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FORMATION AND MICROSTRUCTURE OF LOCALIZED SHEAR BAND IN A LOW CARBON STEEL

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Introduction

Over the past few years, the thermal-assisted shear localization of metals and alloys occurring during dynamic deformation has been an interesting subject of experimental and theoretical investigations because the occurrence of localized shear deformation can frequently lead to failure in low ductility and low toughness for materials. A variety of deformation and fracture modes have been proposed to describe this phenomenon, but the relationship of the mechanical condition for the formation of macroscopic shear band with the microstructure is not well understood at present.

In the first paper(1), we presented an investigation on the microstructure characteristics of localized shear deformation bands occurring in a low carbon steel which consists of ferrite-pearlite structures. As part of a series of studies on the formation of localized shear deformation during dynamic torsional testing at high speed rate, the study we present here examines the microstructure characteristics of the localized shear band and its associated mechanical condition in a quenched low carbon steel with lath martensite structure.

Materials and Procedures

Low carbon steel, of composition(in we-%) 0.22%C, 0.009%S, 0.35%Si, 0.53%Mn, 0.018%P, and balance Fe, was selected for the present study.

The short thin wall specimens with 2.0mm gauge length, 10.00mm internal diameter and 0.5mm wall thickness were machined from rods, heat-treated at $830^{\circ}C$ for 30 minutes, followed by water quenching.

The torsional tests used for this study were performed in the torsional split Hopkinson bar. The basic apparatus and experimental details can be found elsewhere(2). The specimens for both optical and scanning electron microscopy were sectioned after testing by spark machining and prepared by standrd metallographic grinding, polishing and etching methods. Microstructure investigations by transmission electron microscopy were performed on a Philips EM420 analytical electron microscope operated at 100KV, including both thin foil techniques and electron diffration.

Results and Discussion

Evaluation of the Temperature Distribution within the Shear Band

In specimen, plastic deformation takes place by dislocation motion and interaction of dislocations. A small part of the work of plastic deformation is stored as elastic strain energy. The remaining 90 to 95% is converted into heat(3). The localized shear deformation is considered to be an "adiabatic" process, so that the heat loss may be neglected. In other words, the plastic work is converted into heat completely. The temperature raised within the band during the course of the testing according to the following relationship:

$$\Delta T = \tau^{*}\gamma^{*}/\rho C_v$$

is about $220.5^{\circ}C$ which is much lower than that of the phase transmission temperature of the steel, where τ^{*} and γ^{*} correspond to shear stress and strain respectively. ρ ; material density and Cv: heat capacity. In fact, the eventual temperature rise in the band may be more or less than this value because of heat conduction.

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Mechanical Property

Fig.1 shows a typical shear stress-strain curve from which it is clear that the work hardening changes from positive to negative at the critical strain of 0.3 at which the localized shear band does indeed develop in the quenched low carbon martensite steel.This strain value that the localized shear band developed is lower than that in low carbon ferrite-pearlite steel(1). the two steels have the same chemistries but are different in the heat treatment.

The comparison of the two tests in the same steel show that the higher the strength of the material, all other material properties remaining the same, the more susceptible it is to localized shear band formation. These results are consistent with the observation of Costin et al(1979)(4) in cold rolled steel that the shear band developed at a critical strain of 0.3, and Clifton(1983)(5) in hot rolled steel at the critical strain of 0.8-1.0. These are similar to results obtained by Hartley et al(6).

Microhardness measurements transverse to the shear band are shown in Fig.2. it is seen clearly that the hardness values in and near the shear band decrease with distance from the band center until the matrix hardness is reached. This means that on the both sides of the band there are regions where the material has suffered various degrees of deformation strengthening and thermal softening. It should be pointed out that the hardness values in the band have a slight scatter because of the structural damage in the band.

Microstructure Characteristics

One important aspect of the current research on localized shear deformation formation is to study its internal microstructure using SEM and TEM(1,8,9).

Fig.3 shows a macro-etched section of a specimen afetr dynamic torsional deformation at 650 S^{-1} at which a typical localized shear deformation band can be found to distribute over the deformed region, as shown in Fig.4. The width of the band is estimated to be of the order of magnotude of 70μm which is greater than in ferrite-pearlite steel, consistent with the prediction of the model proposed by Dodd and Bai(1985)(7). This implies that the greater the strain rate in the shear band, the narrower the width of the shear band.

A series of observations by scanning electron microscopy indicate that the grains in the band were rotated and elongated at a certain angle with the shear direction due to the material in the band having suffered various degrees of deformation. Careful observations show that the dislocation density in the band is extremly high in comparison with the deformed region to either side of the band; the tangled arrangement of dislocations tends to be aligned along the localized shear band. This feature can be seen more clearly in Fig.5, where dislocation cell structure begins to form.

It is interesting to compare the selected area electron diffraction patterns from the different grains in the band. Fig.6 is the grain A in the band from which a relatively simple pattern is obtained. The crystallographic nature in this grain can be explaned by the trace $\langle 33\bar{2} \rangle$ of slip. On the other hand, Grain B in the same band does not keep a crystallographic nature, as can be seen from the well developed spotty ring pattern produced. this implies that the operation of multiple slip systems could be acted by microscopic region of large misorientations that could be caused by the operation of multiple slip combined with large accumulated plastic strain in the band. Therefore, in grain B, the shear band is non-crystallographic form. This observation shows that the shear band have a spatial distribution. Although some regions in micro-scale involve crystallographic slip processes, the overall macroscopic deformation band can appear non-crystallographic form which is similar to the observation in a commercial aluminum alloy by Korbel et al(8).

Damage and Fracture

As a result of localized shear deformation band formation under dynamic deformation, severe damage of the structure appears along the band. observations by scanning electron microscopy reveal that there are several ways to initiate a microcrack in the band. In other words, the microcracks, in general, nucleate at the grain boundary, the interface between martensite and ferrite laths, and interfaces such as carbides and so on. The degree of structural damage in the band leading to final fracture can be assessed by using the number of cracks per unit area as a function of structural damage(1). Fig.7 shows an SEM micrograph of the fracture surface of this steel where the shear band developed. The fracture surface appears distinctly fibrous. It is composed of series of elongated dimples oriented in the direction of shearing. This result is similar to the observation of Hartley et al(6) in CRS steel. They pointed out that the fibrous nature of the fracture is due to the occurrence of local heating from the large dynamic strain in the shear band.

It is apparent that the localized shear deformation induced fracture is of great significance. A large number of investigations show that the fracture along the shear band is attributed to cumulative microdamage during the course of shear localization. As Bai pointed out(10) recently, there are no predictable theories to describe the evolution of microdamage as well as the associated abrupt of shear strength. In other words, the occurrence of a localized shear band is a complex deformation process involving orientation change, work hardening and heat softening within the band and the the possible deformation of microstructural damage prior to final failure. In some cases, the failure is catastrophic. That is, the initiation and propagation of the failure events are almost simultaneous. Since it is very difficult to follow the whole process of development of the events during the testing, the fracture mechanisms occurring along the band at both macro-and micro-scopic scales is recommended for future study.

Conclusions

1. A localized shear band does indeed develop at the critical strain of 0.3 in the quenched martensite low carbon steel. The width of the band in this steel is larger than that in low carbon ferrite-pearlite steel.

2. The high density of dislocations and tangled and cell structures of dislocations suggest that the materials within the band have suffered a large misorientation and heavy deformation.

3. Because of the large accumulated plastic strain in the shear band, some grains in the band become non-crystallographic form, and some grains still retain their crystallographic nature. This implies that the localized shear deformation band involves a spatial distribution.

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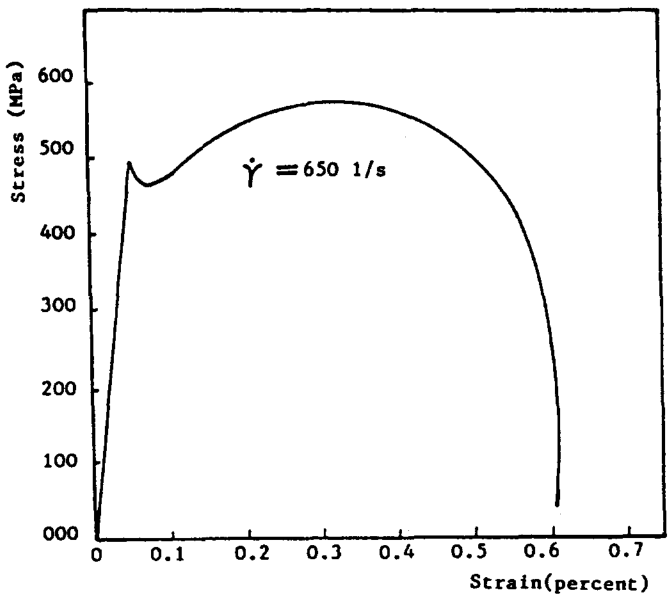

Fig. 1 Stress-Strain curve of the test specimen

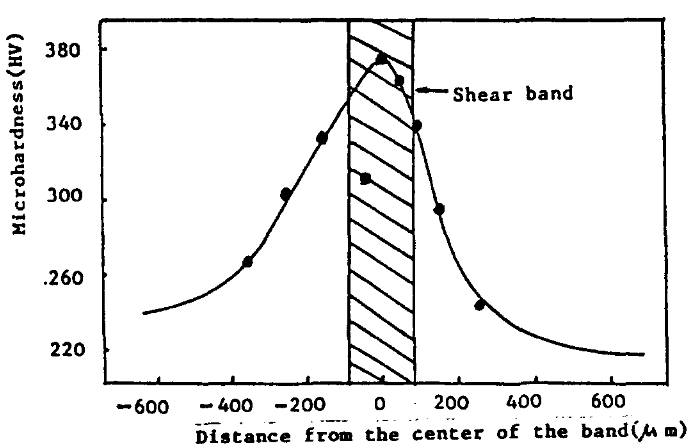

Fig.2 Profile of the microhardness across the shear band in quenched low carbon steel

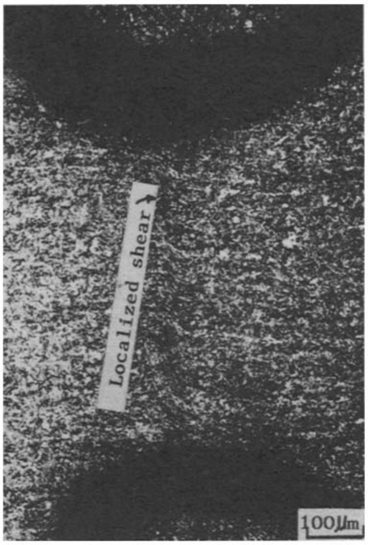

Fig.3 Macro-etched section of specimen

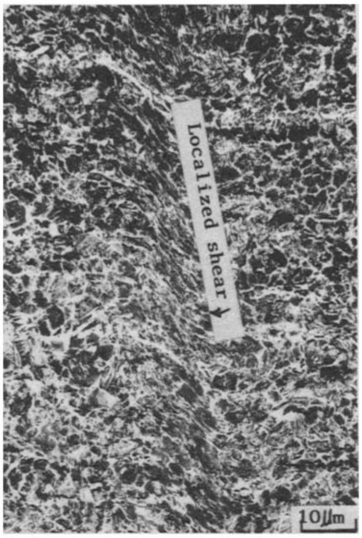

Fig.4 The localized shear deformation in the low carbon martensite steel

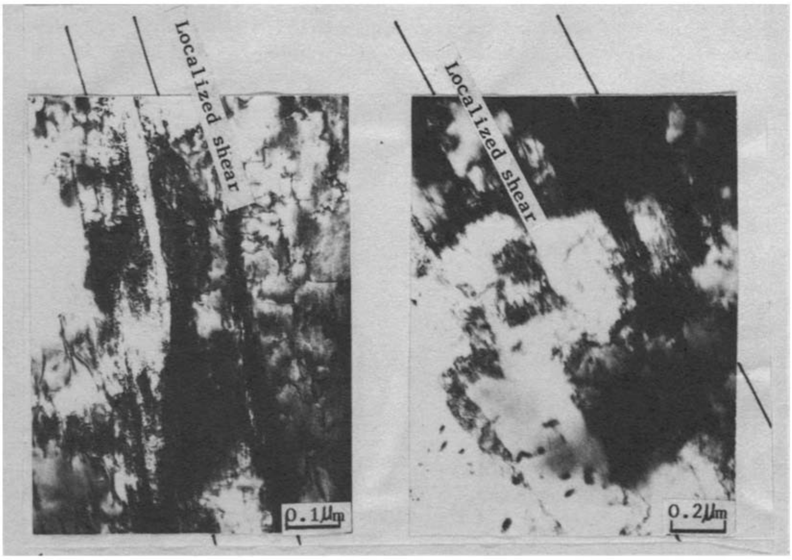

Fig.5 TEM micrographs showing the heavy density of dislocations and cell structure as well as the tangled arrangement of dislocations-tends to align along the length of the shear band

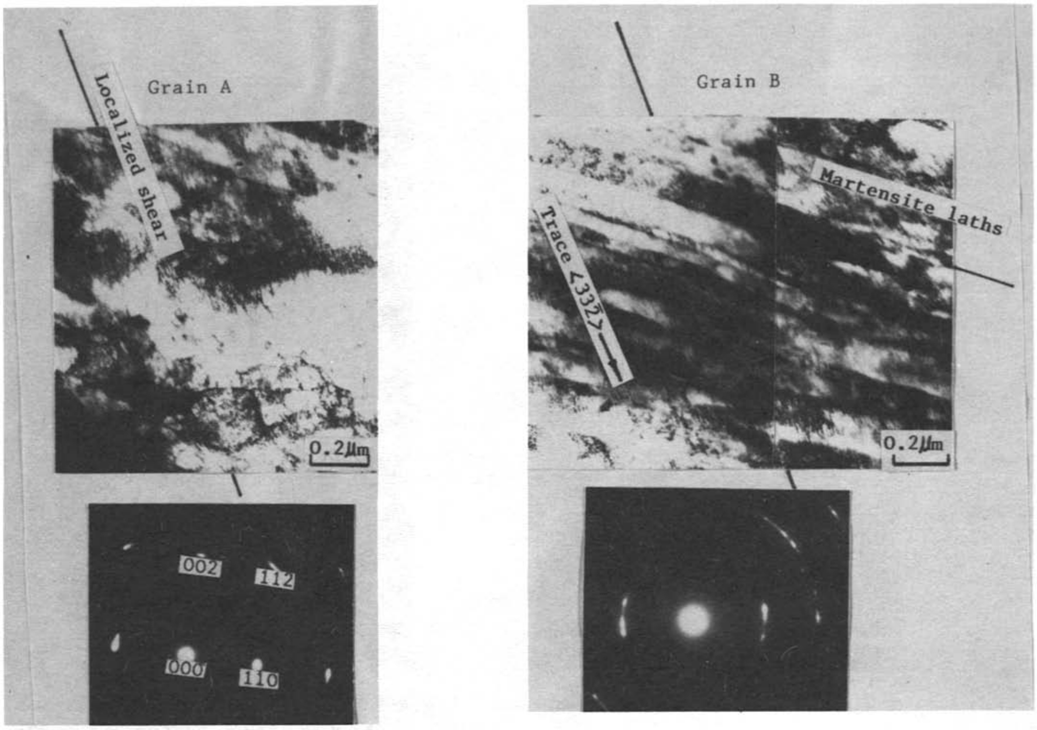

Fig.6 TEM micrographs showing the microscopic characteristics of a localized shear band. The grain A in the band exhibits a crystallographic form; however, in grain B, the shear band is non-crystallographic in form.

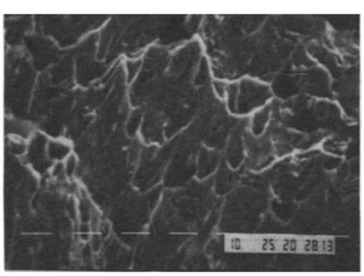

Fig. 7 Shear dimples on the fracture surface