkinson bar test specimen (arrow), (a) bright field and (b) dark field, g = [011]

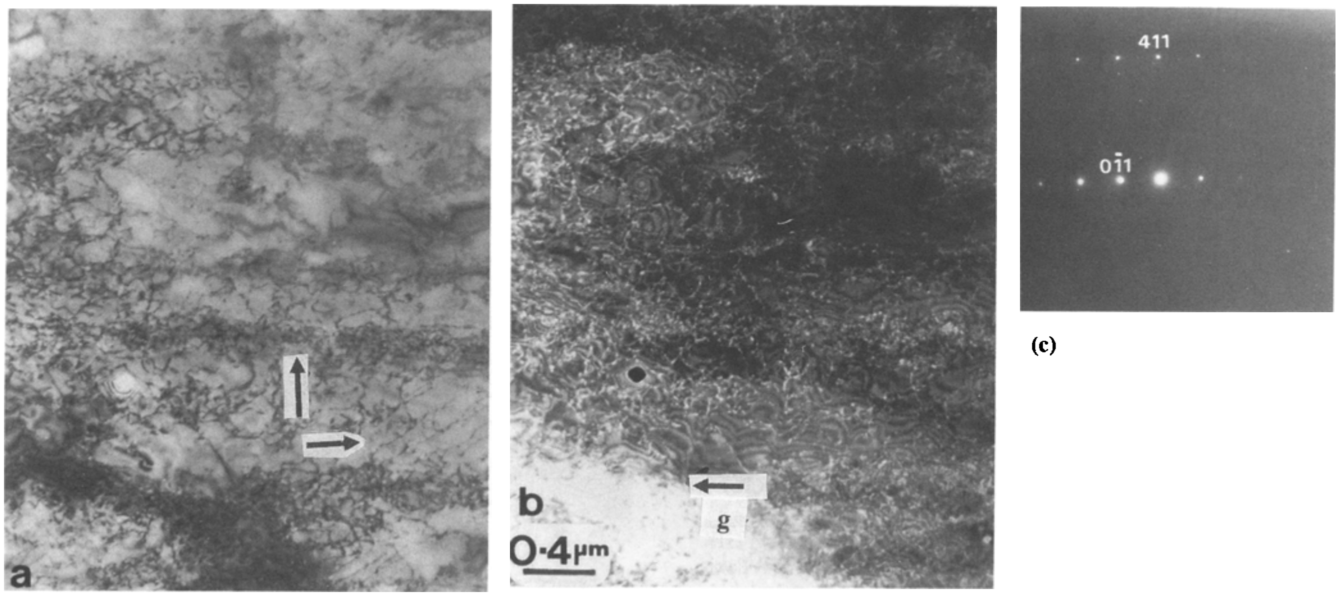

Fig. 4 Matrix dislocations and deformation bands (arrows) (strain rate ~10^4 s^{-1}), (a) bright field, (b) dark field, g = [$0\bar{1}1$], and (c) selected area diffraction pattern

test specimens by cutting slices, from which 3 mm diam disks were cut; these disks were then ground down to 90 µm thickness. Thin foils were electropolished in an electrolyte of 10% perchloric acid in 2-butoxyethanol at –10 °C and an applied potential of 40 V. Thin foils were examined in a Philips CM 20 (Philips Electronic Instruments, Inc., Alpharetta, GA) electron microscope at an operating voltage of 200 kV.

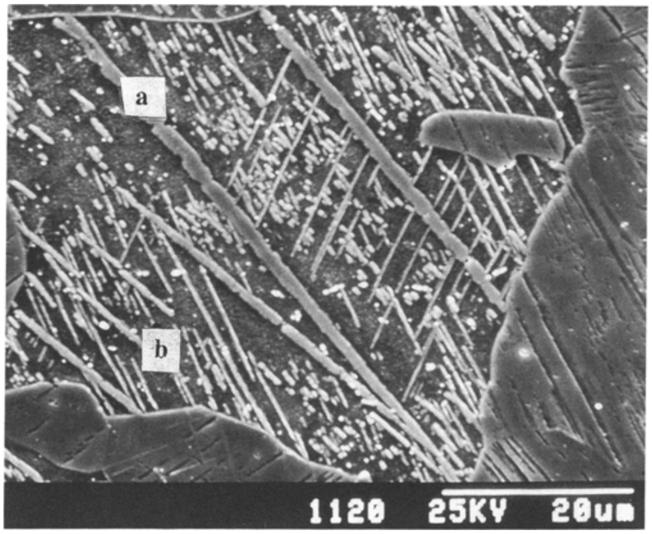

Fig. 5 Deformation twins. (a) Primary twins and (b) secondary twins observed in shock-loaded specimen (strain rate ~10^6 s^{-1}), SEM

3. Results and Discussion

3.1 *Hardness*

Figure 1 shows hardness of the specimens tested at various strain rates. An increase in the hardness values is evident with strain rate. However, the hardness was much higher in the explosively shock-loaded specimen because severe deformation twinning occurred in the specimens. This is consistent with previous work (Ref 3). The characteristics of the deformation twins are described in section 3.2.3.

3.2 *TEM*

3.2.1 Hopkinson Bar Test

Figure 2 shows dislocation structures observed in the Hopkinson bar tensile test specimen. The dislocation structure was analyzed using procedures similar to those described in Ref 11 and 12. TEM revealed long, screw-type dislocations; however, no evidence of deformation twinning was found. Figure 3 reveals some evidence that dislocation loops evolved during deformation, which is in accord with Ref 4. Apparently, dislocation cells did not form at this strain rate level.

3.2.2 Impacted by Flyer Plate

Figure 4 shows arrays of matrix dislocations and deformation bands in the specimen. Note that deformation bands were irregular with no well-defined boundaries and contained a high degree of dislocations as compared with the surrounding matrix. Similar observations were reported in Ref 13. The residual structure appeared to be similar to that observed in the Hopkin-

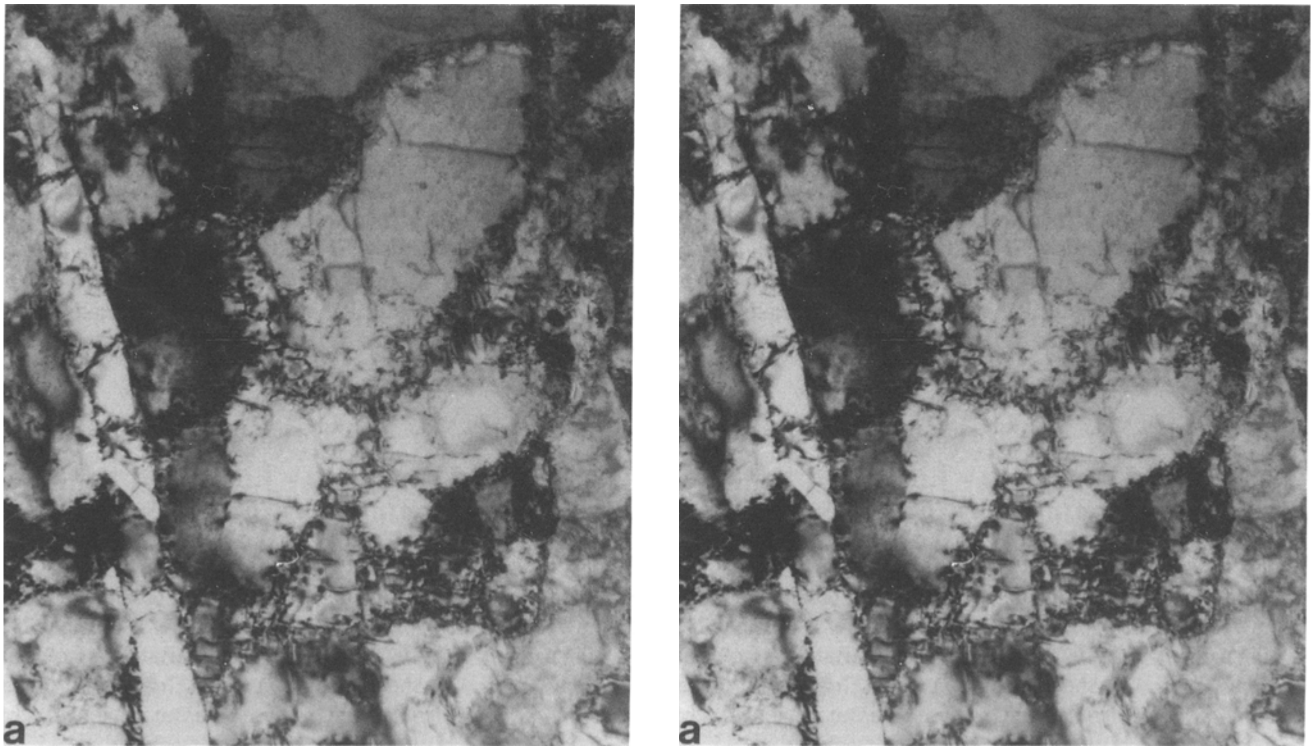

Fig. 6 Dislocation cell structure in the untwinned region of a shock-loaded specimen, (a) bright field and (b) dark field, g = [110]

son bar test specimen. However, no evidence of cellular dislocation structure and twinning was found.

3.2.3 Explosively Shock Loaded

Figure 5 shows densely formed deformation twins ("Neumann bands"); the width of twin lamellae ranged from 0.10 to 0.5 μm. The results are similar to observations reported in Ref 14 and 15. Two types of twins were identified: primary twins and secondary twins, presumably dependent on the stage of deformation at which they form. The long and wide twins were identified as primary twins, and the fine and thin ones, as secondary twins. The primary twins also exhibited a broken morphology. Figure 6 illustrates evolution of the dislocation cell structure in the untwinned region adjacent to deformation twins. Dislocations were also apparent in the cell interior. The development of cell structure in the untwinned region was not reported previously.

4. Summary and Conclusions

TEM examination revealed long, screw-type dislocations in both the Hopkinson bar and impacted specimens. Deformation bands containing a higher degree of dislocations were also observed; however, no evidence of deformation twinning and dislocation cells was found. The shock-loaded specimen showed severe deformation twinning characterized as primary and secondary twins. The formation of these twins resulted in an increase in hardness of the shock-loaded specimen. Dislocation cells were found in the untwinned regions of the shocked structure. Apparently, deformation occurred predominantly by twinning under shock-loaded conditions as compared to dislocation glide in the case of Hopkinson bar and impacted specimens.

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