JOURNAL OF MATERIALS SCIENCE 15 (1980) 1898–1906

Morphology and annealing behaviour of thick shear bands in polystyrene

C. C. CHAU, J. C. M. LI
Materials Science Program, Department of Mechanical and Aerospace Sciences, University of Rochester, Rochester, New York 14627, USA

Shear bands of 0.1 to 0.6 mm thick were produced in polystyrene by compression. These bands were studied by optical microscopy and surface profilometry. Both the as-deformed bands and the bands developed after annealing were investigated. Parameters such as the shear strain, step height and the height-to-base ratio of the band cross-section (ridges or valleys) were recorded.

1. Introduction

Shear bands are important microstructures developed during the deformation of amorphous polymers. An understanding of their behaviour will obviously contribute to the design and development of new polymers with superior mechanical properties. This paper represents our continued effort in the understanding of molecular mechanisms involved in the plastic deformation of polymers.

In our previous studies [1, 2] we characterized two distinct classes of shear bands in polystyrene, namely, the coarse and find bands. Later [3, 4] we concentrated on the coarse shear bands, their surface profile, shear strain distribution, splitting, joining, termination, annealing behaviour, and three types of intersection. In all these experiments, the coarse bands were thin, about 0.1 to 2 μm, and required electron microscopy for their detailed examination. They were originated at a notch or a hole in the form of a packet which consisted of two sets of coarse bands intersecting each other [5] (first type) at about 80°.

However, it was found recently that, by compression at high strain rates, a single thick shear band of 0.1 to 0.6 mm thickness could be produced at a notch. The shape of the specimen must be such that the band could propagate all the way to the free side surface. Otherwise the band would not be well defined. Once fully developed, the band is of uniform thickness along its length which can extend all the way across the width of the specimen. Even though the main band is very thick, the intersecting bands are still thin and there are fewer of them than there were found inside the coarse band packet studied earlier. Because of the thickness, the band can be observed in the optical microscope and its surface profile can be traced by a sloan Dektak surface profilometer. These techniques are not applicable to the thin coarse bands reported before. As will be shown later, there are enough differences between the thick band and the thin coarse bands to suggest that they may not be of the same kind. To avoid confusion the adjectives thick and thin will be used to differentiate between them.

2. Experimental details

2.1. Materials and sample preparation

The atactic polystyrene used, obtained from the Westlake Co, was the same material as that used in the previous experiments [1–6]. The glass transition temperature was 101° C. Blocks of materials were cut from 0.25 and 0.5 in. thick sheets as supplied which were compression-moulded in an amorphous state. To eliminate any moulding strains, they were annealed for 20 h at 115° C and furnace-cooled to room temperature over a period of about 6 h. Specimens of 2.5 × 1 cm^2 were then cut from the blocks by using a milling machine. A 60° notch was made in the middle of one side of the milled specimens to serve as stress concentrator from which the thick bands would initiate. All specimens were polished to 0.05 μm alumina finish. They were then annealed again at 98° C for 20 h to remove any machining and polishing

0022–2461/80/081898–09$02.90/0

strains and then furnace-cooled slowly to room temperature.

2.2. Compression tests

Specimens were compressed in the Instron testing machine at a high strain rate of $0.1\,sec^{-1}$ to start plastic flow. The thick shear bands would initiate from the notch and propagate speedily along a straight path to the other side of the specimen. By presetting the compressive displacement using cross-head control dials, the cross-head was raised at the same speed as soon as the shear bands were fully developed. As mentioned before, it is important that the shape of the specimen is such that the bands can propagate all the way to the free side surface.

2.3. Optical microscopy and surface topography

The deformed specimens were observed under the Olympus Vanox model optical microscope. The surface profile of the banded specimens was traced by a Sloan Dektak Surface Profilometer with a diamond stylus sensing head. The stylus tracking force is about 50 mg, so that the stylus can leave only very fine scratches on the specimen surface after tracing. The surface profiles of the thick bands were recorded on a strip chart recorder. A model MJ Olympus optical microscope was set up on the surface profilometer for the observation of the bands.

3. Results and discussion

3.1. Surface topography of the thick shear band

The thick bands produced in this experiment were usually of uniform thickness in the range of 0.1 to 0.6 mm. They started from the notch, propagated along a straight path toward the other side surface, and invariably displaced all the surface scratches. The angle between the band and the compression axis is about 39°. This is about the same as the angles measured in the case of thin coarse bands. The band and the surface features can be clearly examined under the optical microscope. Fig. 1 shows a section of the thick shear band. Within the band, it is possible to see the strands of fibres inclined toward the shear direction. These strands of fibres are making an angle of 20.9° ± 1.5° (19 measurements along one band) with the band direction. This angle is similar to the angle (21.6° ± 1.6° for 50 measurements) made between the striation and the band in the case of thin coarse bands. Sometimes cracks or openings developed between the strands in a more or less periodic manner as shown in Fig. 2. The shapes of

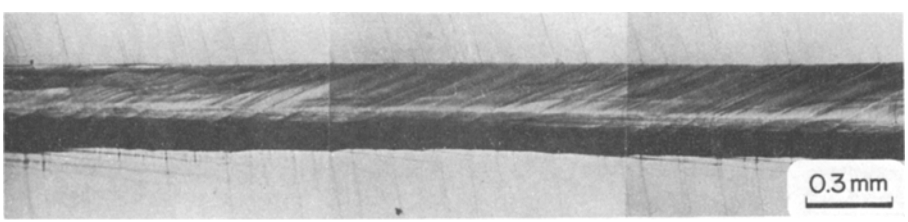

Figure 1 A section of a thick shear band showing the strands of fibres and the intersecting thin bands and their connections.

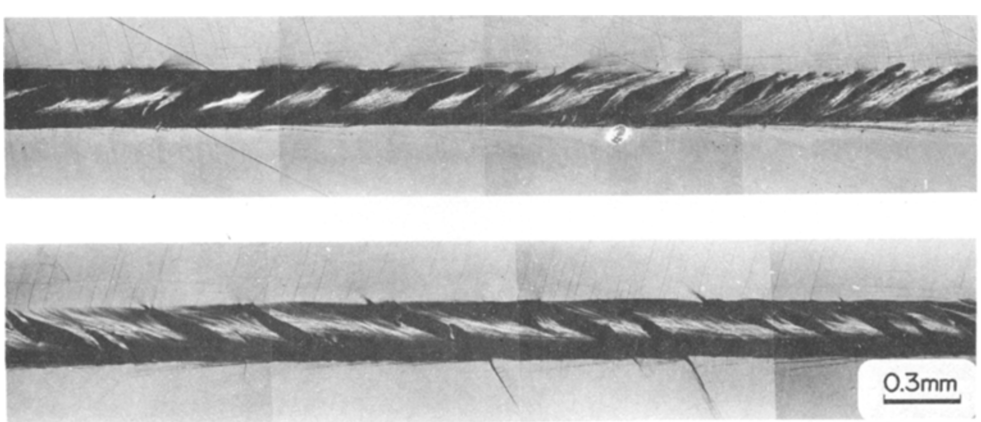

Figure 2 Other sections of a thick band showing the openings and cracks between the strands of fibres.

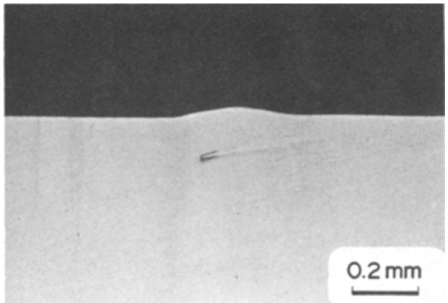

Figure 3 The triangular cross section of a thick band ridge.

the cracks or openings are such that they were usually larger in the middle of the band thickness and gradually became smaller toward the boundaries. These cracks or openings may be formed as a result of differences in the relative shear displacements between the strands inside the band during propagation.

The intersecting set of bands are very thin compared to the main band as seen in Figs. 1 and 2. These thin coarse bands resemble those studied before [1]. They seem to be connected to the end of striations in the main band as seen in Fig. 1. The intersecting angle between the thin bands and the main band is about 80° same as observed before [5] between the thin coarse bands.

As reported before [3] the cross-section of the coarse band is an isosceles triangle with the height to base ratio of about 0.1. This result was indirectly deduced from electron microscopic observations of replicas of thin coarse bands. The same ratio was also directly observed from Dektak traces of thick bands. Fig. 3 shows a section sliced perpendicular to the thick band direction and the shape of the isosceles triangle is obvious. However, the height-to-base ratio is not a constant along a thick band as shown in Fig. 4 although the average ratio is still about 0.1.

Fig. 5 shows the shear strain along the same thick band as the one used for height/base ratio measurements shown in Fig. 4. The average shear strain is about 2.70 which is larger than the usual shear strain (1.8) in the thin coarse bands. A comparison between Figs. 4 and 5 did not reveal any direct relation between the height-to-base ratio of the cross-section and the shear strain along the thick band.

3.2. Morphology of slip steps

On the side surface which makes an angle with the shear direction (50° with the surface normal), a

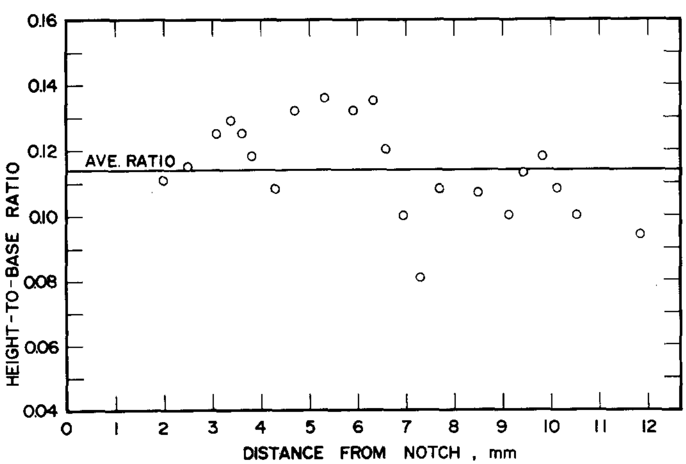

Figure 4 The height to base ratio of the cross section measured along the length of a thick band.

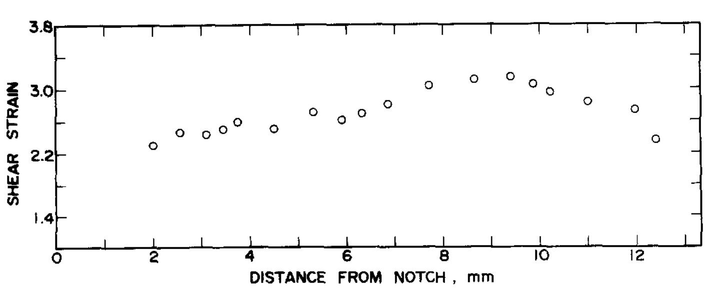

Figure 5 The shear strain measured by the displacement of scratch marks along a thick band.

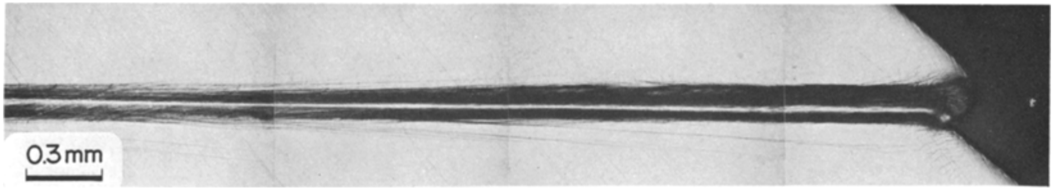

Figure 6 A step produced on the side surface penetrated by a thick band.

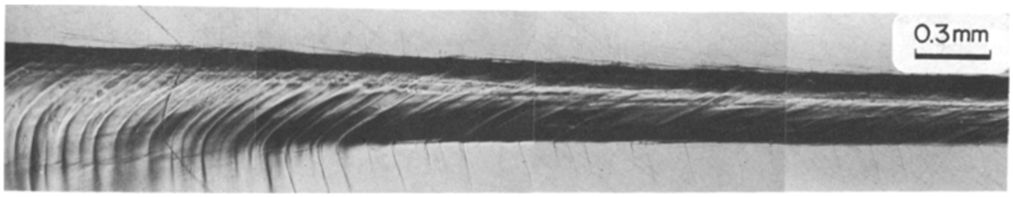

Figure 7 The appearance of a terminated thick band inside the side surface of the specimen.

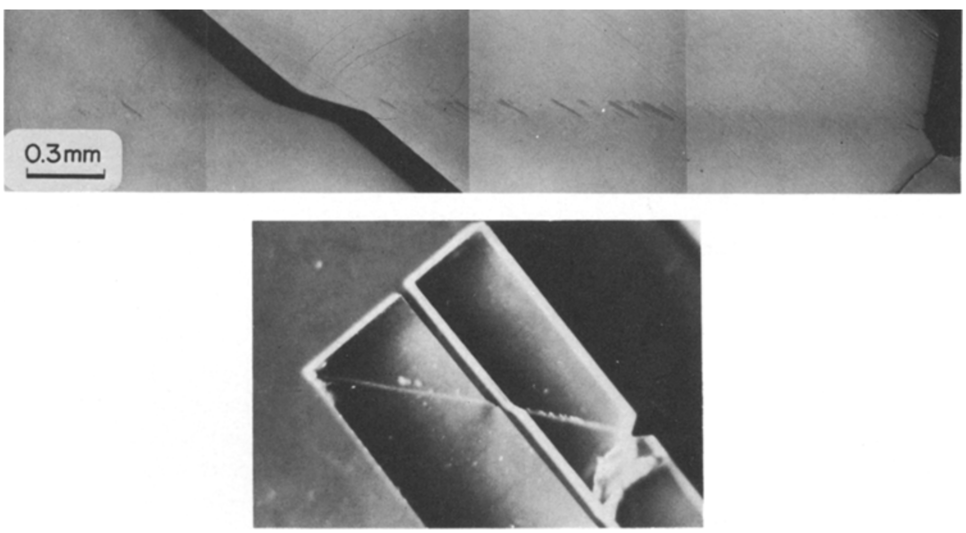

Figure 8 Matching steps developed after annealing of the two halves of a specimen sliced parallel to the side surfaces.

step was produced when the thick band penetrated the surface. Such a step is usually not sharp as shown in Fig. 6. The height of the step or the distance between the two surfaces separated by the thick band is usually 0.1 to 0.5 mm. If the thick band stopped before it penetrated the side surface, no step was produced. Only a kinked area appeared. The thick band gradually lost its identity by converting itself into thin bands and fine bands as shown in Fig. 7.

If the step was polished flat and fully annealed, a reverse step of about the same size developed in the expected direction. If the thick banded specimen was cut into two halves along a plane parallel to the side surfaces and the two cut surfaces were polished before the two halves were annealed for 100 min at 110° C, a pair of matching steps were developed as shown in Fig. 8.

It is clear from Fig. 8 that the thick band extends all the way through the thickness of the specimen. This behaviour is different from that of thin bands which propagate wavily in the thickness direction [3] and may not extend completely through the thickness.

3.3. Annealing of thick shear bands

As mentioned earlier, annealing of thick bands causes their shear strain to recover, and their

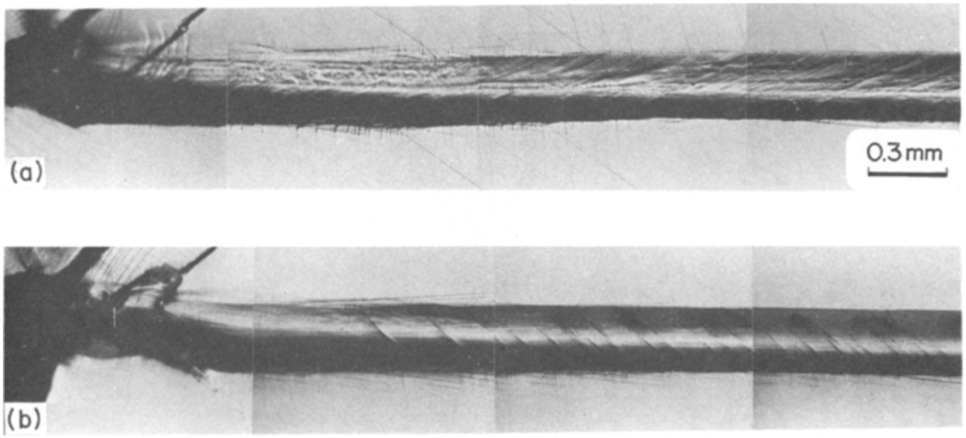

Figure 9 Annealing of a thick band after polishing: (a) original band before polishing, and (b) new band appeared at the old band location after polishing and annealing.

identity to disappear. The kinetics of shear strain recovery of the thick bands have been reported [6]. Here the change of surface profile upon annealing is described. Fig. 9a shows a thick band initiated from a notch. The surface profile of the band was recorded by Dektak as shown in Fig. 10 and the height-to-base ratio was about 0.105. The shear strain along the band as measured by scratch marks was about 2.16. The sample was then polished and annealed for 3 h at 110° C. A new band appeared on the surface as shown in Fig. 9b. A careful comparison of the new band with the old one before polishing shows that the new band is at the old band location. However, the new band is a valley instead of a ridge as revealed by Dektak traces also shown in Fig. 10. The depth-to-base ratio was about 0.099, which is about the same as the height-to-base ratio before annealing. The shear strain measured by scratch marks is about 2.05 which is also about equal to the shear strain measured before annealing. All these seemed to indicate that both the shear strain and the volumetric effects in the band are fully recovered after annealing.

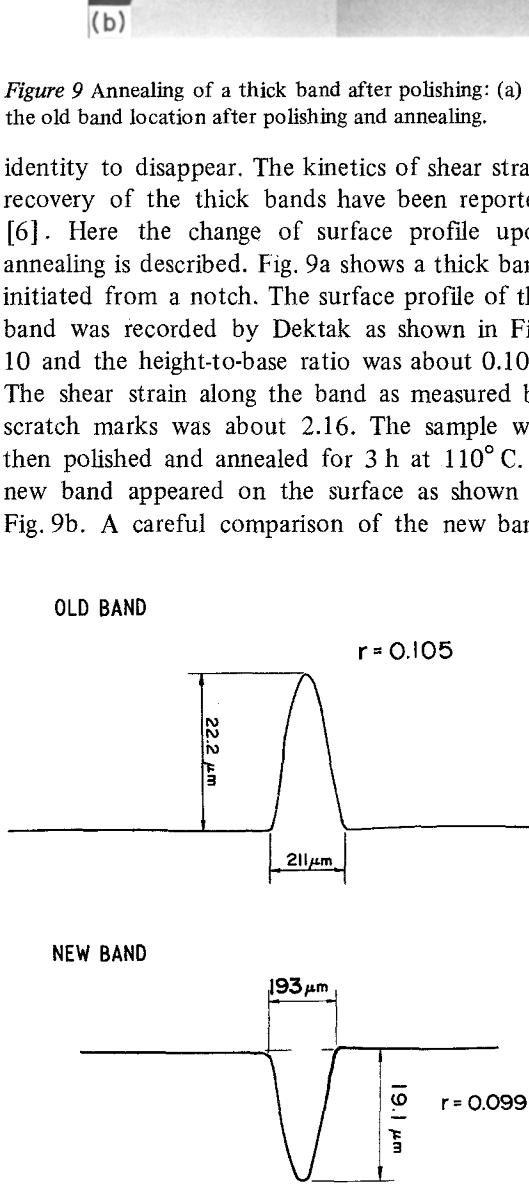

Figure 10 The cross sections of the old band ridge (as deformed) and the new band valley (after polishing and annealing).

As in the case of thin coarse band, the shear strain recovery and the apparent volume shrinkage of the thick bands also occurred inside the specimen. A banded specimen was cut into two halves by slicing along a plane parallel to the shear direction. The cut surfaces were polished and both halves were annealed at 110° C for 3 h. Both halves developed matching patterns of bands on the cut surfaces as shown in Fig. 11. The shear strains measured by the scratch marks on the cut surfaces are about the same and equal to 1.6. The surface profile of the annealed bands was again traced by Dektak, it was found that the bands on the cut surfaces were both valleys. The depths-to-base ratio was about 1/20 on each band. The combined ratio was still about 1/10. Several such measurements were made, they were all very similar.

A set of results are shown in Fig. 12. A notched 0.5 in. thick specimen was first deformed to produce a thick band which developed ridges on both surfaces. Fig. 12a shows the thick band profile on one surface. The h/b ratio is about

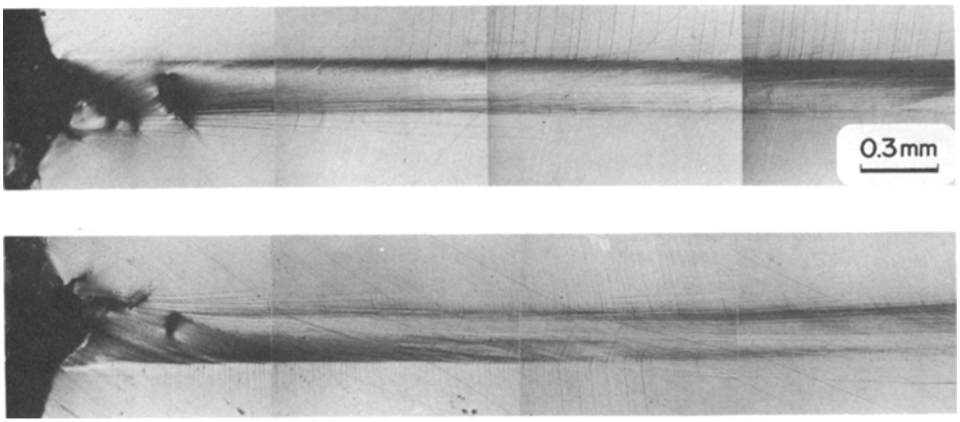

Figure 11 Matching patterns of recovered bands appeared on the two cut and polished surfaces.

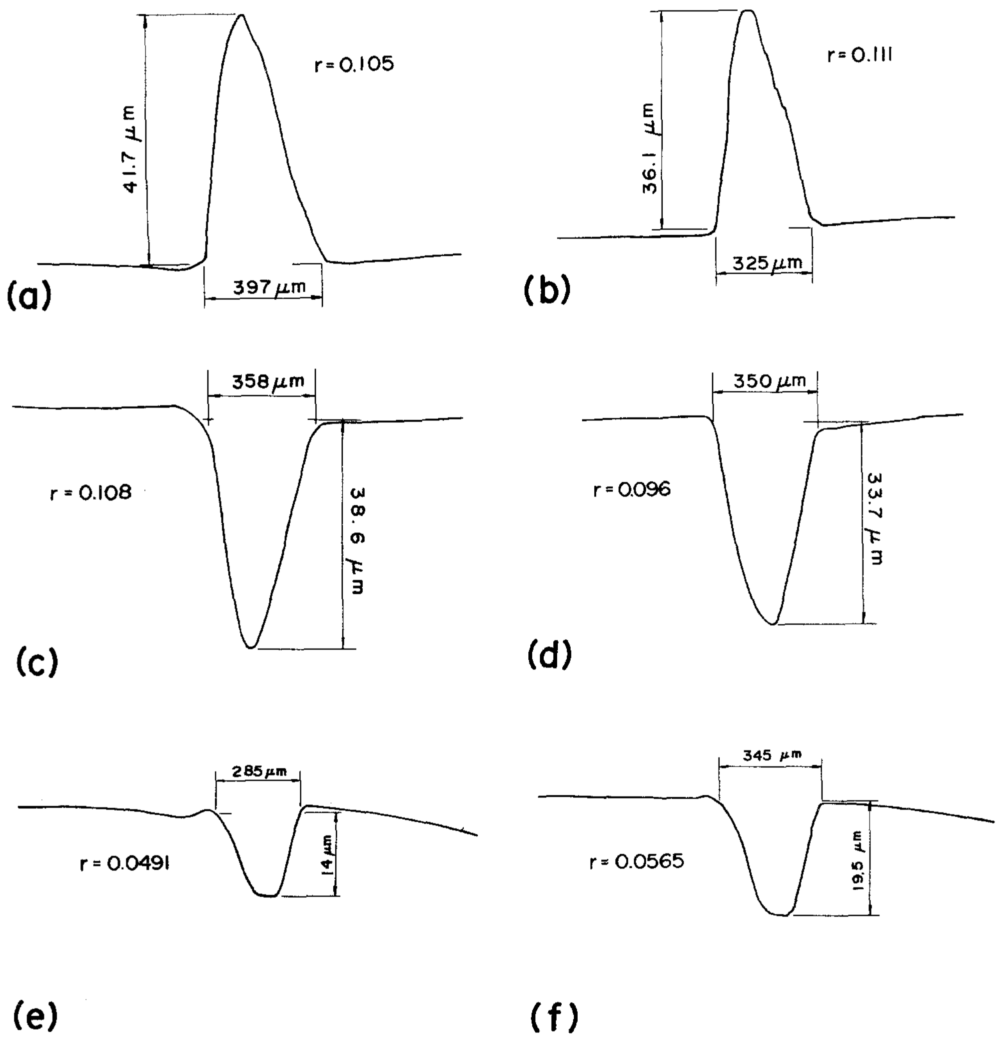

Figure 12 A well-developed thick band and the annealing of the two halves of the specimen cut parallel to the banded surfaces: (a) the ridge on one banded surface, (b) the ridge on the other banded surface, (c) the valley developed on the polished surface of (a) after annealing, (d) the valley developed on the polished surface of (b) after annealing, (e) the valley developed on the cut and polished surface opposite of (c), and (f) the valley developed on the cut and polished surface opposite of (d).

0.105. Fig. 12b shows the profile on the other surface, the h/b ratio is about 0.111. The specimen was then cut into two halves in the middle of the thickness along a plane parallel to the shear direction. The two half specimens were well polished and annealed as just described. Fig. 12c shows the annealed band profile on the same surface as that in Fig. 12a. The depth-to-base ratio was determined to be 0.108. Fig. 12d shows the other surface; the depth-to-base ratio is about 0.102. Fig. 12e shows the band profile on one cut surface. The depth-to-base ratio was determined to be 0.049 while the band profile on the other cut surface is shown in Fig. 12f. The depth-to-base ratio is about 0.052. However, the combined ratio is still 0.101.

3.4. Shear strain inside the specimen

The shear strain within the thickness of the specimen was also measured. Since a thick band, unlike the thin bands, extends from one surface through the thickness to other surface, it is possible to measure the shear strain inside the thickness. A 0.5 in. thick specimen was first deformed to produce thick bands. The specimen was then cut into four thin slices each about 0.1 in. thick. All the eight surfaces were polished and then all the slices were annealed for 3 h at 110° C. Bands appeared on each polished surface due to strain recovery. Since the thick bands were almost fully recovered after annealing [6], the recovered band displaced all the scratches on the polished surface. The shear strain along the band thus can be measured. Fig. 13 shows the strain measured at two corresponding locations on each surface. It is seen that shear strain within the thickness is also a constant.

3.5. Strain localization

From the foregoing results, it is clear that the thick band is a uniformly (more or less) sheared region extending through the thickness of the specimen. To see whether there was any deformation outside the band, a comparison was made between the compressive displacement of the specimen and the displacement contributed by the thick band only. To do this, a single, well-developed thick band was produced in a rectangular specimen with a hole at one of the four corners to initiate the band. The results are shown in Fig. 14. The compressive displacement was measured directly by a micrometer. The displacement made by the thick band was calculated by multiplying the average shear displacement with cos 39.5° to resolve onto the compressive direction. It is seen that the former exceeds the latter by only about 4% which can be attributed to the few thin bands accompanying the thick band. This experiment assured us that the deformation is completely localized inside the shear bands. The material outside the bands is not deformed at all.

3.6. Redeformation of a thick band

Unlike the situation in the case of thin coarse bands where redeformation produces many new

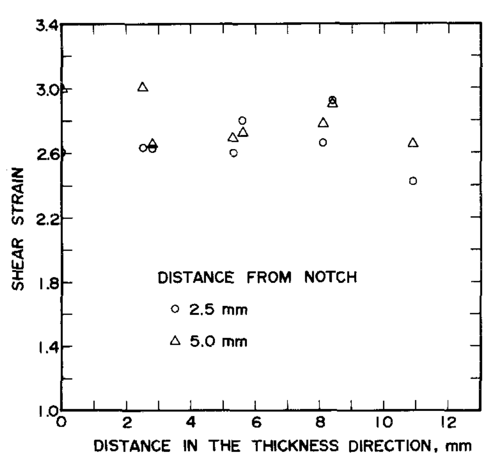

Figure 13 Shear strain of a thick band measured inside the thickness of the specimen by the slicing and annealing technique.

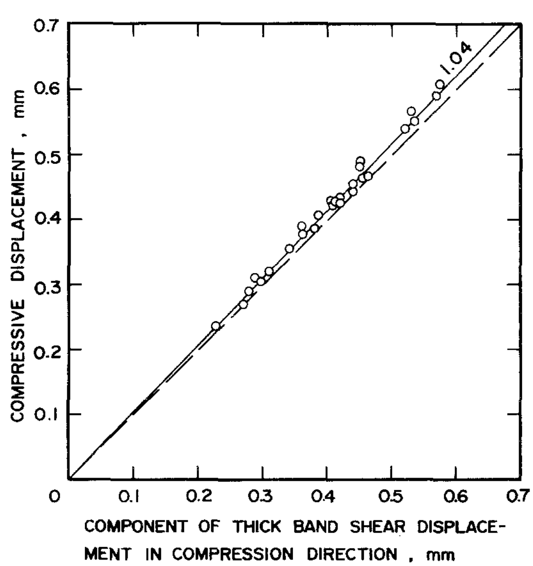

Figure 14 A comparison of the compressive displacements of the specimen and the displacements contributed by the single thick band produced during compression.

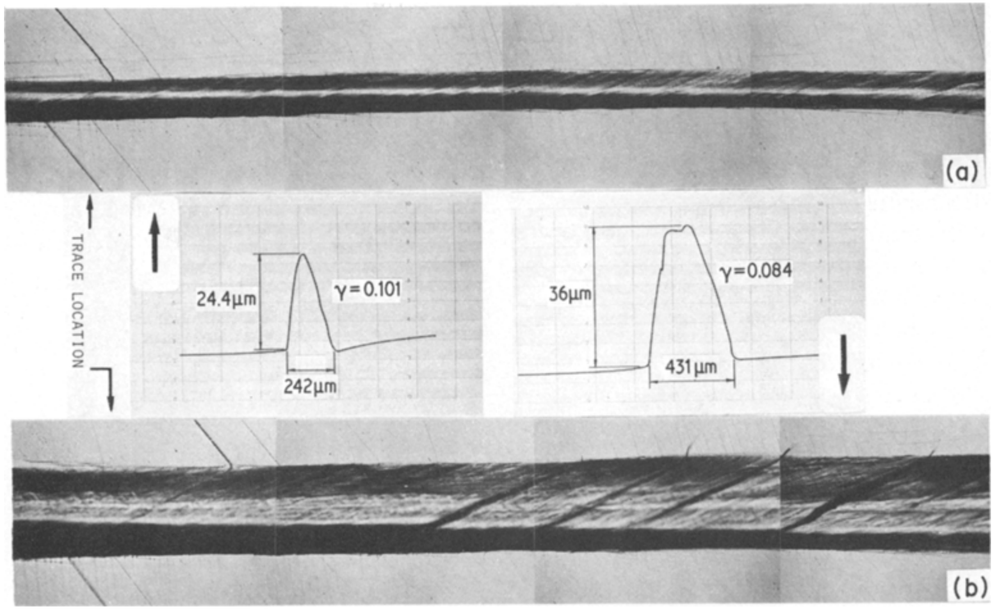

Figure 15 Redeformation of a thick bend: (a) original thick band, and (b) a new thick band produced next to the old band to appear as a single band.

thin bands not related to the old ones, redeformation of a thick band produces a new thick band next to the old one. In fact, the new band is so close to the old one that they can be considered as a single band as shown in Fig. 15. Fig. 15a shows a well-developed thick band whose thickness is 0.24 mm. The shear strain as measured by the big scratch is about 2.75. The height-to-base ratio is shown by the accompanying Dektak trace is about 0.10. The specimen was deformed a second time in the same direction. The same area is shown in Fig. 15b. It is seen that a new band was produced next to the old one. They are so close as to appear as a single band. The thickness of the joined band is 0.43 mm. The strain as measured by the same scratch is still 2.76. Furthermore, the accompanying Dektak trace shows a rugged profile with a height-to-base ratio of 0.08. Fig. 16 shows another combined thick band after redeformation. The Dektak trace shows obvious double ridges in this case.

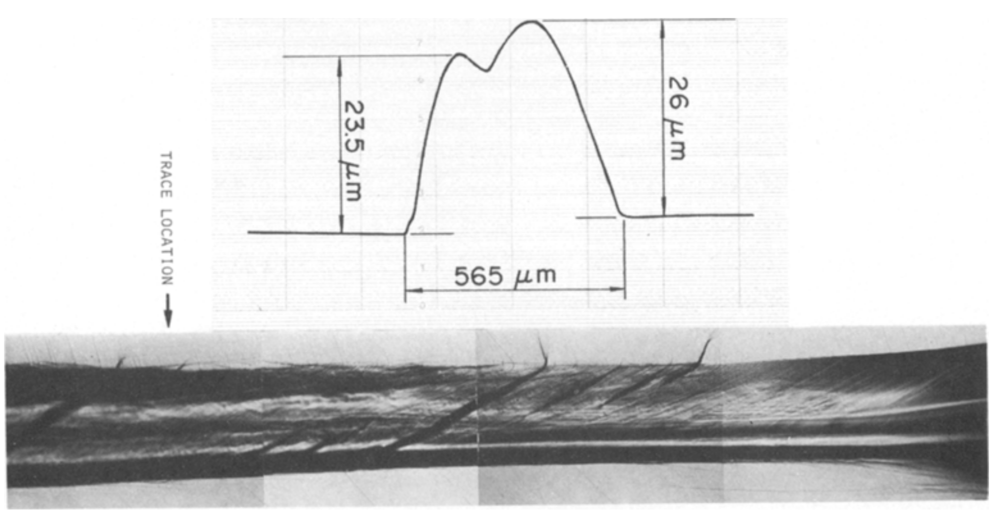

Figure 16 Another combined band after redeformation showing the double-ridge cross section.

4. Conclusions

(1) The thick band consists of strands of fibres oriented at about 21° with the band in the shear direction. This angle is close to that made by striations in the thin coarse bands. Between the strands of fibres there may be openings or cracks which occur more or less periodically.

(2) Like thin coarse bands, the thick band appears as a ridge on the surface whose cross-section is an isosceles triangle with height-to-base ratio of about 0.1. The ratio varies somewhat along the length of the band (Fig. 4).

(3) The shear strain in the thick band is about 2.7, larger than that in the thin coarse bands (~ 1.8). It also varies somewhat along the band (Fig. 5).

(4) The thick band produces a step when it penetrates the side surface. This step disappears after annealing. If the side surface is polished before annealing, a reverse step appears after annealing. If the specimen is cut into two halves along a plane parallel to the side surface, polished and annealed, two matching steps appear on the cut surfaces.

(5) If a banded surface is polished and then annealed, a new band appears in the old band location but it is a valley instead of a ridge. If the specimen is cut into two halves along a plane parallel to the banded surface, polished and annealed, two valleys (each having a depth/base ratio of about 0.05) appear on the cut surfaces (Fig. 12).

(6) By the slicing and annealing technique, the shear strain inside the thickness of the specimen can be measured and the results reveal only some variation about the mean (Fig. 13).

(7) The strain inside the thick band contributes to more than 96% of the total plastic strain of the specimen (Fig. 14).

(8) Redeformation of a thick band produces a new thick band next to the old one to appear as a single band whose cross section may show double ridges but whose height/base ratio is still about 0.1.

Acknowledgement

This work was supported by the US Army Research Office, Research Triangle Park, North Carolina, through contract DAAG-29-76-G0314.

References

1. J. B. C. WU and J. C. M. LI, *J. Mater. Sci.* **11** (1976) 434.
2. J. C. M. LI and J. B. C. WU, *ibid.* **11** (1976) 445.
3. C. C. CHAU and J. C. M. LI, *ibid.* **14** (1979) 1593.
4. *Idem, ibid.* **14** (1979) 2172.
5. B. T. A. CHANG and J. C. M. LI, *ibid.* **14** (1979) 1500.
6. J. C. M. LI, *Met. Trans.* **9A** (1978) 1353.

Received 9 October and accepted 23 October 1979.