

High temperature simple shearing fabrics: a new experimental approach

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Abstract—An example is described of a shearing experiment performed on coarse-grained para-dichlorobenzene at 98% of its absolute melting point. The sample is a thin sheet of material, only about seven times as thick as an ordinary petrographic thin section. It is sheared in its own plane under observation between crossed nicols, through a low-power microscope. Shear strains up to about five occur locally. An array of second-phase marker particles allows the pattern of straining in the material to be observed independently of the microstructural changes that occur. Dynamic recrystallization is seen in an original grain boundary region where the shear strain is concentrated. The new grains are mostly elongate parallel to the direction of the former grain boundary, which is also the direction of shearing. Suitably oriented new grains become filled with transverse subgrains, due to kinking or dynamic polygonization. The appearance of these intragranular features and their relation to the shearing direction recall structures and interpretations described for naturally deformed olivine rocks. It seems probable that thin sheet, analog experiments of this general type can help put kinematic interpretation of rocks deformed at high temperature on a firmer footing.

INTRODUCTION

FIELD WORKERS mapping across ductile high-strain zones are interested in determining the direction, sense and magnitude of the net or total shearing displacements across the zones. The microfabric of the deformed rocks can sometimes provide this information, particularly when the shearing strains are not too big and when the grains present before shearing are still present afterwards. In this situation a simple relationship may exist between the total finite strain and the fabric, and this forms the basis for interpretation. The simplifying relationship to total strain is expected to break down, however, where extensive recrystallization and/or recovery has accompanied the shearing. In the extreme situation, perhaps often met with in high-temperature shear zones, the material is continuously reconstituted by recrystallization and recovery processes while the deformation proceeds, and the microfabric eventually assumes a statistically steady condition. Having reached this 'steady state', the fabric somehow reflects the current rate and direction of the shearing, and all record of the total displacement is lost.

Little is known of how to interpret these high-temperature fabrics. A general problem is to establish grain-scale criteria for distinguishing between transitional fabrics and steady-state fabrics, and between steady-state fabrics and partly annealed fabrics. Then, with such distinctions possible, the fabrics need to be interpreted in terms of the direction, sense, and magnitude or rate of shearing, as appropriate. What has been established so far are useful relationships between the rate of shearing and the temperature (hence the stress) and such microstructural parameters as the recrystallized grain size in steady-state fabrics [Luton & Sellars 1969, Sellars 1978, with applications to rocks by for example, White (1975), Mercier *et al.* (1977) and Twiss (1977)].

The point of departure in the present experiments is that it would be interesting to attempt high temperature simple-shearing experiments in a transmitted light apparatus (Means 1977), so that fabric transitions involving recrystallization or recovery effects might be directly observed. The apparatus is restricted to operation near room temperature, so an experimental material with low melting point is employed, namely para-dichlorobenzene ($T_m = 53^\circ\text{C}$). This is mixed in 13:1 proportions by weight with 120-grit silicon carbide grinding powder, which provides an array of inert, internal marker particles to indicate the strain fields. Previous experiments by geologists having most in common with these experiments are the experiments on ice by Kamb (1972) and by C. J. L. Wilson (*pers. comm.* 1979). In both cases the ice was sheared but was not observed microscopically during the shearing.

THE DEFORMATION CELL AND SPECIMEN PREPARATION

The most essential parts of the deformation cell are two square blocks of plate glass 19 mm thick that are held 1.3 mm apart by an enclosing steel box with portholes at either end (illustrated in Means 1977, p. 170). The sample is prepared as a thin sheet of material between the glass windows as follows. Previously compacted pieces of dichlorobenzene and silicon carbide are placed between the windows of the deformation cell and loaded with a piston at room temperature until the material intrudes as a thin sheet over the face of a microscope slide (Figs. 1a and b) and into a cavity about 180 μm thick between the microscope slide and the front window. The specimen sheet is thus about seven times as thick as an ordinary petrographic thin section. The material is fine-grained and rather opaque at this stage. It is converted into clear, coarsely crystalline material by

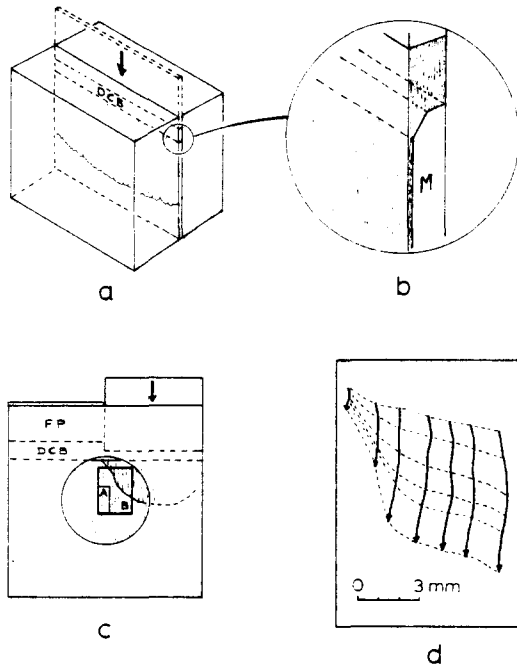


Fig. 1. (a) Thick glass windows of deformation cell, piston (with arrow), and dichlorobenzene piece (DCB) being intruded downward as thin sheet (vertically ornamented). (b) Detail showing microscope slide (M) with bevelled upper edge, over which thin sheet is intruded. (c) Front view showing fixed piston (FP), moving piston (with arrow), and lobe of newly intruded dichlorobenzene below moving piston. Circle is porthole in metal box. Area B is whole area photographed. Area A is part discussed in text and shown in Fig. 2. Dotted lines represent grain boundaries in starting material for experiment TM-146. (d) Particle tracks during TM-146 in area B, in reference frame of boundaries of area B.

static heating through a phase transition to the triclinic, β phase (Jeffrey & McVeagh 1955). Crystals of the β phase grow rapidly to impingement as the temperature passes through about 35°C . For experiment TM-146 described below, the deformation cell was heated from below by a hot plate. This established a vertical temperature gradient along the specimen sheet during crystal growth and a small number of very coarse individuals grew from the bottom of the sheet upwards (Fig. 1c). The temperature was raised from room temperature to the run temperature of 47°C in 30 mins and held there for 10 mins before shearing commenced.

PROVISION FOR SHEARING THE SPECIMEN

The thin specimen is sheared in its own plane by renewed intrusion of dichlorobenzene in such a way that the velocity of intrusion varies laterally across the top of the specimen sheet. This is accomplished by replacing the full piston used for initial intrusion of the sheet with a split piston (Fig. 1c), one half of which is held stationary while the other half is pushed downwards into the deformation cell. Below the moving half-piston a lobe of newly intruded dichlorobenzene appears, and this sets up shear strains in the part of the specimen that is observed photographically (area B in Fig. 1c). Figure 1(d) shows some particle tracks traced out by silicon carbide markers in TM-146. The final shear strain across area B is only about 1, but higher shear strains occur

locally in specimen TM-146, in area A (Fig. 1c). This is the part of the specimen to which the remaining observations and photographs are restricted.

AN EXAMPLE OF OBSERVED BEHAVIOUR: EXPERIMENT TM-146

Experiment TM-146 has been the most successful run to date. The shear straining in the most highly strained region took place at an average rate of $2 \times 10^{-4} \text{ sec}^{-1}$, at a temperature of $47^\circ \pm 2^\circ\text{C}$, or at about 98% of the absolute melting point of the material. The area shown in Fig. 2 stands athwart an original grain boundary aligned approximately parallel to the direction of shearing. The two large original grains are referred to as the 'upper' and 'lower' grains, according to their positions in Fig. 2, which has been turned 90° anticlockwise relative to Fig. 1. During the deformation the boundary between these grains, or more precisely the top part of the lower grain, became the locus of high strain and dynamic recrystallization. Some developments can be seen in Fig. 2 as follows.

Figure 2(a) shows the state of the material immediately before shearing began. The lower grain contains lamellar structures of unknown nature, possibly twins. The inked dashed lines connect two initially orthogonal lines of silicon carbide markers. The same markers are similarly connected in subsequent photographs, to indicate the approximate magnitude of the shear strains achieved by each stage. The subhorizontal line was picked approximately parallel to the local shearing direction. This line is, however, extended by as much as 10% in subsequent photographs. Departures like this from ideal simple shearing are normal in the experiments to date. The material is sheared and simultaneously extended somewhat in the direction of shearing.

By stage (b) in Fig. 2, the shear strain in the grain boundary region has reached values of the order of 1 or more, and material in a new orientation has started to appear (the narrow light strip along the former grain boundary). It is not known how or where this material began to grow, but motion of its high-angle boundaries with respect to the markers in the lower grain is certainly indicated. Dynamic recrystallization has started. This is true dynamic recrystallization (see, for example, Sellars 1978) and not just the geologist's synkinematic recrystallization, because the starting material of stage (a) can reasonably be assumed to have been strain-free. The driving force for the recrystallization was thus provided somehow by the current deformation. (Synkinematic or syntectonic recrystallization seem best kept as general geological terms for *any* recrystallization during deformation, including, for example, recrystallization during deformation where the temperature is increasing, where the driving force may be provided by strain energy stored during the first part of the deformation at low temperature.)

By stage (c) there has been further shearing strain in

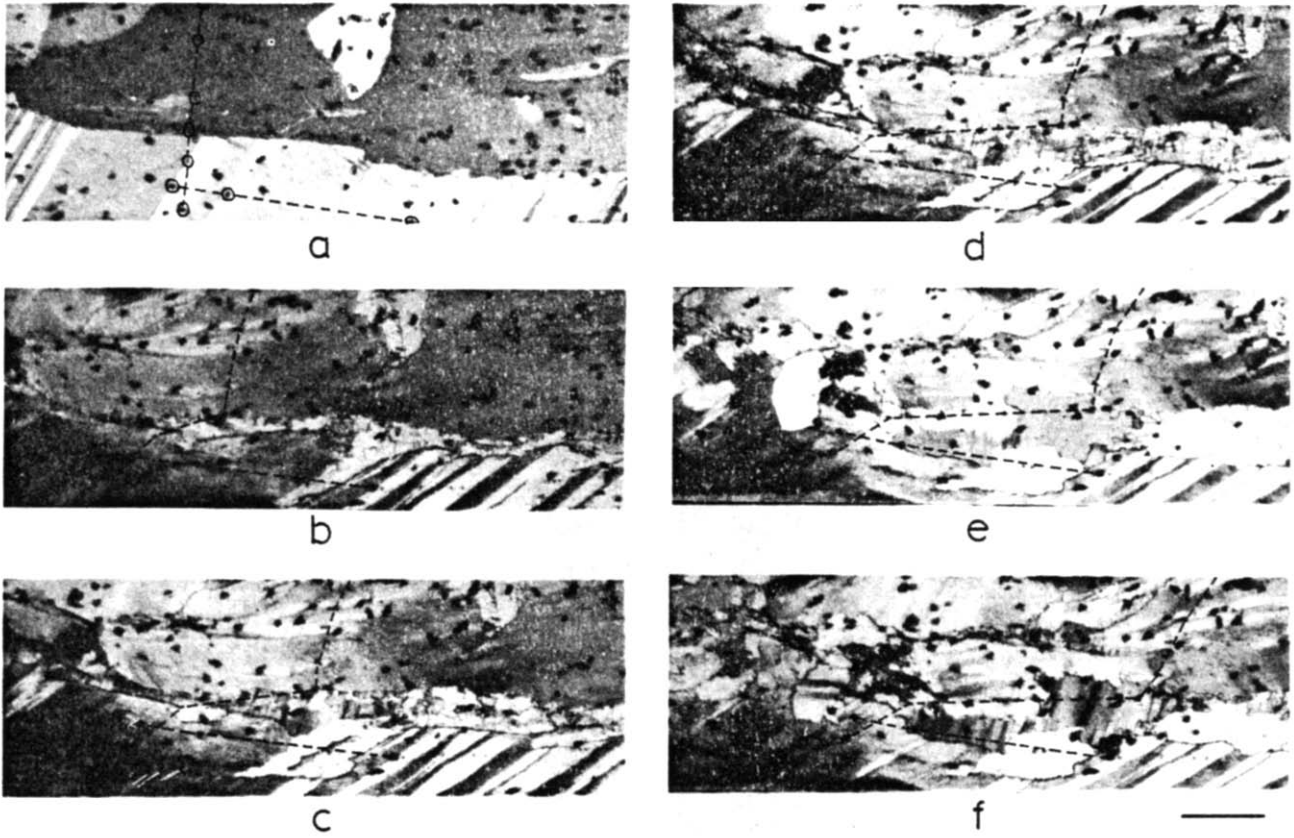


Fig. 2. Para-dichlorobenzene in successive stages of shearing in experiment TM-146. Area shown is area A of Fig. 1(c). Black granules are silicon carbide marker particles. Dashed lines connect selected markers (circled) that lie on orthogonal lines in the undeformed state (a). Crossed nicols, parallel and perpendicular to length of photos. Scale bar lower right is 1 mm.

the former grain boundary region, and further migration of the new high-angle boundary into the original lower grain. A uniformly oriented lamellar feature has appeared in the left portion of the recrystallized material, suggesting this is a single, very elongate grain. It is not known whether the lamellar features are kinks in a flat-lying slip plane, or products of dynamic polygonization (or both), or yet some other structure. (c) also shows two other new grains, the irregular white grain near the middle of the photograph, already initiated in (b), and the large new grain along the right-hand part of the original grain boundary.

In (d) the deformation of the original lower grain has come to a virtual halt, but an additional shear strain of 1–2 has been taken up somehow by the material in the former grain boundary. The lamellar features are now less conspicuous than in (c), but similarly oriented, suggesting that this microstructural element has become steady despite continued shearing. In both (c) and (d) there are many marker particles in the original upper grain around which can be seen strain shadow-like features. Here the markers are clearly interfering with strain or polygonization processes. Elsewhere, and in general, the markers seem to have a desirable minimal influence on the microstructural behaviour. I see no obvious examples of pinning of new high-angle boundaries by the markers.

By stage (d) the deformation had been going on for 390 mins, and a total shear strain of up to about 5 had been attained in the former grain boundary region. The drive motor was turned off overnight at this point, but the temperature was maintained at 47°C. The next morning revealed the structure shown in Fig. 2(e) and evidence of some further deformation relative to (d), probably at a decaying rate. The former grain boundary zone is now occupied by seven large and relatively strain-free grains, six of which are elongate in the general direction of shearing and of the original grain boundary. The drive motor was then started again for one additional increment of shearing. This resulted in the configuration shown in (f). The familiar lamellar structure visible in (c) and (d) has reappeared in two grains near the centre of the field of view and several other grains are also inhomogeneously deformed. By comparing (e) and (f) various examples can be seen of migration of high-angle boundaries with respect to the marker particles. Dynamic recrystallization has resumed.

The strain fields in TM-146 have not been investigated in detail, and there are perhaps not enough markers to do this satisfactorily, considering the inhomogeneity evident. However, one strain determination is shown in Fig. 3(a). This is the incremental strain relating (e) to (f), for the area spanned by the 31 markers shown in Fig. 3(b). The strain estimate was made by determining the stretch of each of 30 vectors formed by connecting the marker shown with an open circle to all the other markers. The stretches are plotted in Fig. 3(a) in the deformed orientations of the vectors, and a best-fitting ellipse is drawn in the manner of Elliott (1972,

p. 2631) and Mitra (1976). The incremental strain ellipse can be compared in orientation with the microstructural features that arose during the corresponding increment of deformation, namely the lamellar features in (f) that are not present in (e). Note that one of the directions of unchanged length, the local direction of shearing, is approximately perpendicular to the lamellar features. This relationship and the appearance of the lamellar features recall the interpretation and appearance of subgrains in deformed olivine rocks described by Nicolas and coworkers (Nicolas & Poirier 1976). An example is reproduced in Fig. 3(c).

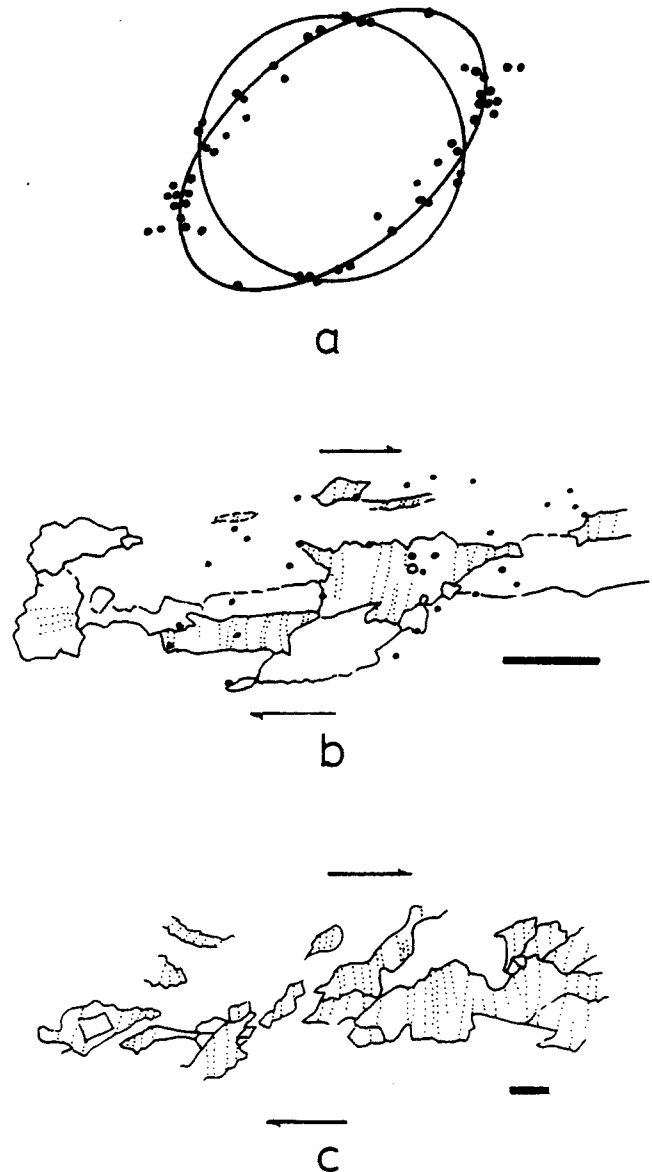


Fig. 3. (a) Incremental strain ellipse, with circle of unit stretch, for stages (e)–(f) of Fig. 2, for the area spanned by the markers shown in Fig. 3(b). (b) Tracing of recrystallized grains of para-dichlorobenzene in Fig. 2(f), showing lamellar structure (dotted lines) developed in some of them during the increment of deformation (e)–(f). Dots show positions of markers used to construct incremental strain ellipse of Fig. 3(a). Arrows show observed direction and sense of shearing. Scale bar is 1 mm. (c) Tracing of coarse olivine grains in part of a thin section from the core of the Lanzo massif, as illustrated by Nicolas & Poirier (1976 p. 364 after Nicolas 1974), showing subgrain boundaries (dotted lines). Arrows show direction and sense of shear as interpreted by Nicolas & Poirier (as inferred from their text by W.D.M.). Scale bar is 1 mm.

DISCUSSION

The experiments so far have been entirely concerned with working out techniques for making samples and shearing them, and with finding out whether para-dichlorobenzene can be made to exhibit recrystallization or recovery effects under the experimental conditions. The material does seem to display interesting high temperature behaviour, and I have been pleasantly surprised to encounter no serious complications in the strain fields resulting from frictional forces exerted upon specimens by the glass. The next steps in the programme include further technical developments, to permit room temperature universal stage measurement of grain orientations before, during and after an experiment. This should be feasible since the β form of dichlorobenzene can be cooled to room temperature for some hours or days before inversion to the room temperature α form begins. The main problem is to find a way of taking the thin sample in and out of the deformation cell at will. This can probably be accomplished by intruding the material between two glass slides and moving this sandwich as a unit. It will clearly be necessary to find out the optical orientation of β para-dichlorobenzene and the crystallography of its slip and twinning systems. The structure is known (Housty & Clastre 1957), and this suggests the possibility that the material has only one slip plane, the (001) plane, parallel to which there are widely spaced planes of benzene rings.

While para-dichlorobenzene itself may not turn out to be a useful rock analogue, it seems to me that thin specimen, transmitted light, analogue experiments of this general type promise to provide an instructive supplement to ordinary triaxial tests. They offer a rela-

tively quick, safe and inexpensive way of investigating some kinds of behaviour in deforming solids that are clearly of interest to geologists, yet not so conveniently studied in real rock samples.

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