Reverse shearing of shear bands in polystyrene

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Shear bands produced in polystyrene by compression can be reverse sheared by a second compression in a perpendicular direction. The net shear strain can be zero or negative. Like the forward shear, the reverse shear also produces a ridge on the surface. The height of the ridge seems to be proportional to the reverse shear strain. On the side surface the reverse shear produces a step whose height increases at an average rate of 1.17 mm sec^{-1} (at a crosshead speed of 1 mm sec^{-1}), estimated by high-speed cinematography at 1000 frames sec^{-1}. During the reverse shear the second compression experiences a yield drop whose size increases with the forward strain due to the first compression. The implications of these results are discussed.

1. Introduction

It is known that mechanical deformation of a polymer introduces microstructural changes. Although it is still difficult to describe these changes on a molecular scale, the differences between deformed and undeformed materials are quite obvious. These differences occur in density [1–4], stored energy [5], shape recovery [6–8], the Bauschinger effect [9, 10], and molecular transport [11]. When the deformation is localized into shear bands, we find additional evidence for the difference between shear band material and undeformed material. These include chemical etching [4, 12], birefringence [13], intersection with another shear band [14], intersection with crazes [15], recovery of shear strain [12, 16], recovery of surface features [17, 18], microcracking [19], and solvent swelling [20].

So far, the implications on microstructural changes are as follows:

1. The Gibbs free energy density increases at some spots as indicated by local chemical activity [4, 12] (etch pits).

2. The structural modifications may have opposite signs which annihilate each other during recovery as implied by the second order kinetics [7, 16].

3. The deformed material is anisotropic as evidenced by the Bauschinger effect [9, 10], intersection of shear bands [14], recovery of shear strain [16], and normal strain [6–8] and birefringence [13].

4. There may be broken or weakened bonds as indicated by easy crack nucleation at the shear band boundaries [19].

5. Channels may be created for easy passage of diffusing molecules [11, 20].

For crystalline materials, all these implications can be explained by dislocations. Here, without a crystalline structure, it is difficult to detect dislocations by diffraction methods. For the same reason, the slip vector is not a constant, the dislocation line may not be continuous, and the propagation cannot be confined to a single plane. Because of long chain molecules, the slipped area must have a different structure from that before the slip. This is a major difference between polymers and crystals, since in crystals when the slip vector is a translation vector, the slipped area has an identical structure to that before the slip. Because of this fundamental difference, the shear band in a polymer can be sheared in reverse so as to return the shear strain to zero. Such reversibility, although possible, has not been reported in crystalline materials. A study of shear strain reversal in a thick band in polystyrene is reported in this paper.

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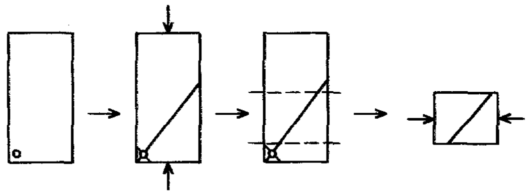

Figure 1 Experimental procedure for reverse shearing of a shear band.

2. Experimental details

2.1. Materials and specimen preparation

Atactic polystyrene sheets of 0.635 cm thickness were obtained from the Westlake Co. They were of the same material as used in our previous studies. Blocks cut from the sheet were annealed at 115° C for 20h. They were furnace-cooled to room temperature for a period of over 6h. Specimens of 1 cm x 2 cm were cut by a milling machine. A hole, 1.1 mm in diameter, was drilled at a corner to initiate a shear band. All specimens were polished to a 0.05 μm alumina finish. They were annealed again at 98° C for 16h to minimize the residual stresses.

2.2. Compression testing

The testing procedure is shown schematically in Fig. 1. As shown specimens were first compressed in the length direction in an Instron at a strain rate of 0.1 sec^{-1} to initiate a shear band from the hole. They were then cut along the dotted lines which intersect the shear band and polished first on emergy paper and then with alumina slurries. The small specimens were compressed in the perpendicular direction to cause the shear band to shear in the reverse direction. It is important that during the second compression the shear band intersects the side surfaces. Otherwise the shear strain cannot be effectively reversed.

2.3. High-speed cinematography

To observe the time sequence of the reverse shear process, high-speed photography was used. As before [19, 21], a Redlake Hycam model 41 16mm camera, operated at 1000 frames sec^{-1} under 300W small tungsten bulb illumination, was used. Films were developed by Kodak and viewed with a L & W analyst projector.

2.4. Dektak surface profilometry

The surface profile of the shear bands was traced, as before, by a Sloan Dektak surface profilometer with a diamond stylus sensing head [17, 19]. The profiles were recorded on a strip chart recorder. A model MJ Olympus optical microscope was set up on the Dektak in order to be able to observe the shear bands at the same time.

3. Microscopic observations

3.1. Morphology and surface topography

On the top Fig. 2 shows the original shear (thick) band developed on a polished surface. The shear strain along the band as measured by the displacement of scratches was about 2.07. The surface step was polished down (see Fig. 1) during the preparation of the smaller specimen for reverse shear. The shear band was then also polished down to a 0.05 μm alumina finish as shown in the middle of Fig. 2. After reverse deformation, the band reappeared (as shown in the bottom of Fig. 2). A detailed examination using surface marks showed that the location of the new band was the same as that of the old band.

The reverse strain along the new band as measured by the displacement of scratches was about 2.92, indicating that there was a net shear strain of $2.07 - 2.92 = -0.85$ in the reverse direction. As often observed in the old band, cracks and openings were produced in the new reversed band. In addition, a large sharp step appeared on the side surface. An inspection of the angle made between the step and the side surface shows that the step is parallel to the striations in the old band. This observation implies that the reverse shear starts in the direction of the striations in the old band. Since the striations were parallel to the fibrous sheets as reported before [17], the part of the reversed shear band exposed to the side surface was separated from the unsheared part and became curled up as shown. An enlarged picture of this feature is shown in Fig. 3. This curling up effect is a good indication of the strain energy stored in the shear band, which provides the driving force for thermal recovery of the shear strain [16].

To observe an early stage of the reverse shear process, the reversed shear strain was limited to a smaller amount. Fig. 4a shows the original band before the reverse shear. The shear strain is about 2.0. A Dektak trace shows the height to base (h/b) ratio of the surface ridge to be 0.114. The band was then polished away and slightly reverse sheared as shown in Fig. 4b. It can be seen that many thin bands appeared first within the old band area. The shear strain was only about 0.37

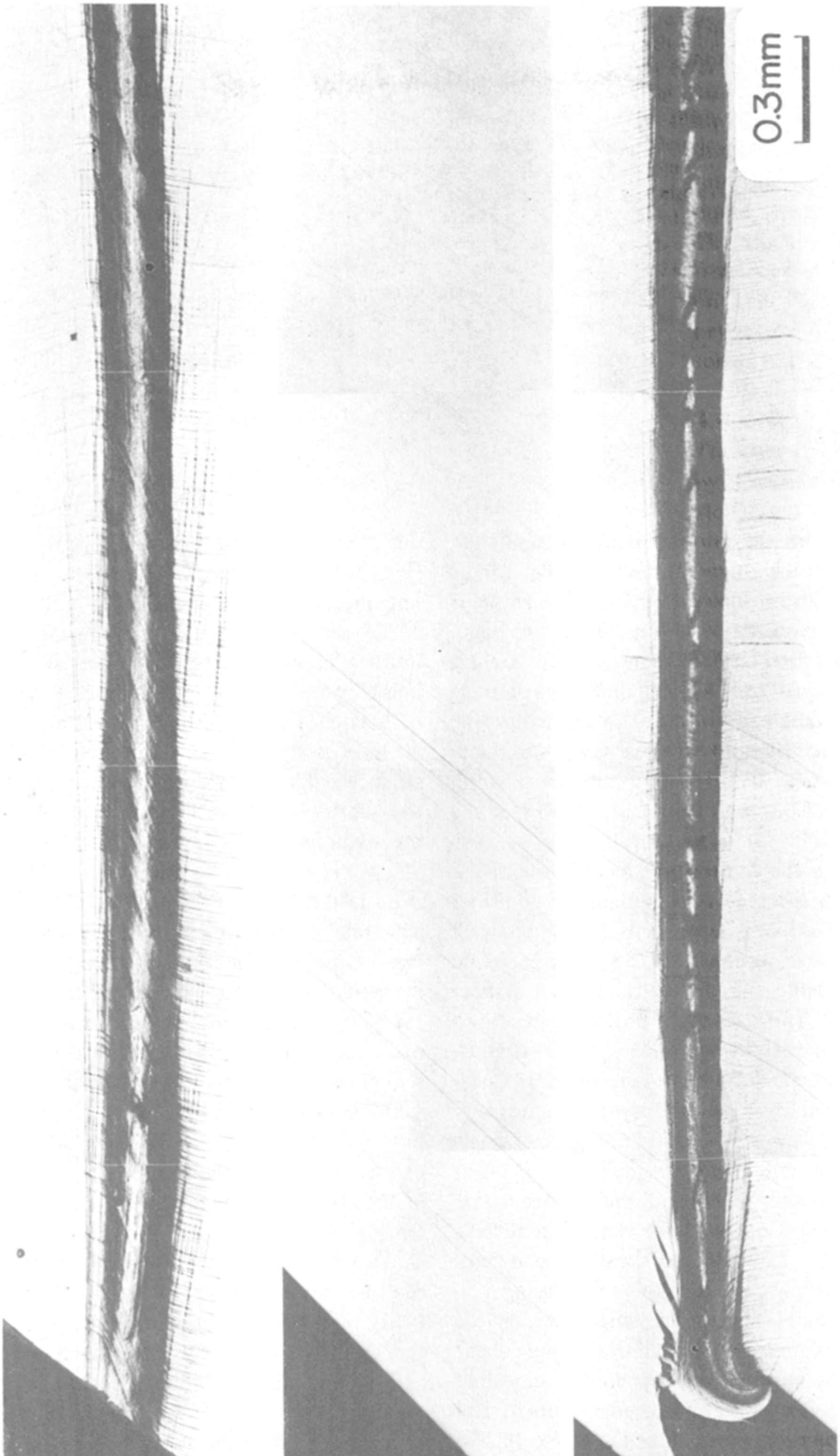

Figure 2 Surface appearance of the original band (top) which was polished down (middle) and the reappearance of the band after reverse shearing (bottom).

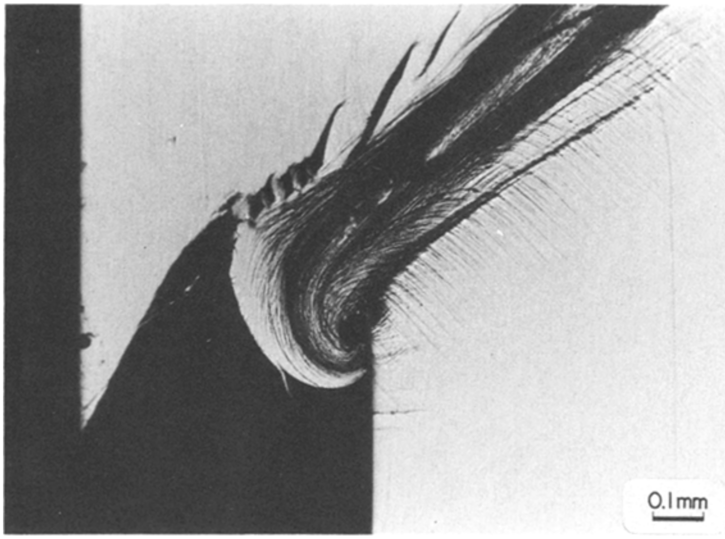

Figure 3 Details of the step shown in Fig. 2 and the curling up of the fibrous structure.

as indicated by the displacement of scratches. While most of the thin bands are parallel to the old band direction, some are oriented at an angle closer to the striation directions of the old band. At this strain the Dektak trace showed a ridge given by $h/b = 0.026$. The fact that this is a ridge instead of a valley shows that the surface profile relates more to the normal stress across the thickness of the shear band than to the shear strain ($2.0 - 0.37 = 1.63$, which is still positive) of the shear band.

To see how the ridge height increases with the reverse strain, the second compression in another test was divided into four steps at progressively increasing reverse strains of -0.58, -1.32, -2.22 and -2.84, while the original band had a shear strain of 2.39. The results are shown in Fig. 5a to e. While the h/b ratio was 0.126 for the original band, it increased during the reverse shear (after the original band was polished away) progressively from 0.048, 0.102, 0.215 to 0.263 for the respective reverse strains. There seems to be a linear relationship between h/b and the reverse strain as shown in Fig. 6. The fact that at a reverse shear strain of -2.39, the net shear strain is zero, did not seem to have affected this relationship.

The fact that the surface bulges are related more to compressive deformation than shear deformation is indicated further in the annealing results of the fourth-time reversed specimen. The polished surface showed a deep valley ($h/b = 0.428$) after annealing as shown in Fig. 7. This ratio is just about equal to the sum of 0.126, due to the first compression (Fig. 5a), and 0.263, due to the accumulated four-time reversals (Fig. 5e). The difference may be the result of baseline uncertainties as seen in Fig. 7.

To see whether the reverse shear strain was uniform along the band, local shear strain measurements were carried out from the displacement of scratches after each compression. The results are shown in Fig. 8. It can be seen that the shear strain was fairly uniform along the band although the scatter seems to increase with the extent of reverse deformation.

3.2. The rate of reverse shearing

The rate of the reverse shear appeared to be as fast as that of the forward shear. The speed was measured using high-speed cinematography. A set of these movie pictures showing the formation of a step is assembled in Fig. 9 (not a consecutive sequence) from a movie strip originally taken at 1000 frames sec^{-1}. The original band was not polished away and so was visible all the time. It can be seen that the reverse step was produced at exactly the same place as the original band. During the later stages of the reverse shear thin shear bands were produced along the band so that the thickness appeared greater.

By measuring the step height under an enlarger, the time variation of the step height was plotted as shown in Fig. 10. It can be seen that the reverse shearing rate was almost a constant except for a somewhat faster rate at the beginning. The crosshead speed during reverse deformation was 1 mm sec^{-1} which corresponded to an initial strain rate of 0.04 sec^{-1} with a specimen length of about

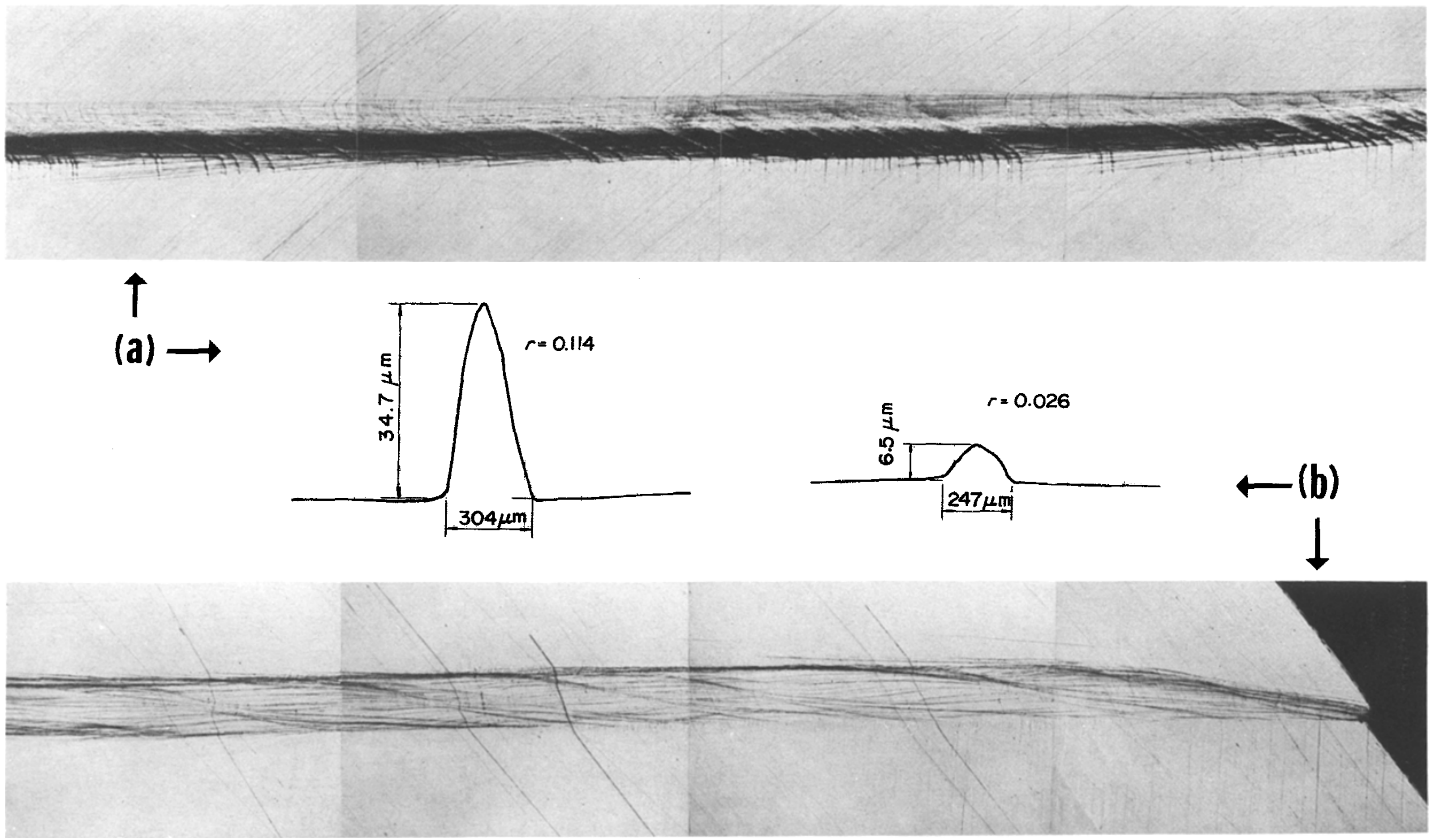

Figure 4 Surface profile of (a) the old band and (b) the reversed band (after the old band was polished down) after a small amount of reverse shearing.

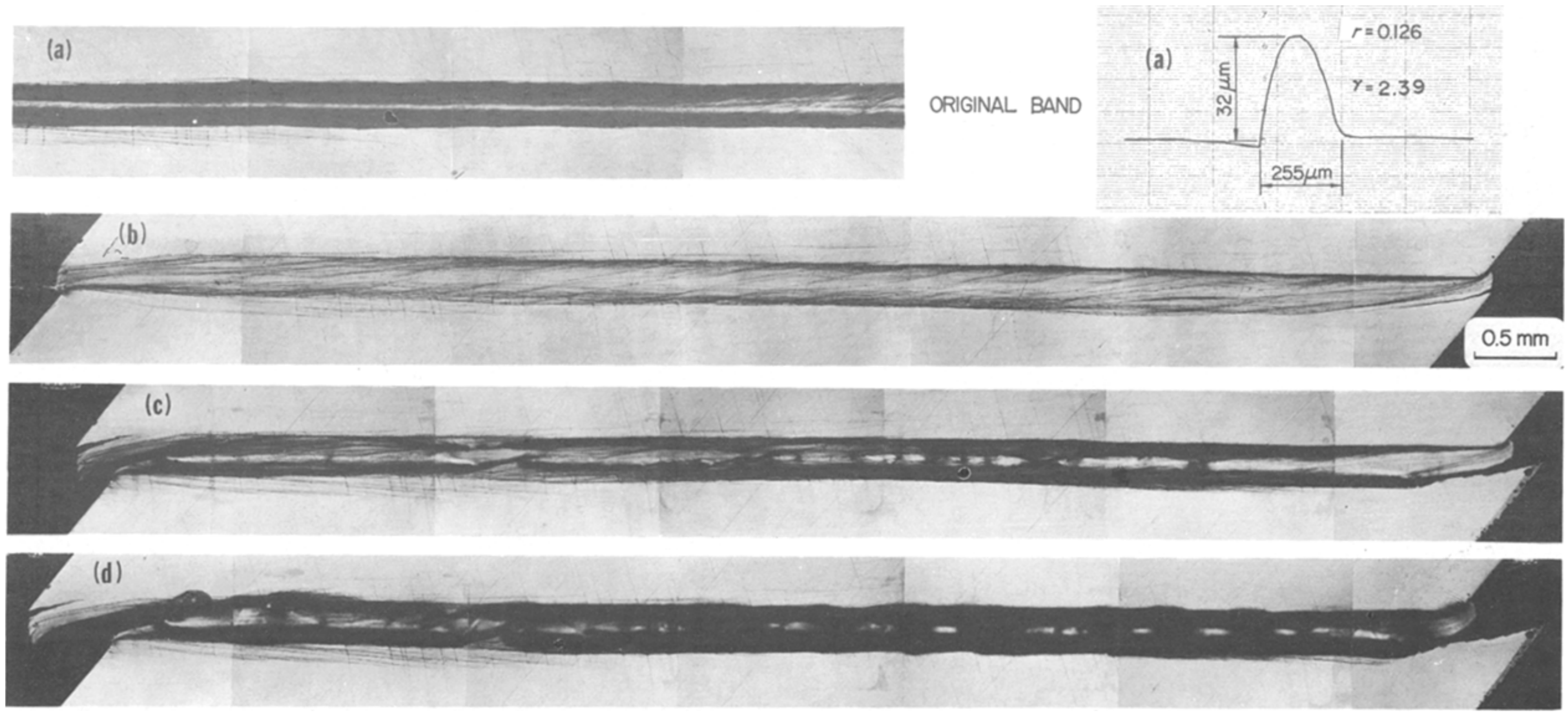

Figure 5 The effect of the reverse strain on the height of the surface ridge: (a) old band (b) 0.58 (c) 1.32 (d) 2.22 and (e) 2.84 reverse strain.

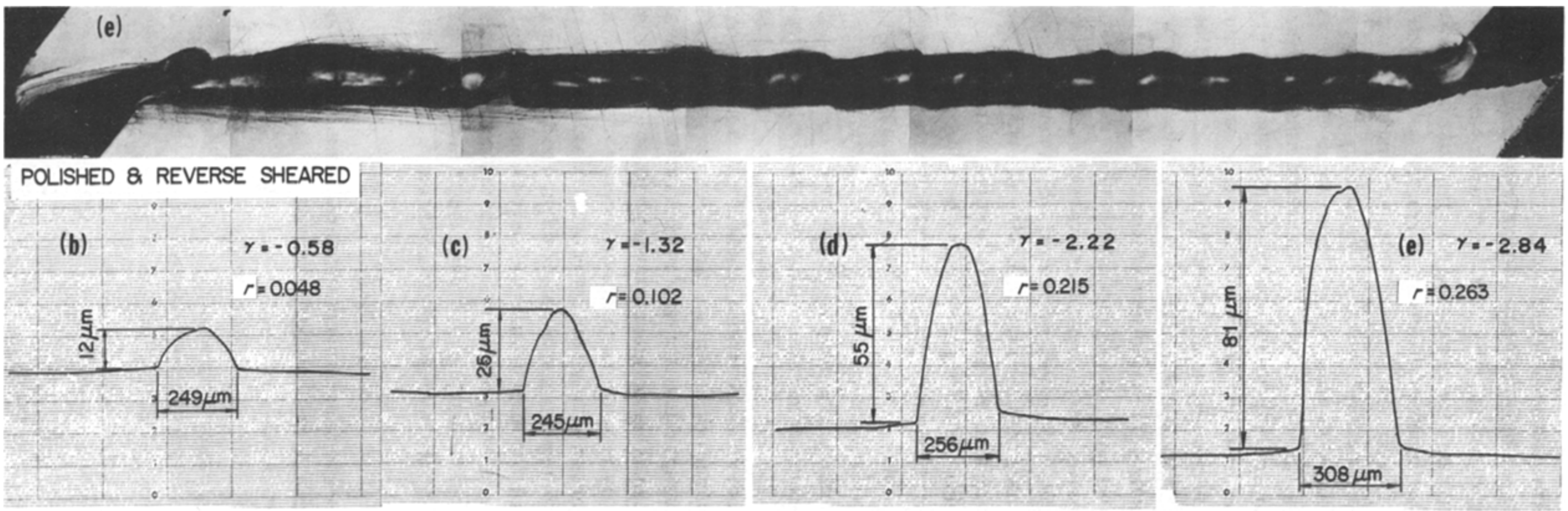

Figure 5 Continued.

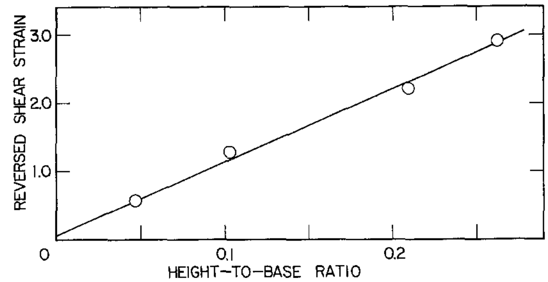

Figure 6 The linear relationship between the reverse strain and the height to base ratio of the surface ridge.

2.5 cm. The average rate of step height increase was about 1.17 mm $\sec^{-1}$. Since the angle between the shear band and the compression axis was about 50° and tan 50° is 1.19, it indicates that all the deformation was contributed by the reverse shear of the original shear band. As will be shown later, the reverse shearing took place during a small yield drop. Hence the crosshead speed was also the compression speed of the specimen. The deformation process went through a zero shear position as indicated in Fig. 10 without any apparent effect on the shearing rate. The total deformation time was 0.74 sec. Since the strain rate was not very high, it did not result in shear fracture of the specimen.

3.3. Strain localization during reverse shear

In the movie sequence, the rate of step height growth seemed to correlate with the crosshead speed indicating that the deformation was localized in the shear band. To study this in some detail, two specimens each having several steps of the reverse deformation and 13 other specimens each having a different extent of reverse shear were examined. In each case, the compressive displacement as measured by the height of the specimen was compared with the resolved component (sin 39.5°) of the reversed shear displacement of the shear band as indicated by the scratches. The results are shown in Fig. 11. It is seen that they are indeed the same except for large strains when new thin coarse bands and/or fine bands were developed. Then the compressive displacement was larger than the reverse shear

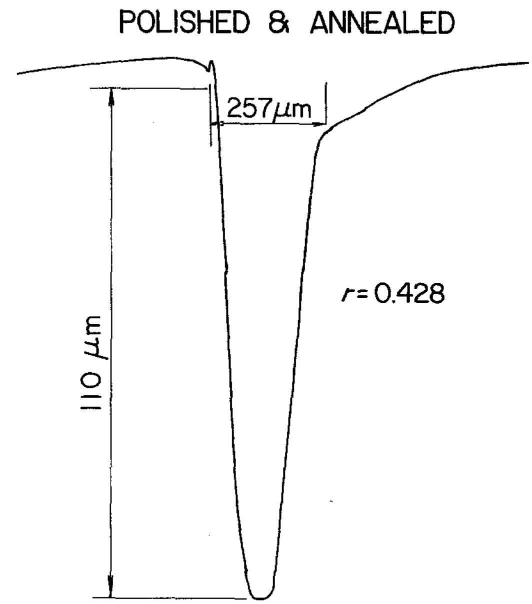

Figure 7 The surface valley developed after the annealing of a reversely sheared band.

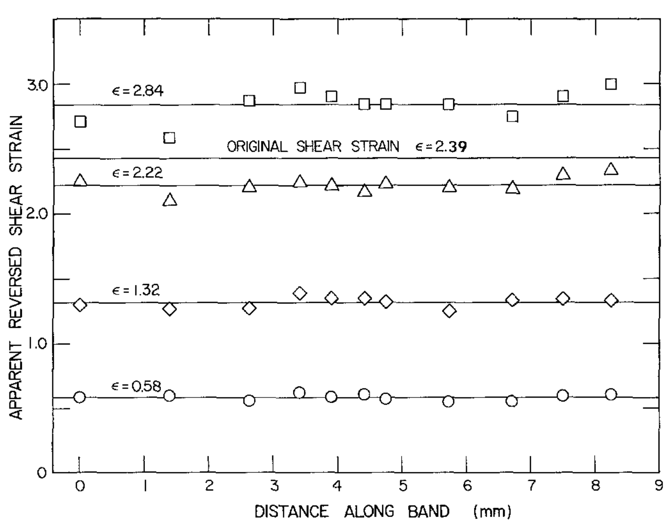

Figure 8 Variation of the reverse shear strain along the shear band.

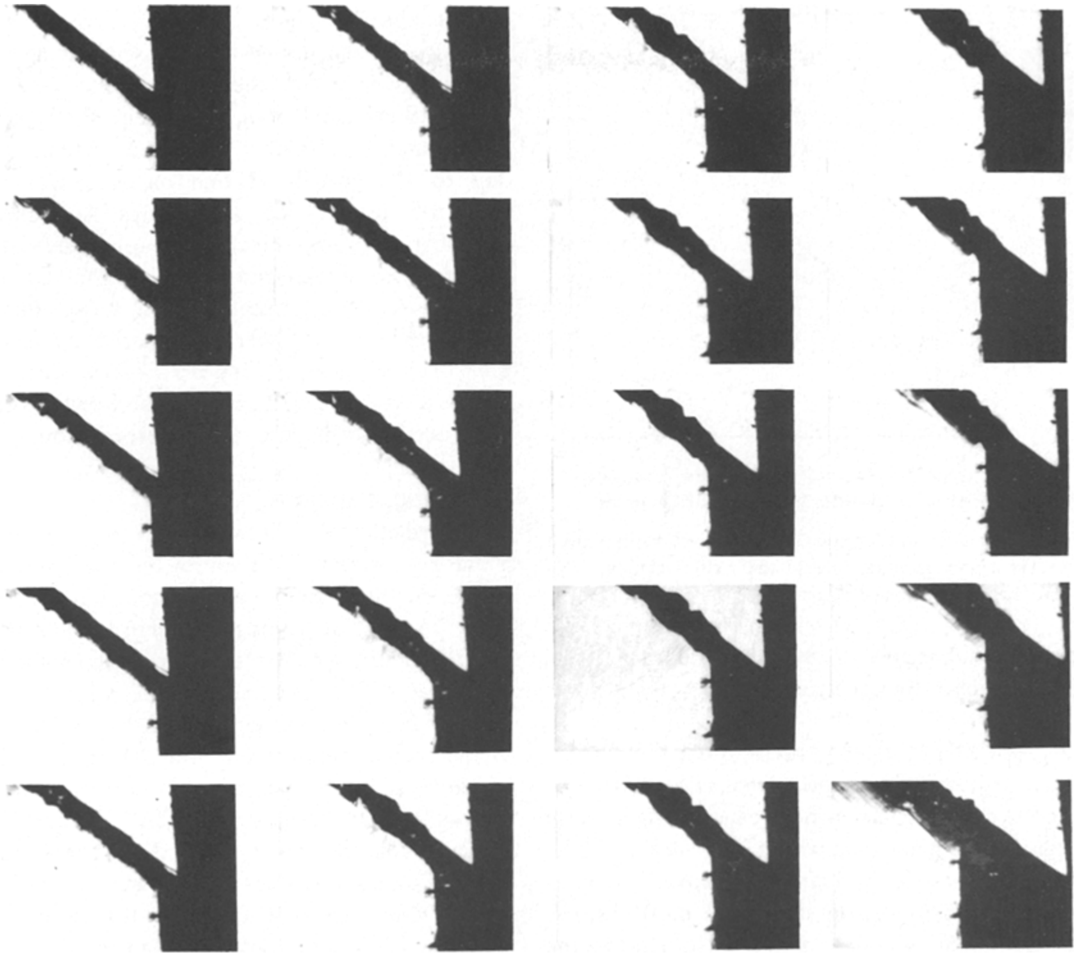

Figure 9 High-speed movie sequences (not consecutive) in the development of a reverse shear step.

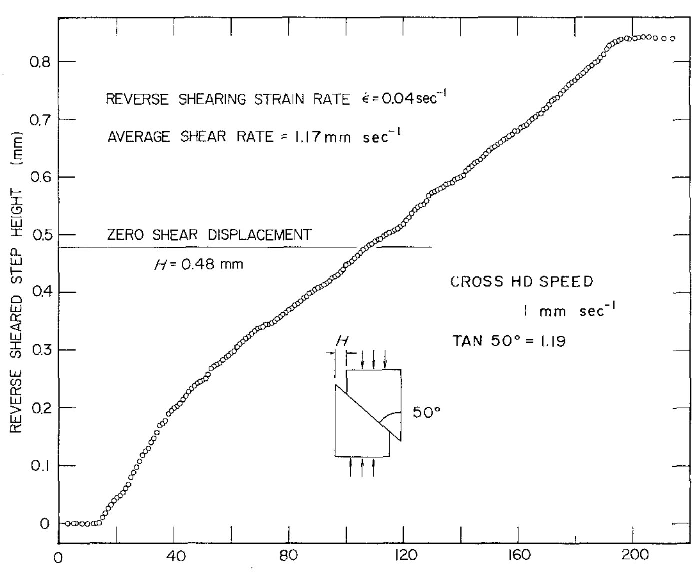

Figure 10 Time variation of the step height during reverse shearing.

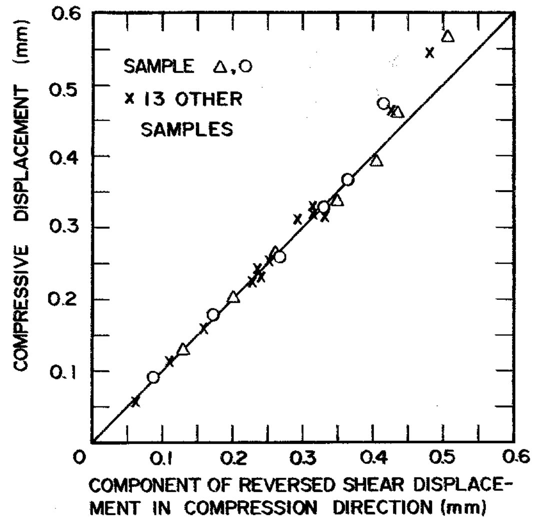

Figure 11 A comparison of compressive displacement with the component of reverse shear displacement indicating the localization of shear within the band.

component because of these extra contributions to the strain of the specimen.

3.4. Annealing after reverse shear

Fig. 12 shows the annealing behaviour after the second compression which caused the reverse shear. The original band with a shear strain of 2.44 and a thickness of 0.22 mm (not shown) was produced at a compressive strain rate of $0.15\,\text{sec}^{-1}$. The specimen was then polished to remove the step (not the band). The second compression strain rate was $0.04\,\text{sec}^{-1}$ and the total reversed shear strain was −4.38 with a net reverse strain of −1.94. The situation after the second deformation and before annealing is shown in Fig. 12a. The specimen was then annealed at 108° C for 4 min. It can be seen from Fig. 12b that the step height was reduced. Some stress concentration or deformation occurred near the step apparently due to uneven recovery rates along the band. After 12 min annealing, these stress concentrations seemed to decrease while the step height was further reduced as shown in Fig. 12c. The general recovery of surface features was also apparent. After 22 min one of the stress concentrations seemed to disappear with a further decrease of step height and recovery of surface features as shown in Fig. 12d. By 42 min the step height recovery seemed complete. Since the step was polished away after the first shear, a step such as the one shown in Fig. 12e would have appeared if the specimen was then annealed without the reverse shear. The residual microcracks were probably formed during the reverse shear and the horizontal parts of the cracks delineated the original shear band boundaries. Here the reversed shear band was thicker than the original band due to the growth of thin bands and/or fine bands because of slow strain rates. Also due to the slow rates, no cracks were observed inside the increased thicknesses. It is clear that the step recovery did not proceed in two stages, one to reverse the reverse shear and another to reverse the forward shear. It appears possible that the reverse shear cancelled some of the forward shearing processes during the second deformation.

3.5. Fatigue shearing

To see whether the shear strain in the shear band could be reversed once more, the specimen was cut after the second compression and polished again so that it could be compressed a third time. The direction of the third compression is such that the shear strain can be reversed once more, namely, in the opposite direction to that of the second compression and the same as that of the first compression. A set of results are as follows: forward shear strain + 2.19, first reversal or second compression − 1.38 or + 0.81 remaining, second reversal or third compression + 1.25 or + 2.06 remaining. The fact that the third compression did not exceed the strain of the first compression could suggest that the forward strain of 2.19 is close to the upper limit of shear deformation. The Dektak trace surface profiles obtained are shown in Table I. The surface was polished smooth after each compression. The small bulge for the third compression may indicate a saturation effect of surface bulges.

4. Macroscopic measurements

4.1. The stress–strain (engineering) curve of the second compression which caused the reverse shear

Fig. 13 compares schematically the engineering stress–strain curves for the forward compression without a hole and for the second compression

TABLE I Dektak trace surface profiles

	h (μm)	b (μm)	h/b
Forward strain 2.19	38	265	0.143
Reverse strain −1.38	40	275	0.146
Forward again 1.25	13.5	253	0.053

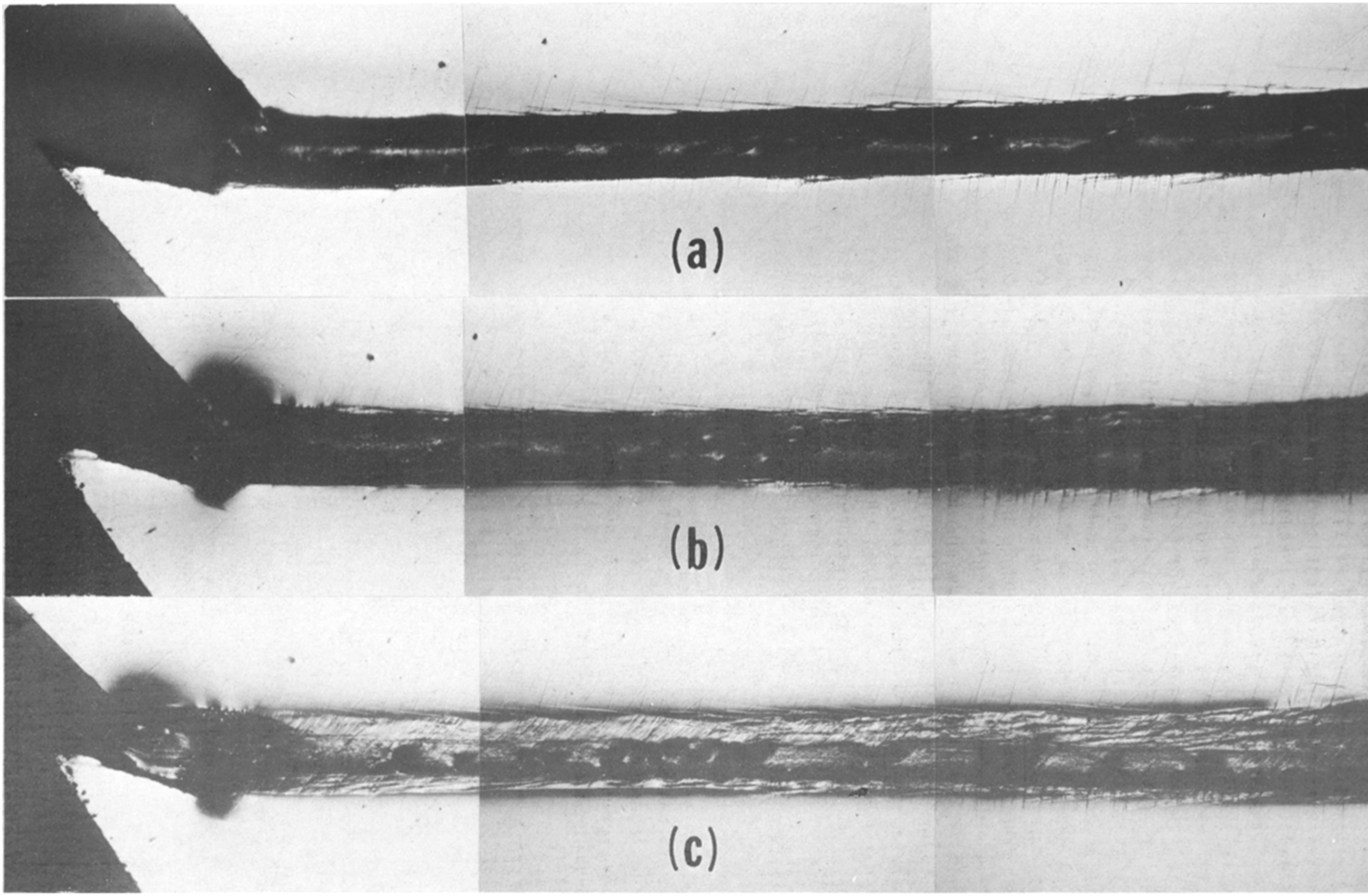

Figure 12 Annealing of the reversely sheared band at 108° C (a) before annealing, (b) after 4 *min*, (c) 12 *min*, (d) 22 *min*, and (e) 42 *min annealing*.

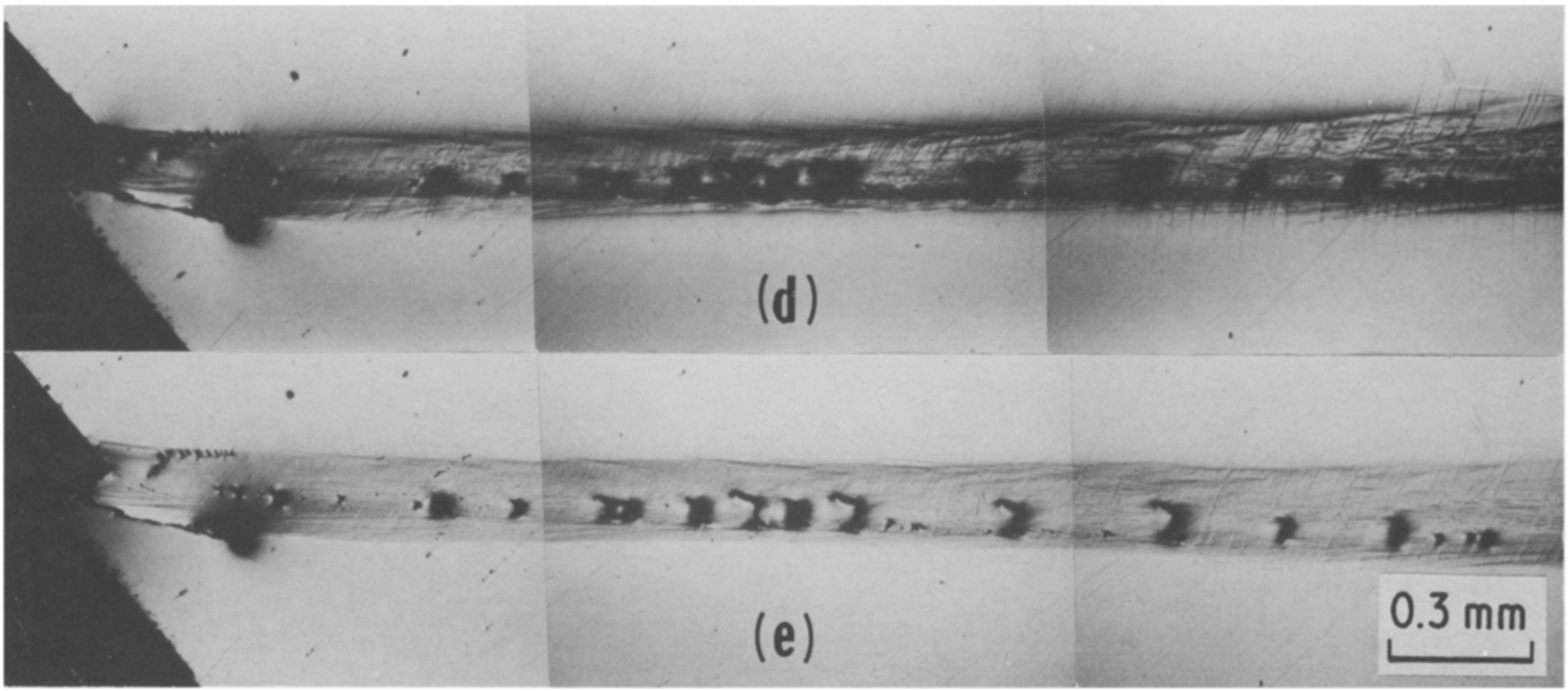

Figure 12 Continued.

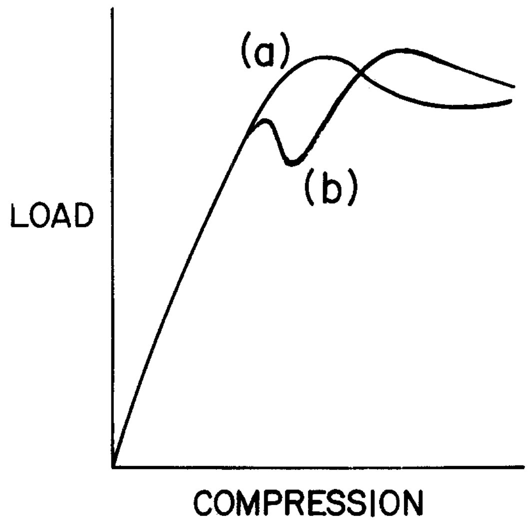

Figure 13 Schematic comparison of compressive stress–strain curves (a) without, and (b) with an existing shear band to be sheared in reverse.

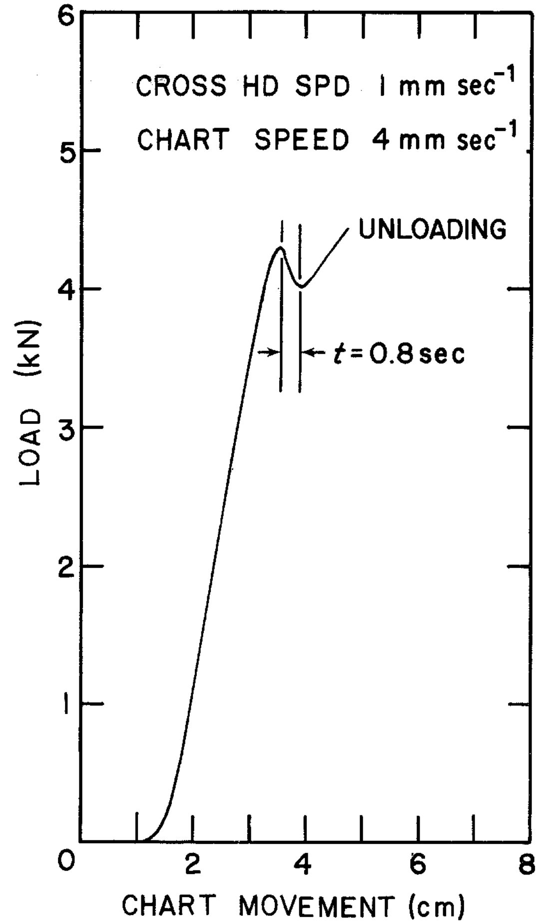

Figure 14 Instron tracing of the load elongation curve during the second compression which caused the reverse shear with the movie sequence shown in Fig. 9.

which produced the reverse shear of a shear band both at the same strain rate of 0.02 to 0.04 sec^{-1}. The shear band before its reversal was created by using a hole and a compressive strain rate of 0.10 to 0.15 sec^{-1}. Two differences are apparent: the second compression had a lower yield stress than the first and also a yield drop. Unloading before the yield point for the second compression showed no evidence of reverse shear. However, reverse shear did take place after the yield point. To see when the reverse shear took place, the Instron chart (Fig. 14) taken during the high-speed movie cinematography was compared with the movie pictures shown in Fig. 9 and the step height measurements of Fig. 10. The time between the yield point and the minimum load on the Instron chart is seen to be about 0.8 sec which compares favourably with the 0.74 sec for the reverse step formation as indicated in Fig. 10. Thus it is likely that the yield drop is due to the reverse shearing of the shear band. While the low yield stress of the second compression may have its origin in the internal stress in the shear band as in Bauschinger effect [9], the yield drop phenomenon must stem from a sudden increase of mobile or flow units inside the shear band contributing to the reverse shear. After the yield drop, the reverse step ceased to increase as seen in Fig. 10. Further straining and work hardening are due apparently to thin band activities attempting to thicken the main band as indicated in Fig. 5.

4.2. Effect of forward strain on reverse yielding

Fig. 15 shows the effect of the forward compressive strain (measured by a micrometer after unloading) on the yield stress during the reverse shear at a compressive strain rate of 0.043 sec^{-1}. The forward compression was carried out on specimens each with a corner hole under a 0.08 sec^{-1} strain rate and stopped at various cross-head displacements. When the forward strain is small only thin coarse bands appeared. Under increasing compressive strains these thin bands gradually joined together into a thick band [21]. Both the thickness and the shear strain of the thick band were not controllable during compression. Fracture would occur if the compression was not stopped in time. The variations in forward strain were mainly due to different thicknesses or displacements of the shear band. The shear strain of

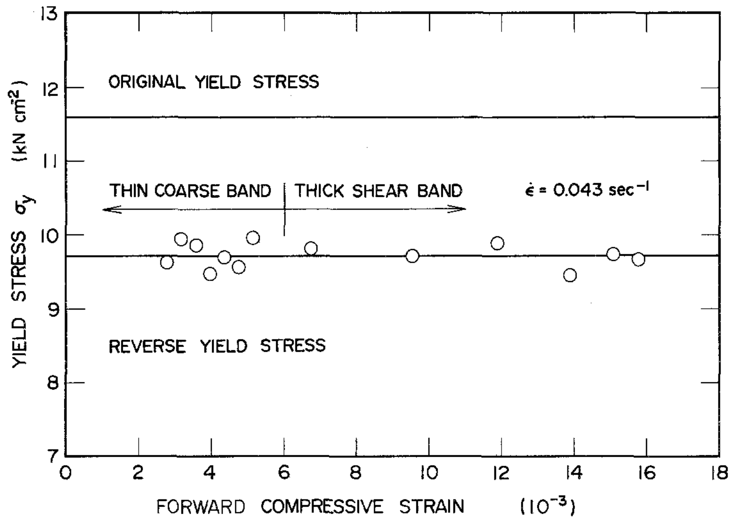

Figure 15 Effect of the forward compressive strain on the reverse yield stress.

the thick band varied only slightly between the limits of 2.50 to 3.0 as reported previously [17]. It is seen from Fig. 15 that within the experimental scatter the yield stress for reverse shear does not vary much at all with the forward strain. If such yield stress is due to the internal stress in the shear band (Bauschinger effect in shear), the fact that the forward shear strain in the shear band did not vary with the forward compressive strain [17, 18] would suggest a constant internal stress which contributes to the low yield stress of the reverse shear. The forward compressive yield stress at the same strain rate of 0.043 sec^{-1} for a specimen without a hole is also shown in Fig. 15.

On the other hand the yield drop (the difference in stress between the yield point and the first minimum) increased considerably with the extent of forward compression as shown in Fig. 16. If the yield drop is due to a sudden increase of mobile or flow units, it is reasonable to expect that a large yield drop corresponded to a large increase of mobile units which could happen in a specimen with a large forward deformation. As discussed above, the larger forward deformation was effected by a thicker shear band of similar

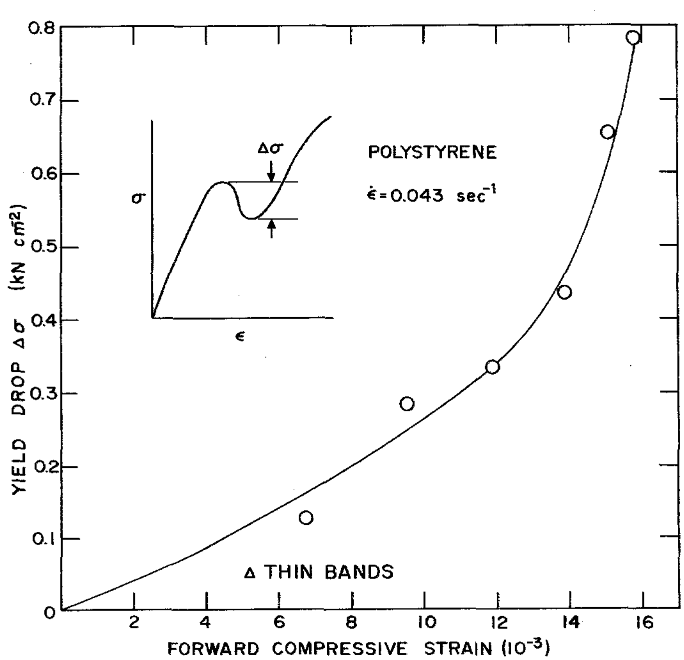

Figure 16 Effect of the forward compressive strain on the yield drop during reverse shear.

strain and hence could contain more mobile units during the reverse shear.

5. Summary and conclusions

1. The shear strain in a thick shear band can be reversed by compression in a perpendicular direction. The net shear strain can be zero and even negative.

2. The reverse shear process seems to start by shearing in the striation direction or between the fibrous sheets in the form of thin bands which appear to cover the original band area.

3. The reverse shear produces a surface ridge just as much as the forward shear and it appears that the height is proportional to the reverse strain.

4. The ridges produced by both the forward shear and the reverse shear are recoverable to yield a deep valley in the polished surface.

5. High-speed cinematography showed that during the reverse shear the surface step forms at an average rate of about $1\,\text{mm}\,\text{sec}^{-1}$ which agrees very well with the crosshead speed of the reverse compression.

6. Detailed comparisons between the specimen dimensions and the shear displacements during the reverse shear showed that the deformation is localized entirely in the shear band before its thickness changes.

7. Annealing of the reversely sheared specimen showed that both the forward shear and the reverse shear are recoverable by a one-stage process which recovers the net shear strain.

8. A shear band can be reversely sheared a second time in the forward direction. All three compressions produce surface bulges on a polished surface.

9. During the reverse shear the compressive stress–strain curve showed a yield drop. While the reverse yield stress appeared independent of the forward compressive strain, the yield drop increased with this strain. A sudden increase of mobile or flow units is believed to cause the yield drop.

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Note added in proof: N. Brown *et al.* [22] also observed reverse shear in polyethylene terephthalate.

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