Fracture of shear bands in atactic polystyrene

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Thick shear bands in polystyrene formed by compression could cause fracture or the formation of cracks by intersecting with themselves, by relaxing after the removal of the load, by propagating all the way to the side surfaces and by subsequent tensile deformation. The microstructural mechanisms involved in all these fracture processes are discussed.

1. Introduction

Early in our studies of plastic deformation of atactic polystyrene, it was realized [1] that coarse shear bands were the source of brittle fracture and fine bands were the source of ductile fracture. While the latter fracture process was slow, the former one was extremely fast and took place along the shear band. Cracking of shear bands both along the band and inside the band was also observed [2, 3] at shear band intersections. In a thick band [4] cracks inside the band were developed between strands of fibres after unloading. These processes as well as fracture of shear bands in tension are described in this paper. Some implications of the shear processes as revealed by the morphology of fracture surfaces are included also.

2. Experimental procedure

2.1. Materials and sample preparation

Atactic polystyrene of 0.25 inch (0.635 cm) thick was obtained from the Westlake Co. It was the same material as used in the previous studies [1, 2, 4]. Blocks cut from the sheet were first annealed at 115° C for 20 h. They were furnace-cooled to room temperature over a period of about 6 h. Specimens were then made from the annealed pieces by using a milling machine. Three kinds of specimen configurations were prepared. They are shown schematically in Fig. 1. Square specimens with two small holes were used in the study of the intersections of shear band packets. Notched specimens of smaller size were used for the study of shear fracture, and those of larger size were used for the compression–tension tests. All specimens were polished to 0.05 μm alumina finish. They were annealed again at 98° C for 16 h to minimize the residual stresses.

2.2. Compression tests

Specimens were compressed in an Instron testing machine at a strain rate of 0.1 sec^{-1} to initiate plastic flow. The compressive displacement was controlled by using crosshead control dials. To produce shear fracture of a specimen, the pre-set compressive strain should be as large as 8% or more to complete the process. In the compression–tension experiments, a thick shear band as described in the previous paper [4] was produced first in each rectangular specimen. The testing procedures are described in the Discussion.

2.3. Optical microscopy and surface topography

The deformed specimens were observed under the Olympus Vanox model optical microscope. The surface profile of some banded specimens was traced by a Sloan Dektak surface profilometer with a diamond stylus sensing head. The stylus tracking force was about 50 mg, so that the stylus could only leave 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 installed on the surface profilometer for the observation of the bands.

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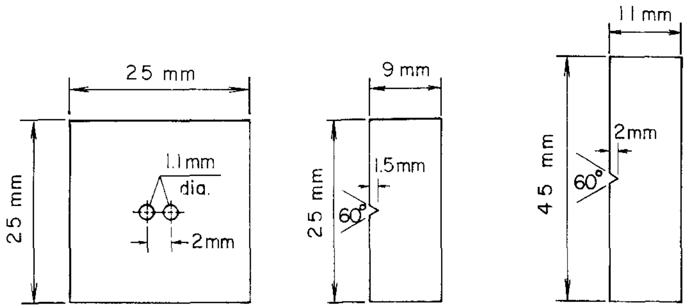


Figure 1 Specimen configurations for the study of crack formation and fracture at shear bands.

2.4. High speed cinematography

Since shear fracture usually occurred at a very high speed, a Redlake Hycam model 41 16 mm high speed movie camera was used for the study of the shear fracture process. The camera speed used was 1000 frames sec^{-1}. Films were viewed at regular movie speed (24 frames sec^{-1}) or slower by using a L & W Analyst projector. Pictures were printed from the films. Details of the high speed photography will be reported in a later communication.

2.5. Scanning electron microscopy

The fractured pieces were coated with a thin layer of gold by using a Technics Hummer II sputtering equipment (at a voltage of 10 V and a sputtering period of 4 min) and were examined under a Coates and Welter model HPS-70B field emission scanning electron microscope with a tilt angle of about 45°. Pictures with large depth of focus field were taken.

3. Fracture at shear band intersections

Specimens with two small holes were compressed to generate four band packets from each hole so that they intersected as shown in Fig. 2. Even though the compression axis was vertical, cracks both parallel and perpendicular to the compression direction were produced as shown when viewed after unloading. It is obvious that intersection of band packets severely hindered the propagation of

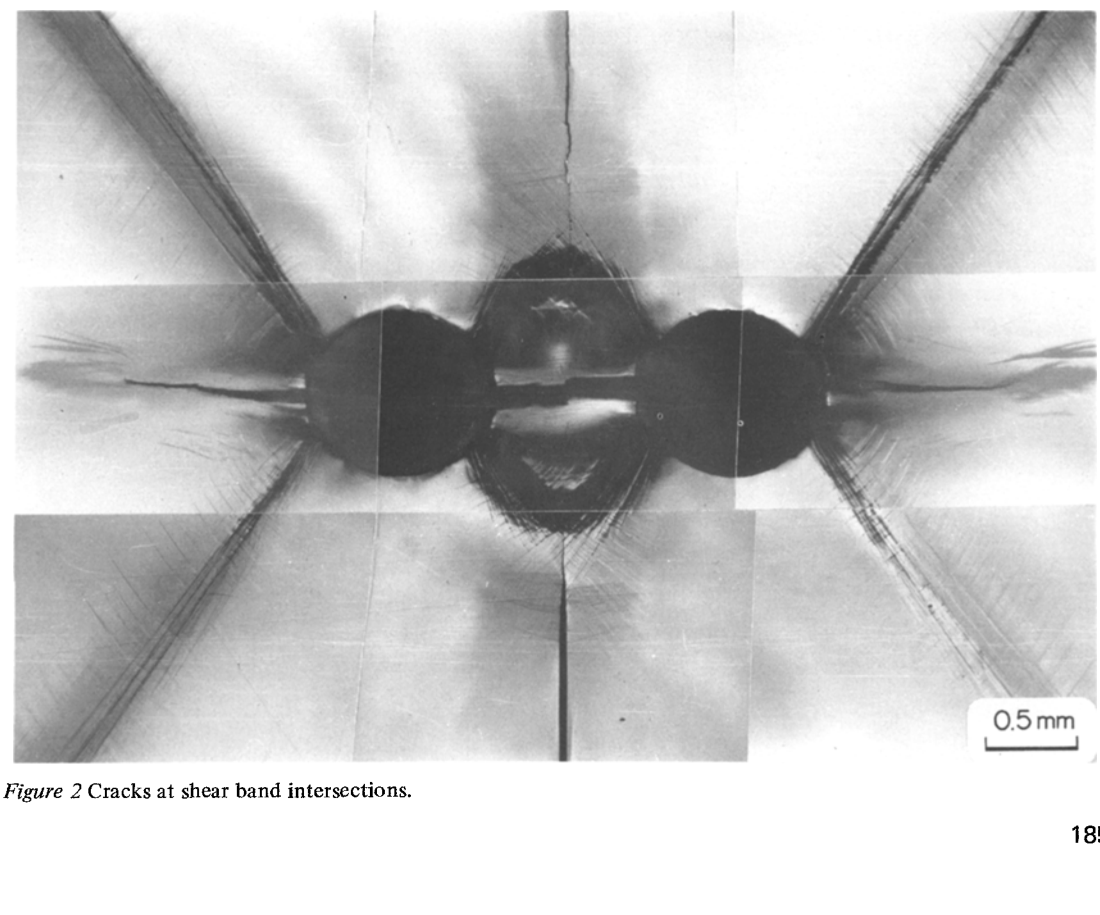


Figure 2 Cracks at shear band intersections.

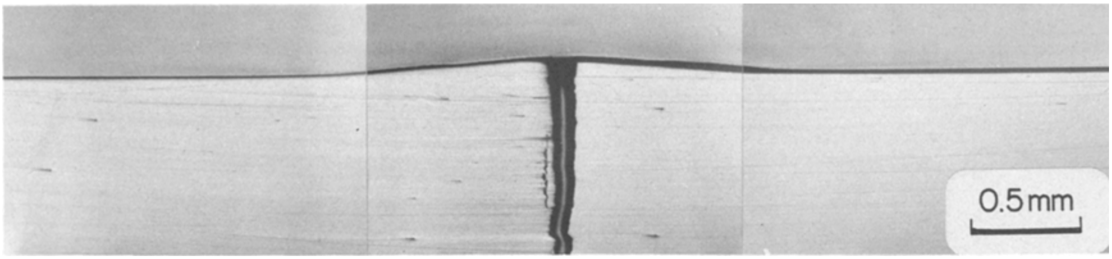


Figure 3 A polished vertical crack surface showing the bulging at the shear band intersection.

these packets when the extent of their propagation was compared with that of the other four freely propagating ones. However, considerable plasticity was evident around the holes since the circular holes were deformed into elliptical shapes. As the intersection localized the plasticity between the holes, the compression caused bulgings on the surface as shown in Fig. 3 which was a polished vertical crack surface. No bulging was observed on the surface to the right or left of the two holes as the long shear band packets spread out the deformation.

Crack formation at shear band intersections is probably caused by internal stresses as proposed previously [1] in the understanding of craze formation at the intersection of shear bands. In that case, the crazes parallel to the compression axis were formed during compression and those perpendicular to the compression axis were formed after the load was removed. To determine whether this was the case here, an Olympus model MJ microscope was mounted next to the specimen during compression. Sure enough a vertical crack (parallel to the compression axis) was formed during compression as shown in Fig. 4a. No horizontal crack was seen. However, as soon as the load was removed, horizontal cracks (perpendicular to the compression axis) were formed as shown in Fig. 4b.

While the cracks were formed in the direction of maximum tension caused by the intersection of shear bands, some cracks were formed along the shear bands in a zigzag manner as shown in Fig. 5a and an enlarged portion in Fig. 5b. Similar observations were reported by Camwell and Hull [5]. Since the tensile stress across the shear band was smaller (see the dislocation model in Fig. 5a) than that across the main crack, it showed the weakness of the shear bands with respect to fracture. Friedrich and Schafter [3] attributed such shear band weakness to chain scission at shear band intersections. Another view of shear band fracture is shown in Fig. 6. It seems that the fracture mode along the shear bands is a combination of Mode I and Mode II.

4. Cracking and crazing of shear bands

This mixed mode fracture of shear bands was achieved in another way as follows: A small hole was drilled at the centre of a square specimen about half way through the thickness. The specimen was compressed to generate four coarse band packets which appeared only on the face of the

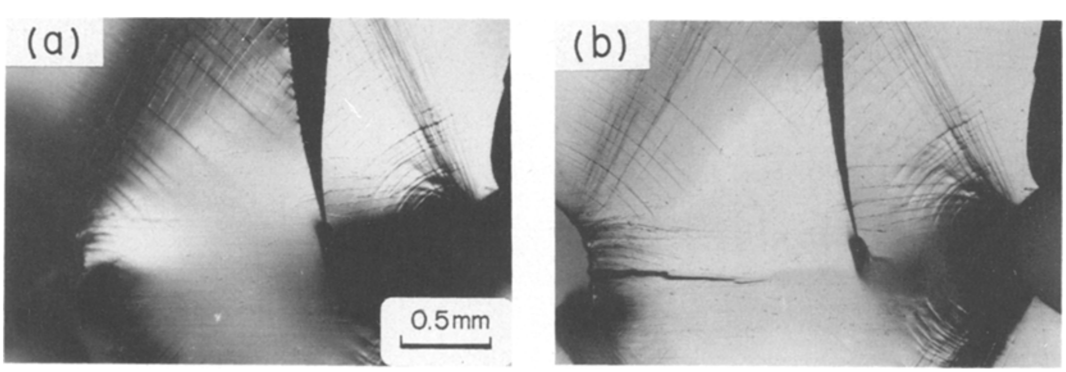
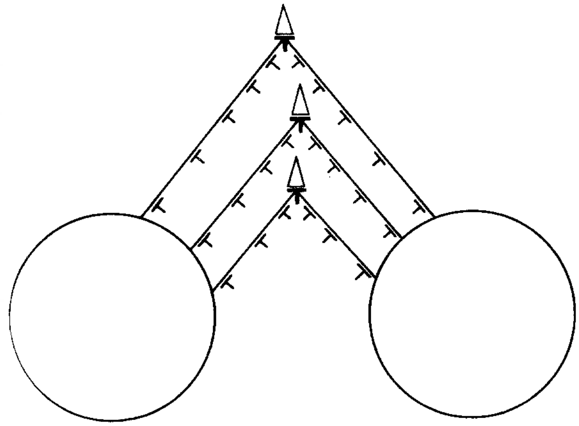


Figure 4 (a) A crack formed in the direction of compression during loading, (b) cracks developed in the horizontal direction after unloading.



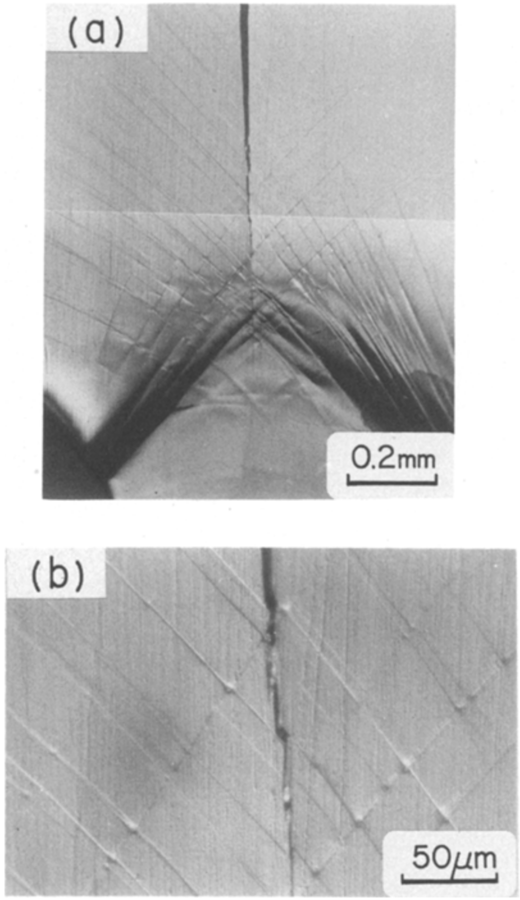


Figure 5 (a) Cracks formed along shear bands in a zigzag manner, (b) a magnified view of the cracks.

specimen with the hole. The other face through which the hole was not drilled showed no bands. Thus the specimen was compressed partly plastically (the half thickness with the hole) and partly elastically (the half thickness without the hole). After unloading, the elastic part would return to the original length but was constrained by the plastic part which would not. Hence the elastic part was under compression and the plastic part was under tension although bending and the recovery of the plastic part would somewhat moderate the stress parity. After about half an hour in the unloading condition with internal stress existing in both parts of the specimen, the shear bands opened up as shown in Fig. 7a. It is seen that the shear bands became cracks with a fibrous structure inside. On account of such fibrous structure, these cracks could be considered as shear band crazes. However, due to the existing fibrous structure inside the shear bands, the fibres were not perpendicular to the opened-up surfaces as in normal crazes although the mixed mode fracture stress might be another factor. A scanning electron micrograph of such shear band craze is shown in Fig. 7b. Still, this experiment shows that the shear bands are weaker than undeformed material since the maximum tensile stress orients at about 50° with the normal of the shear bands. A similar observation was reported by Brady and Yeh [6] in the case of thin films where shear bands produced by drawing opened up after a second drawing in the perpendicular direction. Here the weakness of the shear band cannot be explained by chain scission at the shear band intersections [3].

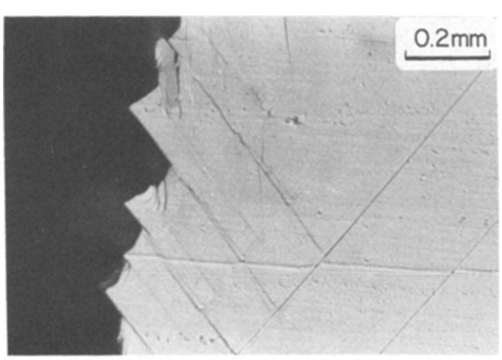
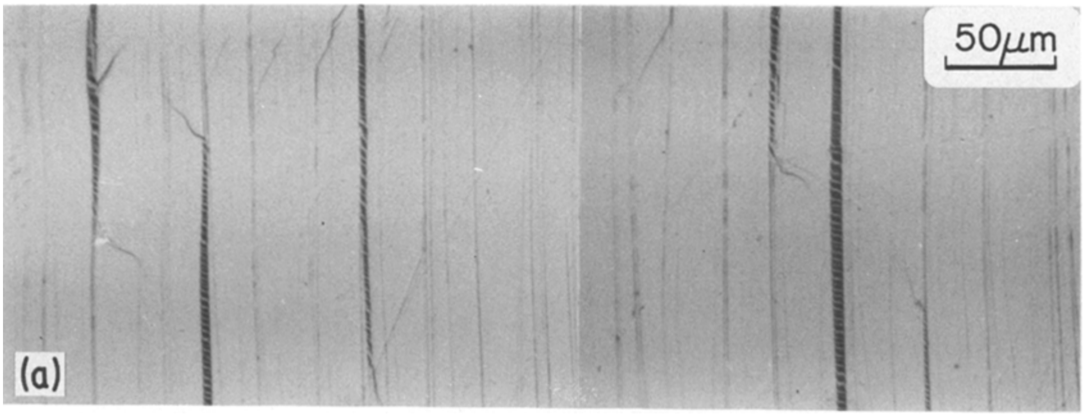


Figure 6 Another view of the fracture surface showing a zigzag path.

5. Crack formation inside shear bands

The fibrous structure of a thick shear band was shown previously [4] together with cracks or openings which separate the strands of fibres. Some enlarged views of these internal cracks are



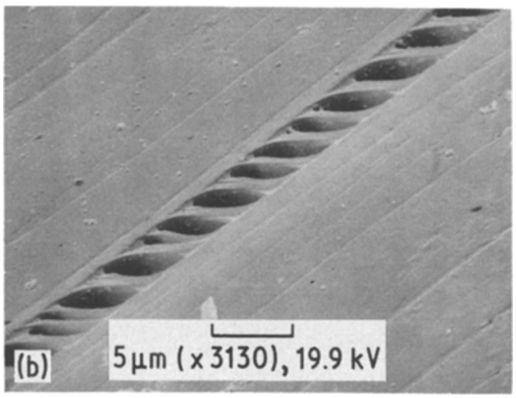


Figure 7 (a) Shear bands opened up by residual tensile stresses in an elastic–plastic specimen, (b) the shear band crazes under the scanning electron microscope.

shown in Fig. 8. Most of these cracks are clean, namely, there are no fibres inside them. However, some cracks in the middle of the thickness still contain fibres as shown in Fig. 9 which is a cross-sectional view (by sectioning parallel to the side surface in the direction of compression) of the shear band. It is seen also in the same figure that the cracks have a curvature convex in the direction of propagation. Such curvature is shown schematically in Fig. 10. It seems as though the propagation of the shear bands is easier inside the thickness of the specimen than near the surfaces. A more detailed scanning electron microscopic picture will be shown later.

An *in situ* observation using the model MJ Olympus microscope attached near the specimen during compression showed that these internal cracks were not formed during compression but appeared only after unloading. As pointed out before, the reason for the cracks can be attributed to the difference in the extent of relative shear displacements between the strands of fibres inside the band. Such differences create tensile stresses between the strands but apparently not sufficiently large to exceed the applied compressive stress so as to cause fracture. However, it is large enough to cause fracture after unloading. On the other hand, previous annealing experiments [7] showed the development of stress concentrations during recovery. The internal stresses caused by the differences in shear displacements between strands

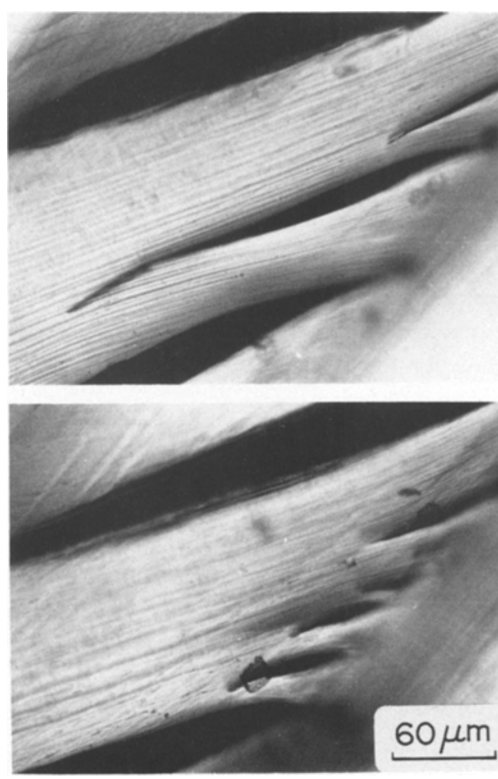


Figure 8 Magnified views of cracks inside a thick band.

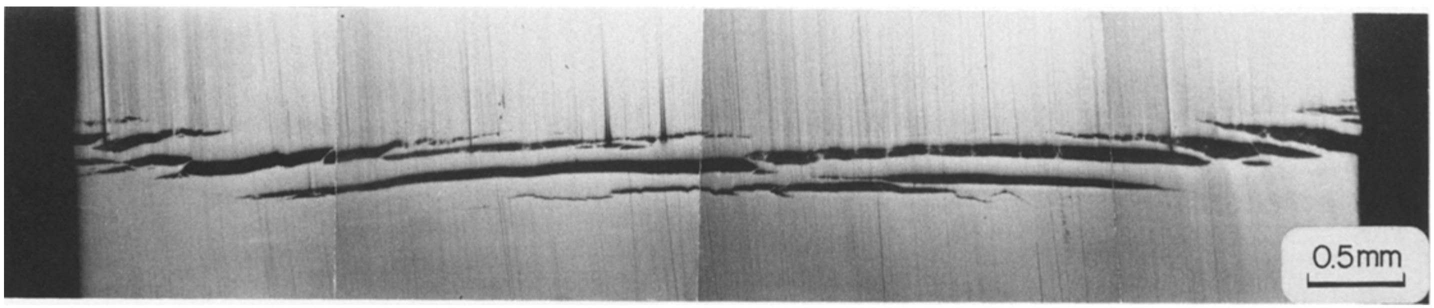


Figure 9 Cross-sectional view of a thick shear band containing cracks.

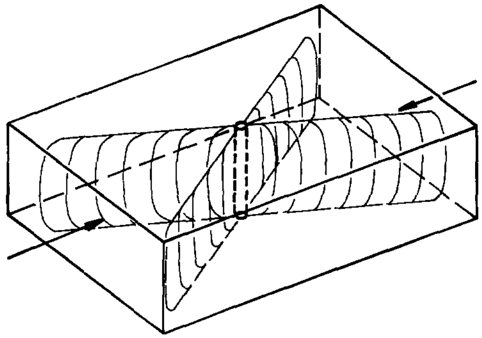


Figure 10 Schematic drawing of thick shear bands inside a specimen showing the curvature of cracks.

of fibres could arise also during relaxation after unloading.

6. Shear fracture of thick shear bands

When thick shear bands propagated all the way across the specimen during compression, shear fracture along the shear band took place. The fracture event happened within 1 m sec as shown in Fig. 11 which was a high speed movie sequence at 1000 frames sec^{-1}. No further shear inside the shear band seemed to take place shortly before or during shear fracture.

The fracture surface did not lie inside the band

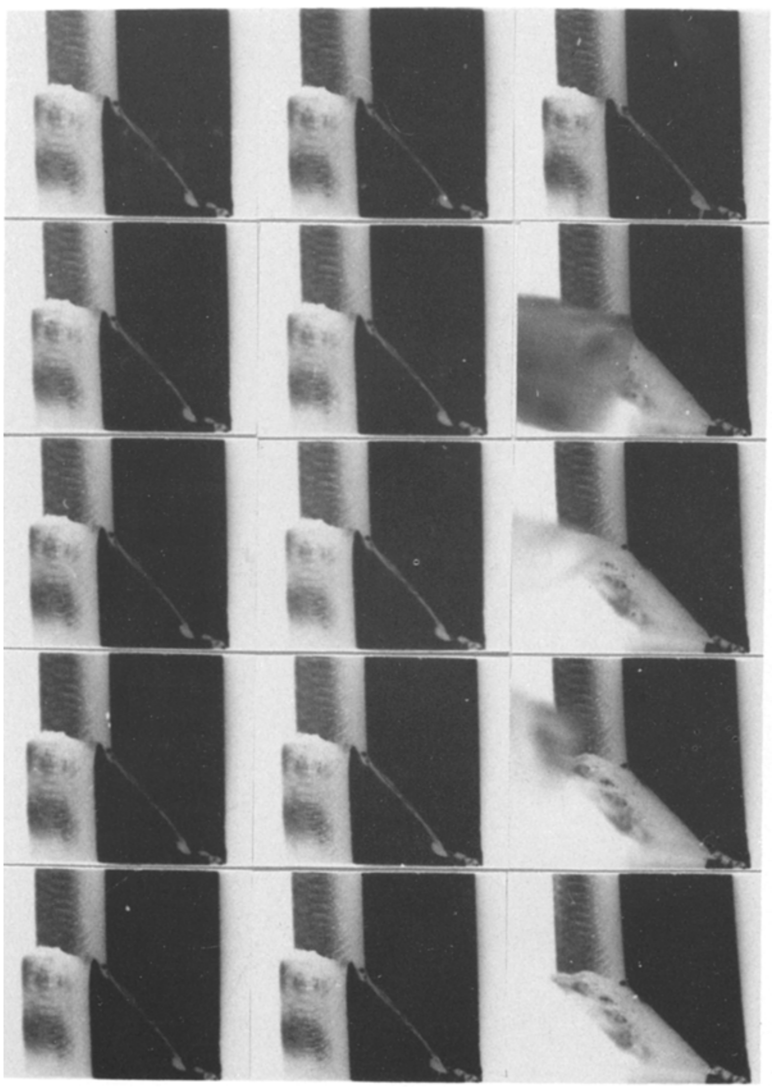


Figure 11 High speed movie sequence showing the shear fracture of a thick shear band.

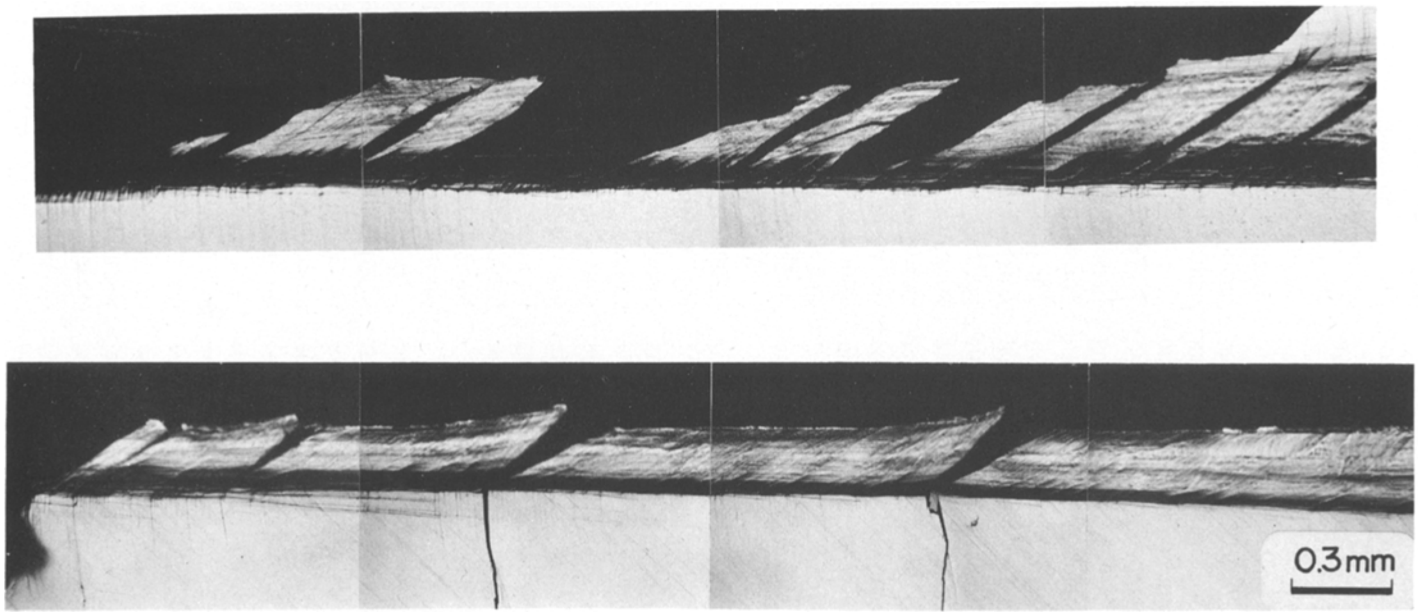


Figure 12 Morphology of thick shear bands after shear fracture.

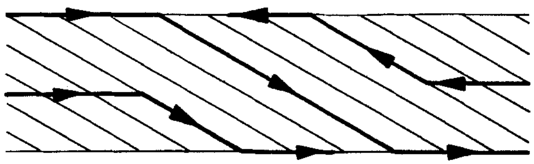


Figure 13 Schematic drawing of crack propagations inside a thick band.

but at the band surfaces (interfaces between the shear band and the undeformed material) as shown in Fig. 12. The fracture could take place along one band surface only, or along the other surface only, or change from one surface to the other during propagation. In the latter case, the change from one surface to the other took place at the location of an internal crack. As just reported, the internal cracks were not observed during deformation but were formed after unloading. Nevertheless, the internal stresses caused by the differences in shear displacements between strands of fibres could be the reason for the shear crack to change from one surface to another. The internal cracks in Fig. 12 were produced probably after the fracture of the shear band.

The internal stress distribution or the fibrous structure inside the shear band may also be one of the causes for the observed shear fracture mode. As illustrated in Fig. 13, suppose that a crack inside a shear band was going to propagate, it would be easy for it to meet an internal crack (or a tensile stress region) and change its course of propagation and hence always end up in propagating along the interface.

Partly because of this interface propagation, the shear strain in the shear band was not affected by shear fracture. After fracture, the piece which contained the shear band as part of the fracture surface was annealed at 110° C for varying lengths of time. The results are shown in Fig. 14. Complete recovery after 3 h was obvious. Apparently no material was lost from the shear band during fracture. Some internal stresses were seen to arise during annealing. They were large enough to cause cracking at some places. However, these internal stresses disappeared after 3 h. The recovery of shear strain (from the straightening of scratches) was similar to the case of the shear band before fracture [7] suggesting once more that the shear bands were not affected by shear fracture at their surfaces.

The other piece after shear fracture which contained no shear band as part of the fracture surface was annealed also at 110° C. Before annealing only some thin coarse bands, some of which cracked, were observed to intersect the fracture surface. During annealing, no internal stresses were seen to arise and no shape changes were detected. Finally after 3 h the only observable difference was that the thin coarse bands disappeared. This experiment shows that the material outside the shear band was not deformed (except for the few thin bands) before or after shear fracture.

7. Tensile fracture of thick shear bands

Existing shear bands can be fractured in tension. The experimental procedure is shown in Fig. 15. The specimen was first compressed with a side notch to produce two thick bands. It was then polished on emery paper to remove the notch. Subsequent tension at high strain rates (0.1 sec^{-1}) always caused fracture along the shear band. On the polished side surface, no steps were observed after tension indicating that there was no reverse shear taking place before fracture and no new shear bands were developed.

More evidence of the absence of plasticity in tension before fracture is seen from the following experiment. The surface profile at some locations along the thick band were recorded by Dektak as shown in Fig. 16a before the tensile test. The height to base ratio of the cross-section was 0.076. After tension the shear band fractured. However, in this particular case a part of the shear band was not fractured as shown in Fig. 16b. Nevertheless, the additional cracks and crazes showed that the part was loaded during tension. A Dektak trace was made again at about the same location and is shown in Fig. 16b. It is seen that the height to base ratio of the cross-section was unchanged indicating the absence of activity inside the shear band.

A morphology of the fracture surface is shown in Fig. 17a. It is seen that the strands of fibres were pulled apart and elongated by the tensile force. To locate the fracture areas, the specimen was annealed at 110° C for 3 h and the same area is shown in Fig. 17b. It is seen that all strands of fibres were returned to their shape before deformation. A careful comparison between the two fracture surfaces after annealing showed that no material was lost during the fracture process and that fracture took place always at the shear band surfaces (interfaces between the shear band and

Figure 14 Annealing of a thick shear band attached to a shear fracture surface.

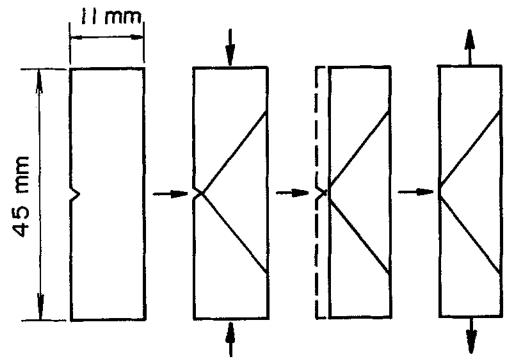


Figure 15 Experimental procedure for producing tensile fracture of thick shear bands.

the undeformed region) or between strands of fibres.

A closer look at the tensile fracture surface before annealing is shown in Fig. 18a which is a scanning electron micrograph. It is seen that the strands of fibres which appeared in the optical micrograph were actually fibrous sheets which extended all the way across the thickness of the specimen. These sheets have the characteristic curvature of the internal cracks as shown in Fig. 10. Another view is shown in Fig. 18b which is a scanning electron micrograph of an annealed fracture surface after being pulled in tension.

To see how the fibrous sheets were formed in tension, a selected set was annealed at 110° C for various times as shown in Fig. 19. It is seen that these fibrous sheets gradually formed blocks which fitted into each other in the shear band in its undeformed state. The fact that these fibrous sheets were not pulled in from outside the shear band during tension is seen as follows: If annealing caused the fibrous sheets to re-enter the space outside the shear band, a reduction of the fibrous sheets volume or their projected area was expected inside the shear band. However this was not found to be so. As shown in Fig. 20 for 25 fibrous sheets, the projected area measured before and after annealing was found to be about the same. On the other hand, if annealing could not cause the fibrous sheets to re-enter the space outside the shear band, it was expected that the thickness of the shear band after recovery should be more than that before tensile fracture. Again this was not found to be so. As shown in Fig. 21 the thickness along a shear band was about the same after recovery as before fracture. Furthermore unless the fibrous sheets were pulled out in some fashion of strict regularity, it was not expected that they would fit each other so well after annealing.

Since the pulling in of fibrous sheets from

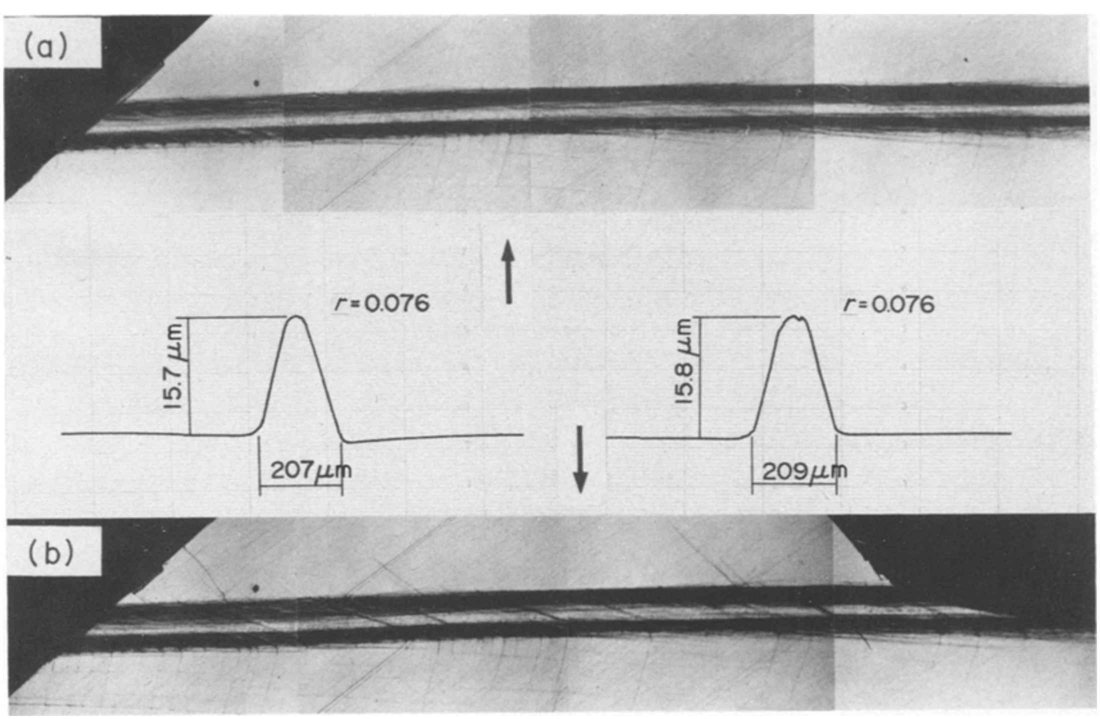


Figure 16 (a) Morphology and Dektak trace of a thick band before fracture, (b) same band after being fractured in tension.

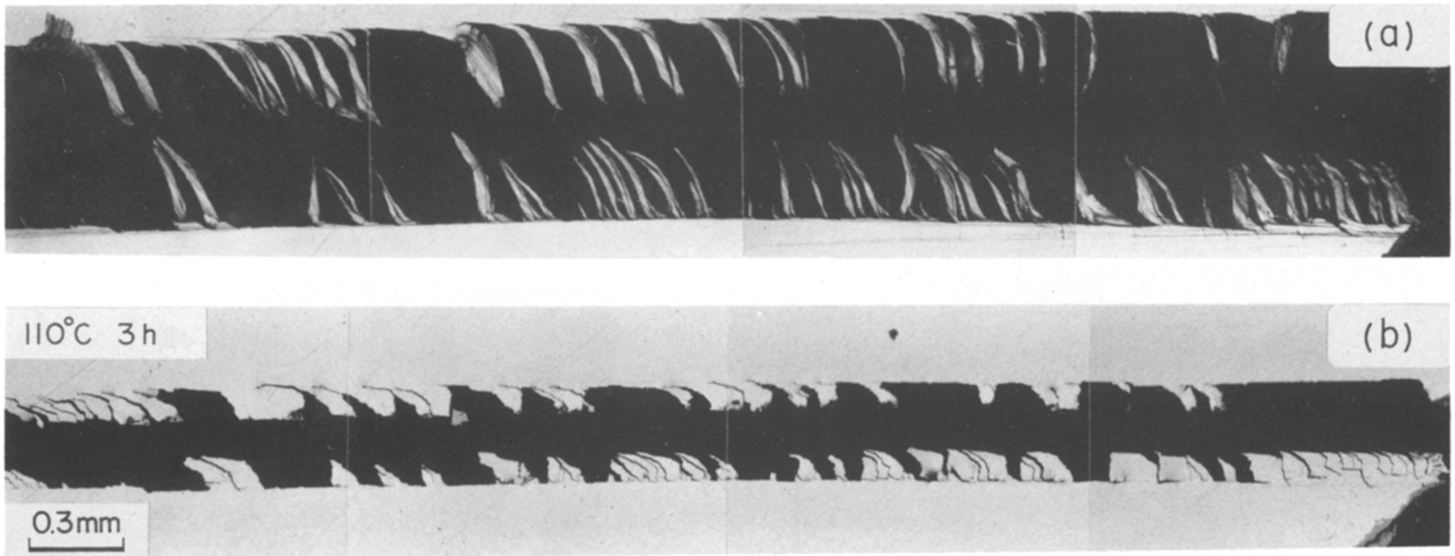


Figure 17 (a) Morphology of the fracture surface of a thick band after being fractured in tension, (b) same fractured pieces after being fully annealed.

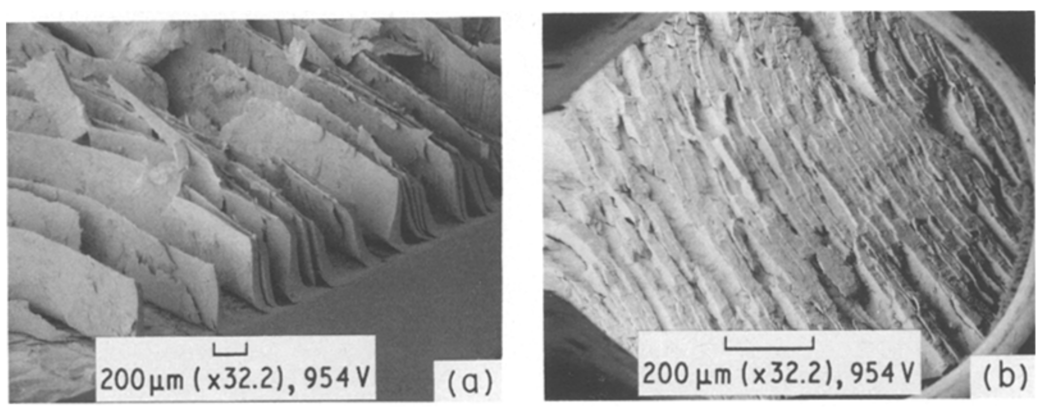


Figure 18 (a) Scanning electron micrograph of a tensile fractured thick band (side view), (b) the same band after being fully annealed (top view).

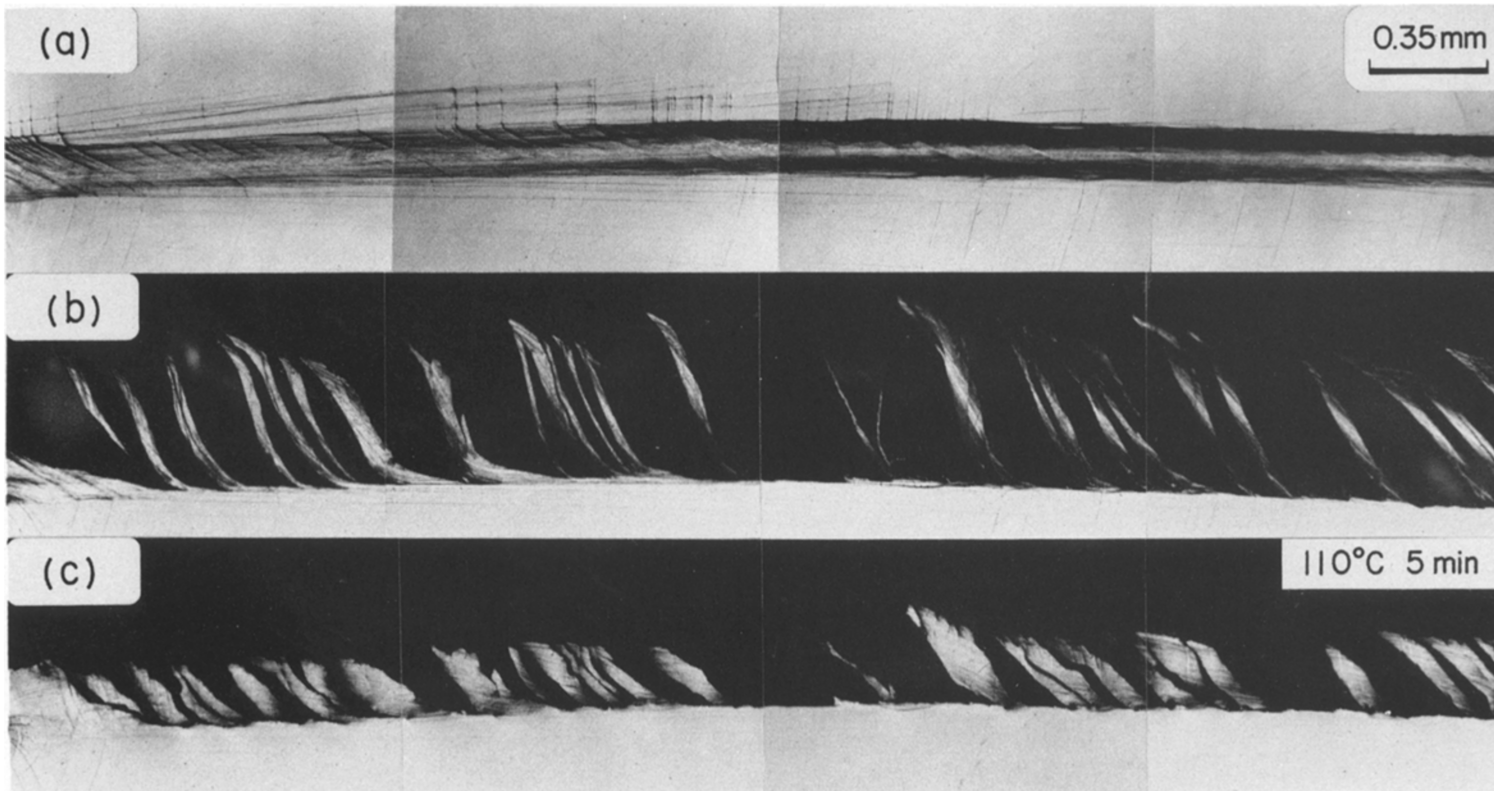


Figure 19 Annealing of the fibrous sheets produced by the tensile fracture of a thick band: (a) original band before fracture, (b) same band after fracture before annealing, (c to e) after different annealing times.

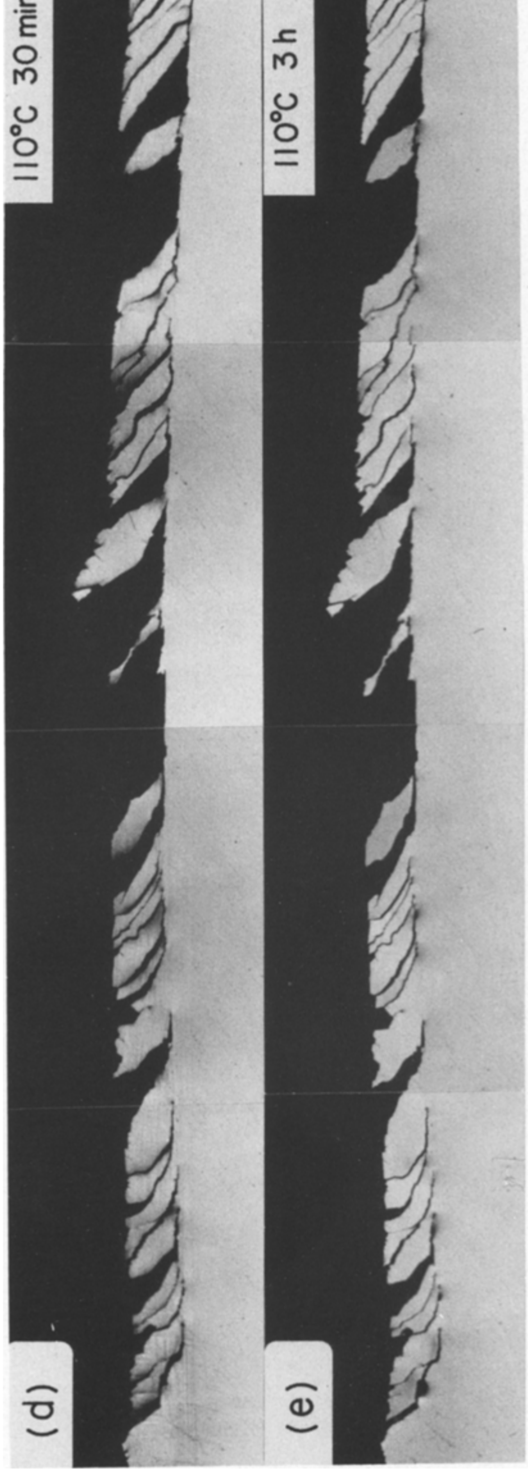


Figure 19 (Continued)

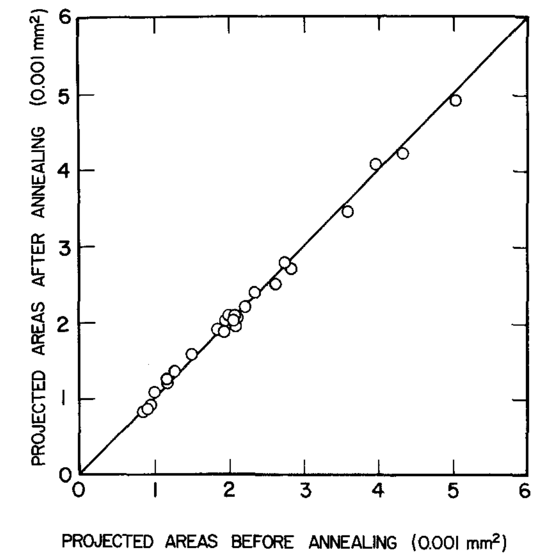


Figure 20 Comparison of projected areas of individual fibrous sheets before and after annealing.

outside the shear band was ruled out, the formation of fibrous sheets by tension must be a result of plastic deformation of the shear band material. Such deformation can take place by relative shear between the strands of fibres as shown schematically in Fig. 22. In this figure, (a) represents undeformed material and (b) represents the formation of strands of fibres in a shear band. The situation after some tensile deformation before fracture is shown in (c). Note the partial fracture at both the shear band surfaces and the relative shear between strands of fibres in the same direction as that in the shear band. Further deformation and final fracture at one of the shear band surfaces is shown in Fig. 22d with the formation of a fibrous sheet.

8. Conclusions

(1) Cracks are formed at shear band intersections due to internal stresses produced by inhomogeneous deformation.

(2) Shear band material is easier to fracture than the undeformed material.

(3) Relaxation after deformation could cause cracking between strands of fibres in a shear band.

(4) Shear fracture along the shear band during compression takes place not inside the band but along either of the two interfaces between the band and the undeformed material.

(5) Shear bands formed in compression showed no evidence of deformation during subsequent tension before cracking. After cracking, the strands of fibres were pulled apart and elongated by the tensile force. These elongated fibrous sheets could be recovered completely at 110° C to return to their undeformed state. Projected area measurements showed no change for these fibrous sheets before and after recovery. The shear band thickness after recovery was also the same as that before tensile fracture. Thus the fibrous sheets were not pulled in from outside the shear bands during tension. They were formed by plastic deformation of the shear band material.

Acknowledgements

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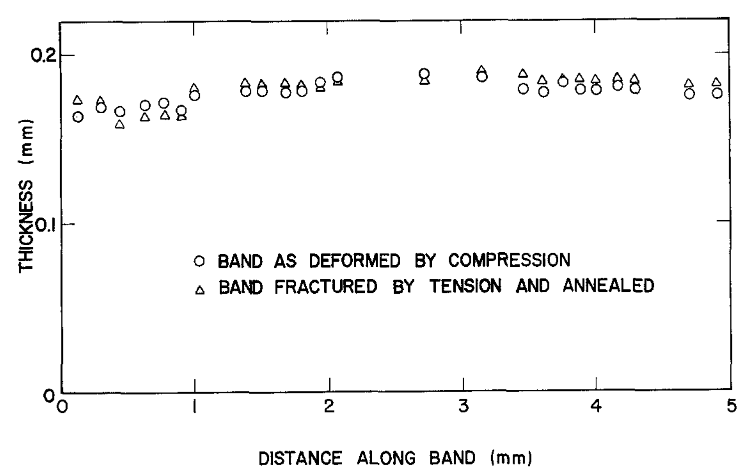

Figure 21 Comparison of the thicknesses of the band before fracture and the same band after being fractured in tension and annealed.

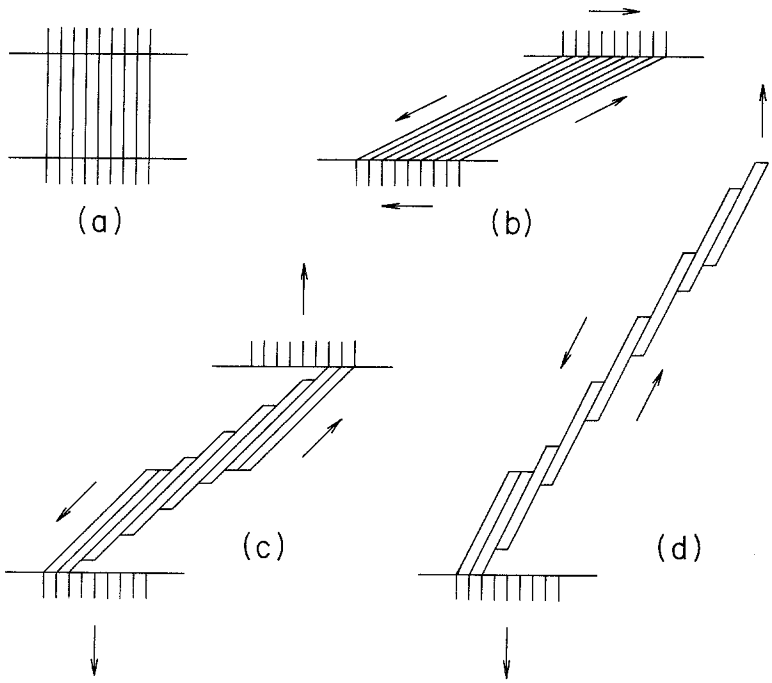

Figure 22 Schematic drawing of the formation of fibrous sheets during tensile fracture of a thick shear band.

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