Letters

Coarse shear bands and fracture in polystyrene

Unlike the inorganic glasses, most glassy polymers can undergo appreciable plastic deformation at room temperature and moderate strain rates before fracture occurs. In most cases this deformation develops inhomogeneously, i.e. only local regions in the material are plastically stretched. Two deformation modes are possible, depending upon the conditions of stress and the ambient. These two modes are shear yielding and normal stress yielding (crazing) [1].

The process of craze formation, which only occurs under tensile-like loading, and the influence of crazes on crack propagation and fracture in polymers have been clarified to a large extent in recent years [2, 3]. There are very few studies which consider in detail the very closely related phenomenon, the formation of shear bands. It is well known that when crazing is suppressed, amorphous polymers such as polystyrene deform by localized shear with the appearance of intense shear bands [4].

More recently Wu and Li [5, 6] have reported that two slip processes during the compression of bulk atactic polystyrene are characteristic. Individual, coarse shear bands appear in high speed deformation. They are also observed when deformation is carried out at low temperatures.
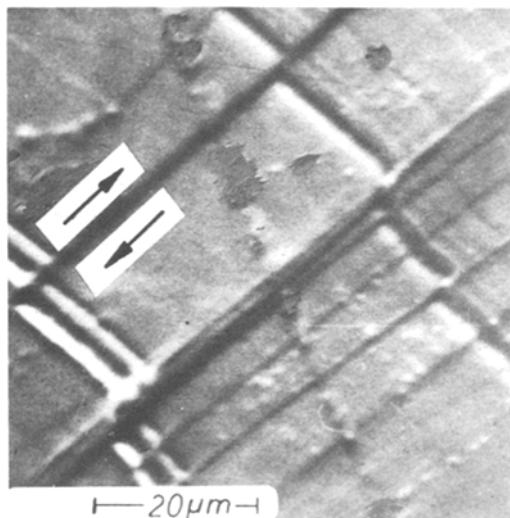

Figure 2 Discrete displacement of scratches on the specimen surface by coarse shear bands viewed in the scanning electron microscope.

Fine slip bands arranged in a broad diffuse shear zone are found in low speed deformation and/or at higher temperatures. The authors mentioned that brittle fracture occurred in the coarse bands after they had extended across the specimen (Fig. 1), while the diffuse shear zone caused ductile fracture behaviour after large strains.

The purpose of this work is to investigate the brittle shear fracture process in more detail, mainly by scanning electron microscopic (SEM)
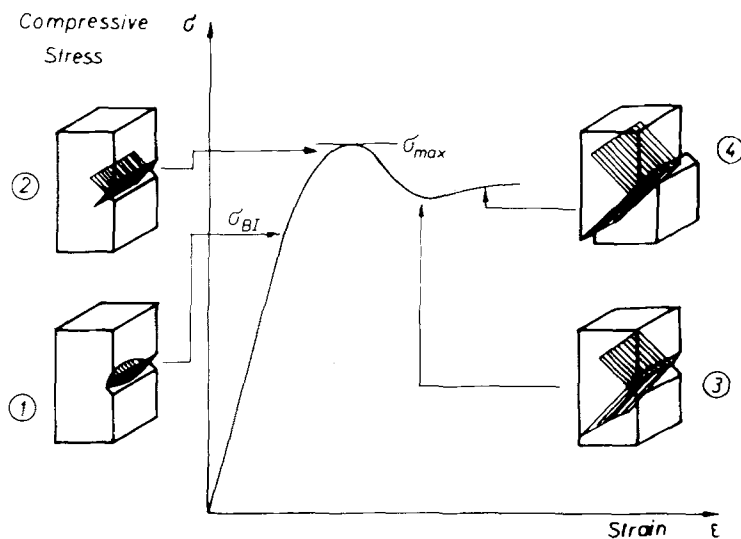

Figure 1 Schematic representation of the stress–strain curve during compression of a notched specimen. The stages of deformation inside the specimen are indicated: (1) Shear band initiation; (2) Maximum at a band length of about $\frac{1}{3}$ of the way across the specimen; (3) Minimum when one band packet has crossed the specimen; (4) Sliding of the specimen pieces to each other combined with final fracture.
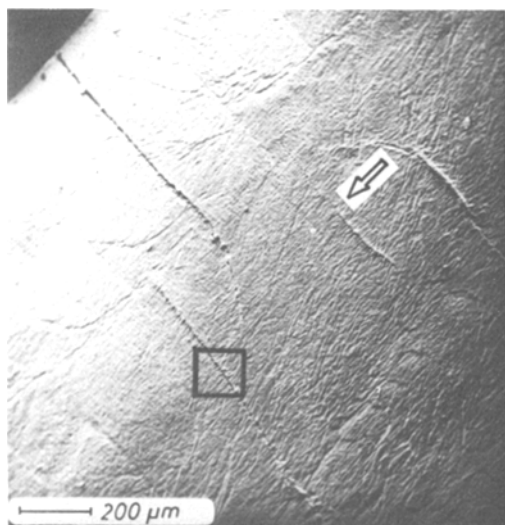
Figure 3 Fracture surface obtained by real shear fracture in a coarse shear band of polystyrene (SEM). The arrow indicates the sliding direction of the viewed specimen piece.
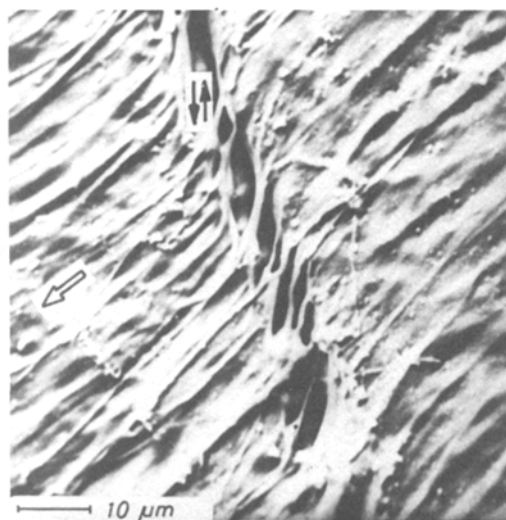
Figure 4 Details of a trace in Fig. 3, indicating that a step has formed on the fracture surface at the intersection of two shear bands by sliding in a second plane.

methods. Features on the fracture surfaces obtained by shear fracture in the coarse bands are compared with those found on craze fracture surfaces in polystyrene.

Fig. 2 shows a sector of the shear zone on the specimen surface. The notched specimen was loaded under compression at $-70°C$ with a strain rate of $\dot{\epsilon} = 4 \times 10^{-4}$ sec^{-1}. Plastic deformation occurred in discrete, coarse shear bands. The direction of these bands ran at an angle of nearly $38°$ to the external compression axis. The local shear strain ϵ_i, which can be estimated by the displacement of the scratches divided by the thickness of the coarse bands, was found to be nearly 50 times greater than the external compressive strain ϵ_a.

In addition to the coarse bands starting from the notch, a second set of short shear bands is observed running in a second direction at $38°$ to the external load. Thus the slip bands are sheared by each other at their intersections. Due to the small shear volume inside the coarse shear bands, the macroscopic plastic strain of the specimen is very small. Shear fracture is induced as soon as the shear band packet has reached the other side of the specimen. The smooth fracture surface is macroscopically brittle (Fig. 3).

At higher magnification coarse fibrillar regions are found on the fracture surface indicating a large plastic deformation of the material within the slip bands. Individual traces running more or less perpendicular to the sliding direction of the specimen pieces are due to the second set of short, coarse shear bands. Slipping in these bands perpendicular to the shear plane provides steps on the final fracture surface. The steps are bridged by shear band fibrils (Fig. 4).

The mechanisms which occur during shear band formation until fracture are represented schematically in Fig. 5. The stretched polymer fibrils in a shear band formed at first will be further stretched when sheared by another slip band. At these places first chain scission occurs predominantly, and thus the intersections of the shear bands act as nuclei for crack formation and fracture. Hull has pointed out the similarity between shear bands in glassy polymers and slip bands in metals in this respect [7, 8].

When the sliding process of the specimen pieces is prevented by the steps due to the intersection of the bands, a craze-like opening of the short shear bands can be produced during further deformation. Cracks which are induced by chain scission in these crazes at least provide a catastrophic onset of fracture at many sites of the shear zone.

In this case the specimen can break into many splinters. Then one part of the fracture surface
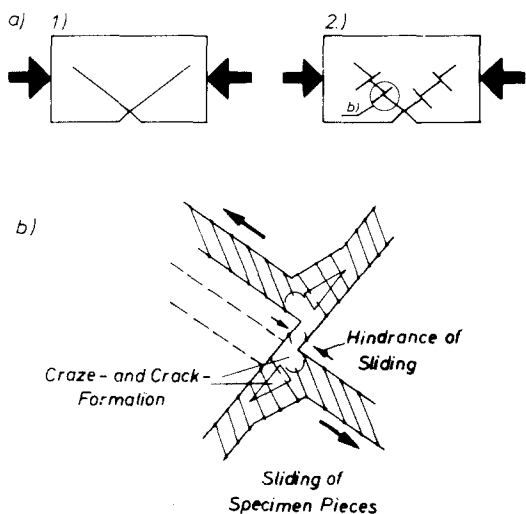
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Figure 5 Mechanism of crack formation at the intersections of shear bands. (a) Sequence of shear band formation. (b) Chain scission at the intersection.

shows typical features of true shear fracture, while the residual fracture surface consists of rough striation zones. This striation pattern is always found when a fracture develops by a periodic formation of craze bundles during rapid crack propagation under normal stresses [9, 10].

In contrast to observations on the diameter of fibrils in coarse shear bands by Brady and Yeh [11] who used a variety of replication techniques for the transmission electron microscopy, the fracture surface fibrils due to the shear band fracture are one order of magnitude thicker (Fig. 6).

From this fact and a comparison between the morphologies of craze and shear band fracture surfaces, it can be deduced that similar fracture processes must occur in both deformation zones.

During crack propagation in crazes a random rupture of stretched fibrillar regions takes place at the upper or lower craze edge (Fig. 7). Thus a patchwork of formerly stretched filaments remains on the fracture surface [9]. The fracture process in the polymeric substance of a shear band must also be connected with a separation of stretched fibrillar regions at both side of the shear band. Contrary to craze fracture, no speckles are found on the fracture surface, because another stress condition acts on the shear band. Instead coarse fibrils are observed on the fracture surface, which itself consists of formerly stretched, fine fibrillar domains of the unfractured shear band.

In conclusion it can be said that the fracture surface morphologies obtained by shear yielding in coarse shear bands or normal stress yielding in crazes are quite similar. Both depend initially upon a random rupture at the edges of the deformation zone and a relative shear displacement of
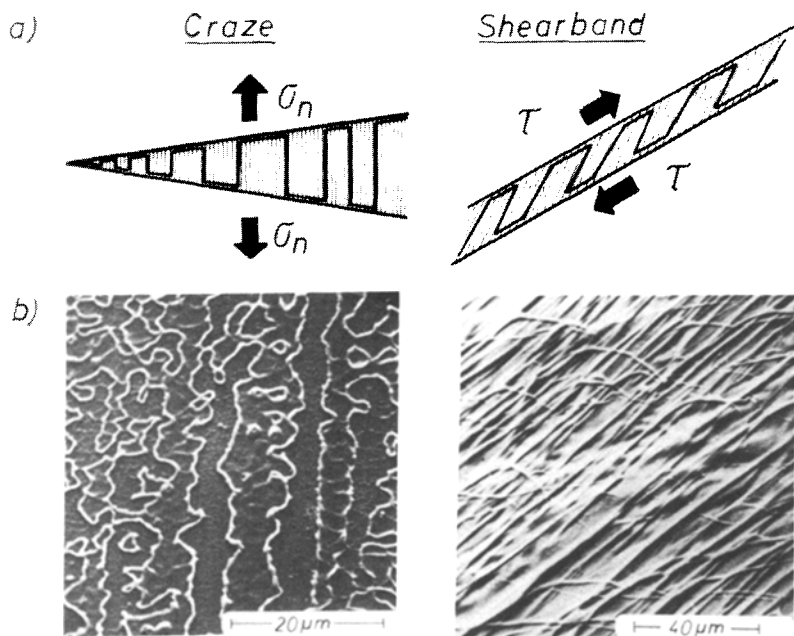

Figure 6 Comparison of the deformation processes in crazes and shear bands and the corresponding fracture surface structures.
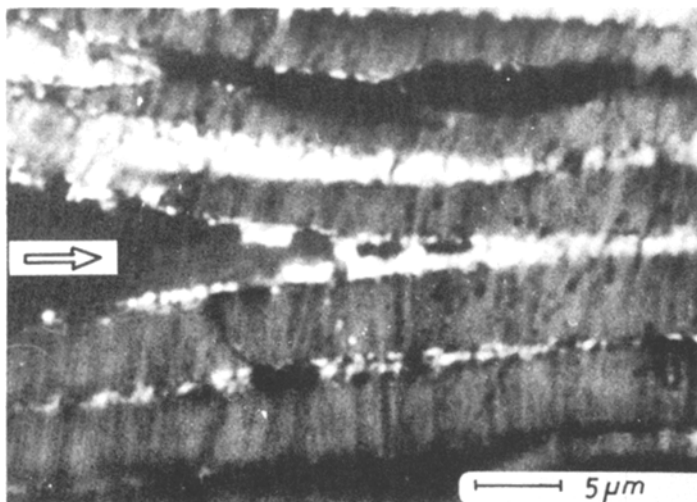
Figure 7 Deformation of craze matter in front of a crack tip (arrowed) in polystyrene.

coarse, fibrillar domains. In both cases, macroscopically brittle fracture behaviour must be expected. When a broad, diffuse shear zone is built up, for example during compression at higher temperatures and low deformation rate, fracture becomes more ductile. This kind of deformation will not be discussed in this letter. Some details about it can be found in another publication by the authors [12].

Acknowledgement

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Initial stages of growth and orientation of bismuth and antimony films

Bismuth and antimony are semi-metals in their bulk form and have primitive rhombohedral unit cell structures which can also be considered as hexagonal or deformed cubic structures. Palatnik *et al.* [1, 2] have carried out condensation experiments on these materials as a function of thickness and temperature, and postulated that in bismuth films deposited on amorphous substrates the nuclei are spherical and that the condensation occurs via a vapour–liquid–solid transformation for substrate temperatures $T_s > (2/3)T_m$ where T_m is the melting point of the bulk material. For $T_s < (2/3)T_m$, the transformation is directly from vapour to solid. On the other hand, in the case of antimony films, the