On the inhomogeneity of plastic deformation in the crystals of an aggregate

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(*Communicated by Sir David Rivett, F.R.S.—Received* 11 *August* 1947)

[Plates 1 and 2]

The variation of plastic deformation in aluminium specimens consisting of large crystals has been determined by measuring elongation and hardness at various points after tensile deformation. The deformation varied from grain to grain, and also within each grain the deformation near the boundary was greater or smaller than at the centre according to whether the neighbour was more or less deformed, i.e. there is not necessarily inhibition of slip near grain boundaries. These results were supported by metallographic and X-ray observations. Their importance with respect to the calculation of the stress-strain curve of aggregates from those of single crystals is discussed. It is suggested that a mechanism other than slip operates near the grain boundaries during deformation, and even within the crystals during large extensions.

Introduction

Any theory of plastic crystal aggregates requires a knowledge of the behaviour of the crystals during deformation and of their interaction. Whereas the behaviour of single crystals under stress is well known, the effect of their interaction is not yet quite understood. Obviously, a crystal embedded in other crystals deforms differently from a crystal which is free from any constraint by neighbours. Such differences have been studied, particularly in aggregates of large-grain size, and the effect of the boundaries has been stated to consist in inhibition of slip.

Carpenter & Elam (1921) observed that during tensile deformation of coarse-grained aluminium the crystals exerted a supporting effect on each other. The deformation at the boundary was much less than in the centre of the crystals, and this effect was still noticeable at a distance of 0·25 in. from the boundary. Moreover, they noted that 'a crystal which narrowed on pulling in contact with one which remained broad tended to make the latter narrow also. In its turn, the crystal which remained broad, tended to prevent the other one from narrowing.'

In subsequent investigations only the fact that the boundaries restrict plastic deformation has been considered. Aston (1926) found that the change of crystal orientation during deformation is less near a grain boundary than at the centre of a crystal. His conclusion that the extent of deformation is correspondingly smaller near the boundary does not seem to be justified, since deformation due to multiple slip gives rise to a smaller change in orientation than the same deformation due to single slip. The diffuseness of the X-ray interferences usually increased as the boundary was approached indicating a greater amount of bending of the lattice planes.

Yamaguchi (1927) determined the local elongations from marks scratched on the surface of aluminium specimens. He found that 'the elongation at the boundary is always smaller than that of the adjacent crystals', although some of his evidence contradicts this statement.

The conclusion reached from all these investigations was that less deformation occurs near a grain boundary than in the centre of a grain. This slip interference producing an increased resistance to shear has been cited as an explanation of the higher hardness observed for aggregates compared to single crystals. The only quantitative investigation of this strengthening effect was carried out by Chalmers (1937). He measured the elastic limit of bicrystalline specimens of tin and found it to increase approximately linearly with the angle between the tetragonal axes of the two crystals. The area of the boundary did not influence the extent of strengthening, and 'the critical shear stress is raised by the proximity of a boundary, and the amount of slip that takes place is decreased'.

Chalmers's experiments clearly show that the change in orientation at the boundary is the important factor for the strengthening effect. The change in orientation also gives rise to different deformations within a crystal at different distances from the boundary. Barrett & Levenson (1940) have drawn attention to this inhomogeneity of the deformation. They have shown the existence of deformation bands which indicate that various parts of a crystal suffer different deformations.

The present investigation was undertaken to obtain quantitative data on the extent of the inhomogeneity and to ascertain whether the deformation is always restricted near the grain boundaries.

Experimental procedure

(*a*) *Preparation of specimens*

The material used was commercial aluminium of 99·15 % purity, the main impurities being Fe 0·5 % and Si 0·28 %. Tensile specimens having gauge length $6 \times 1 \times \frac{1}{8}$ in. were prepared with a grain size of 1 to 3 cm. These were first annealed at 200° C and back-reflexion Laue diagrams made to determine the orientation of the various grains relative to the specimen axis. One face of each specimen was mechanically polished and the specimens annealed again at 200° C. The final surface preparation was by electrolytic polishing, leaving a strain-free surface.

On this surface the grain boundaries could be seen microscopically as fine lines, but to facilitate their location the specimen was very lightly etched. Inclusions of impurities were present, but they were not preferentially distributed at grain boundaries.

(*b*) *Hardness measurements*

Three types of indentation hardness measurement were attempted:

(i) Knoop diamond, load 25 g.
(ii) Vickers diamond, load 200 g.
(iii) Vickers diamond, load 1 kg.

It was found that the first two of these types were not useful after deformation of the specimens, as surface rumpling caused a wide scattering of the results which were not reproducible. Measurements with the Vickers diamond and 1 kg. load were much less sensitive to this effect and were later used exclusively. The probable error of these hardness measurements was calculated as less than 0·3 hardness unit, i.e. approximately 1·5 %.

Hardness before deformation was measured by making a straight line traverse of hardness indentations parallel to the axis of subsequent tensile deformation. The least distance between any two impressions was approximately five times the length of the diagonal of an impression.

The distance apart of the impressions was measured with a cathetometer to $\pm 0{\cdot}001$ cm., illumination being arranged so that one face only of the pyramidal impression reflected the light source. This gave a convenient and accurate reference line which was independent of the size of an impression.

(*c*) *Measurement of local deformation and hardness*

The specimens were then deformed in tension to 5 % elongation. The known distances between hardness impressions made *before* deformation were now used as gauge lengths and remeasured after deformation. The elongations of individual grains and of various areas within particular grains were calculated from the differences between distances measured before and after deformation. The error in each measurement of length was $\pm 0{\cdot}001$ cm., and hence in determining elongation on a gauge length of 2 mm. the error in the value for percentage elongation was $\pm 1{\cdot}0$, and correspondingly larger for smaller gauge lengths. The extent to which elongation measurements could be localized was limited by this factor.

In order to determine the hardness after deformation a traverse of indentations was made parallel to the one made before deformation. Finally, Laue diagrams were made at several points suggested by the results obtained in the elongation and hardness measurements.

One specimen was then further deformed in tension to 17 % total elongation and the local deformation measured as before.

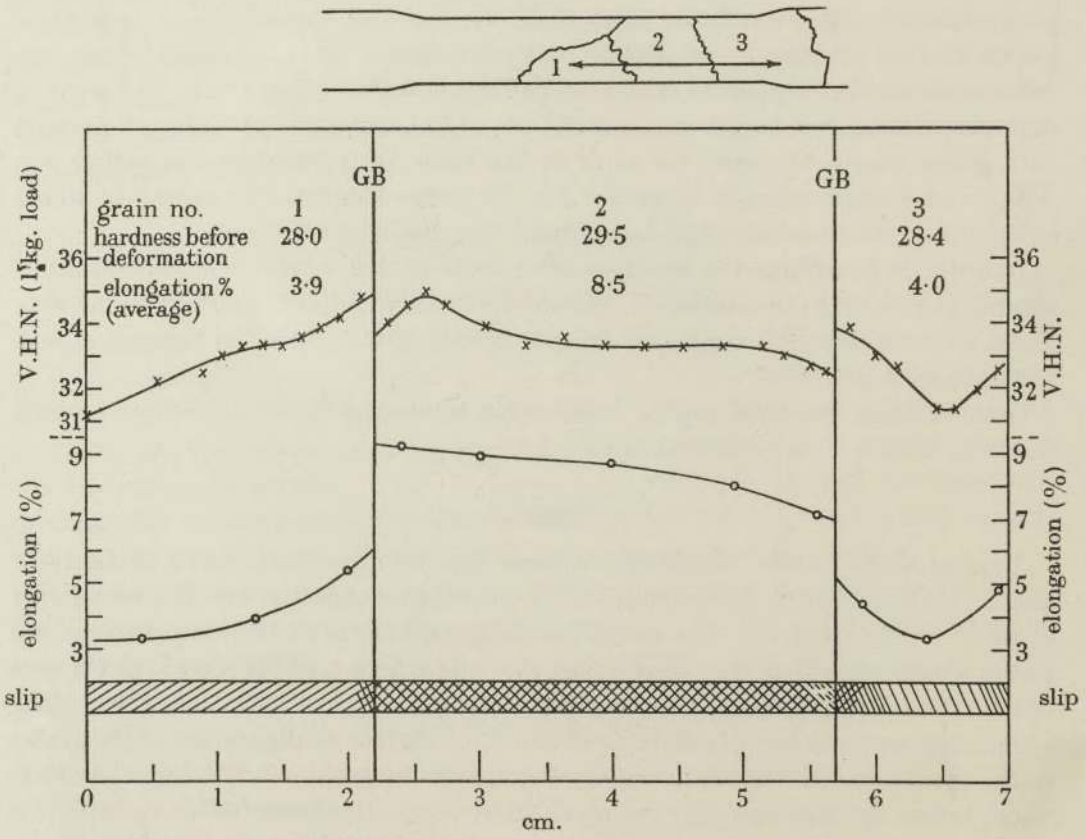
Results

Typical of the results obtained are those for two specimens shown in figures 1 and 2. Hardness after deformation and percentage elongation are plotted against distance on the specimen. The values for elongation are plotted in the centre of the gauge length on which they were measured, and where possible a smooth curve is drawn. The heavy vertical lines represent the positions of grain boundaries; the grain numbers refer to the diagrams showing the surface configuration of the grains in the specimen. Also tabulated for each grain on the graph are the mean hardness value before deformation and the mean elongation. Hardness before deformation was constant in any grain within the limits of experimental error. The type of slip bands observed in various areas is indicated schematically in figure 1*a*.

It is obvious from the curves that the overall elongation of 5 % given to the specimen produces widely different elongations in the individual grains. Moreover, the deformation is not uniform within one grain. As a boundary is approached the deformation becomes larger than at the centre if the average deformation of the neighbour is larger, and in the neighbour the deformation is less near this boundary than at its centre. This feature is even more apparent in the specimen which was extended by another 12 % (figure 2). The elongations which are so different in the central portions of the grains become similar near the boundaries.

It can also be seen that the curves for hardness after deformation have the same trend as the elongation curves. Since hardness before deformation was constant within any grain, the curves for hardness after deformation indicate the distribution of work hardening and therefore of deformation *within one grain*.

The hardness measurements thus complement the observations made above with respect to the effect of the neighbour and give a better indication of the local deformation than the elongation measurements. The latter are average values over their respective gauge lengths, and the extreme variations thus obtained are therefore smaller than the actual variations. However, the degree of work hardening cannot



(*a*)

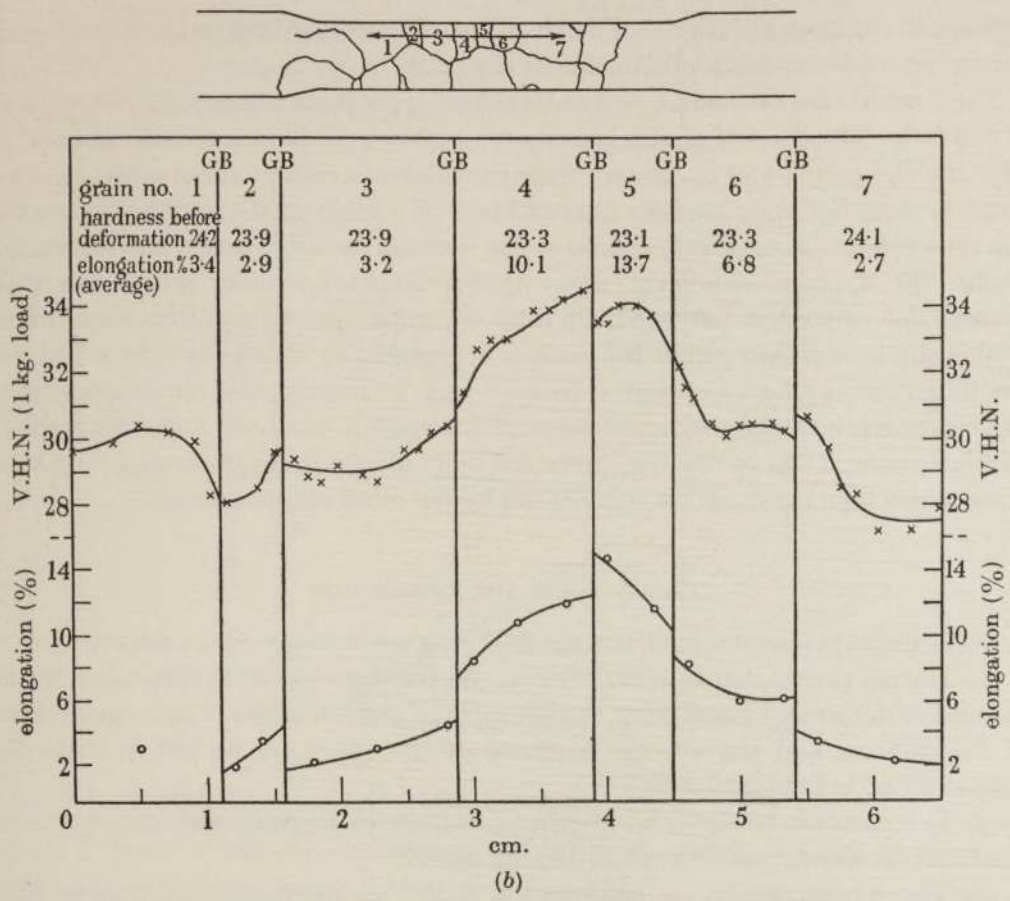


FIGURE 1. Hardness and local elongation of the grains of an aggregate after 5 % elongation. (*a*) Specimen 19. Slip occurring at various points in the grains is shown schematically. (*b*) Specimen 5.

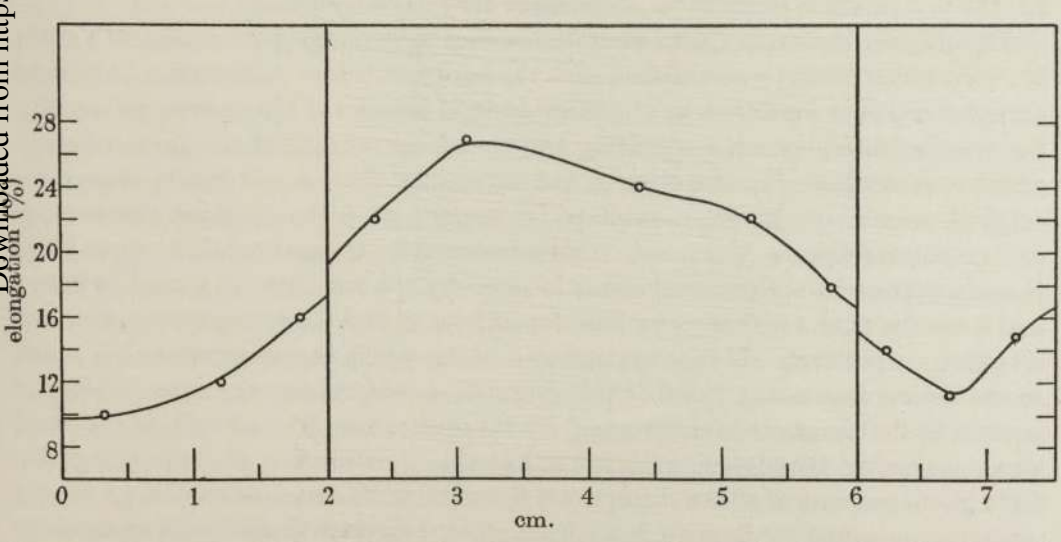


FIGURE 2. Local elongation of the grains of an aggregate after 17 % elongation. Specimen 19.

be used to compare the degree of deformation of various grains as the rate of work hardening varies with the orientation of the grain.

These results are further supported by the evidence from microscopic observation of slip lines. The density of slip lines varies within a grain in a manner consistent with the elongation and hardness values for the grain. Where these measurements indicate more deformation near the boundary of a grain relative to the centre, the slip lines become more closely spaced as the boundary is approached and sometimes double slip appears. Similarly, when approaching a boundary where less than average deformation is indicated slip lines are wider spaced, and sometimes where double slip occurs throughout the grain it is replaced by single slip. These features are illustrated by figures 3 and 4, plates 1 and 2. Finally, the inhomogeneity of deformation is confirmed by observation of the spots in the Laue diagrams made at various points in the grains. The spots are more diffuse in diagrams resulting from areas where high deformation is indicated by the other measurements.

Conclusions and discussion

From the experimental evidence the following conclusions can be drawn:

(1) During plastic deformation of an aggregate there are wide differences in the amount of deformation and work hardening from grain to grain. The overall extent of deformation and the average hardness of the aggregate do not indicate the behaviour of individual grains.

(2) Deformation is also inhomogeneous within each grain and corresponding hardness variations due to work hardening occur.

(3) The inhomogeneity of deformation is due to interaction of neighbouring grains and may extend up to 1·5 cm. from the grain boundary. The direction of this deformation variation is such that the deformation approaches that of the neighbour, i.e. the deformation tends to be continuous across the boundary.

The question now arises as to what determines the average deformation of a grain. No correlation could be established with the hardness before deformation. Although an indentation is produced by the same general process as elongation, i.e. by slip, the particular slip systems operating and the stress conditions are quite different, and hence the lack of correlation is not surprising. One would rather expect the original orientation of the crystal to be important in determining the average deformation of a grain. For purely tensile deformation the ratio of shear stress along the slip system to the external stress is given by the function $\sin\chi\cos\lambda$, where χ and λ are the angles between the direction of tension and the relevant slip plane and direction respectively. If that system acts, along which the shear stress is a maximum, the corresponding value of this function should express the susceptibility of a grain to deformation as determined by its orientation, for not only is the shear stress acting on the system proportional to this function but also the elongation for a given amount of shear. In figure 5 the maximum values of $\sin\chi\cos\lambda$ for the grains represented by figure 1 have been plotted against the average elongations

of the grains. Also plotted from the results of Karnop & Sachs (1927) are the elongations of single crystals of appropriate orientations under the same tensile stress as was used to deform the aggregates in the present experiments.

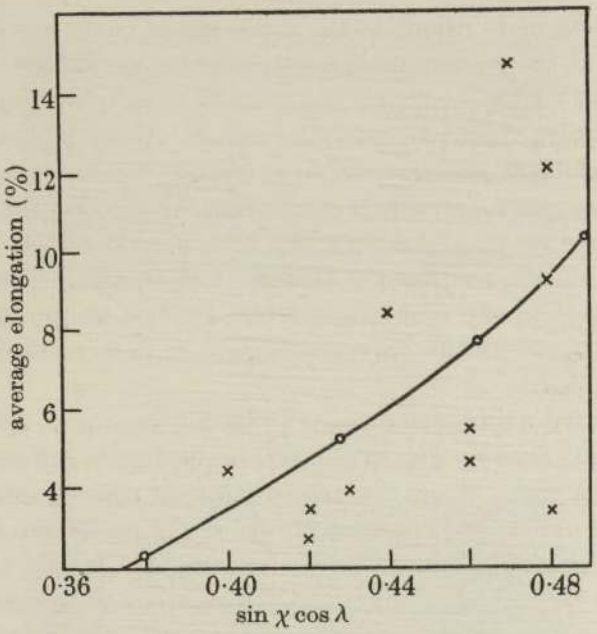


FIGURE 5. Elongations of crystals under the same external stress as a function of their orientation. × Average elongation of crystals in aggregates as observed in these experiments after 5% overall elongation. ○ Elongation of free single crystals observed by Karnop & Sachs.

Two features are evident:

(*a*) While grains of high average elongation are grains for which the value of the function $\sin\chi\cos\lambda$ is high the converse is not true.

(*b*) The points for grains in the aggregates lie about the curve for single crystals under the same stress.

These observations lead to the conclusion that the distribution of stress in the aggregate is not uniform, some grains receiving more and some less than the externally applied stress. Thus while the product $\sin\chi\cos\lambda$ determines the susceptibility of a grain to deformation under a pure tensile stress, the geometry of the aggregate influences the actual stress on the grain and thus the extent of its deformation.

The observations are also of interest with respect to the calculation of the stress-strain curve of polycrystalline materials from the shear hardening curve of the single crystals. The only self-consistent calculation has been carried out by Taylor (1938) for aluminium, and gave good agreement with the observed tensile curve. However, as Barrett & Levenson (1940) have pointed out, the change of orientation of approximately one-third of the crystals in the aggregate is not that predicted by Taylor's theory. This lack of agreement must be due to the assumptions made. The main assumption on which the theory is based is that the material deforms uniformly

irrespective of the presence of grain boundaries and differently orientated grains. The present investigation has shown that not only are there differences in deformation from grain to grain, but also within any grain, thus contradicting Taylor's assumption.

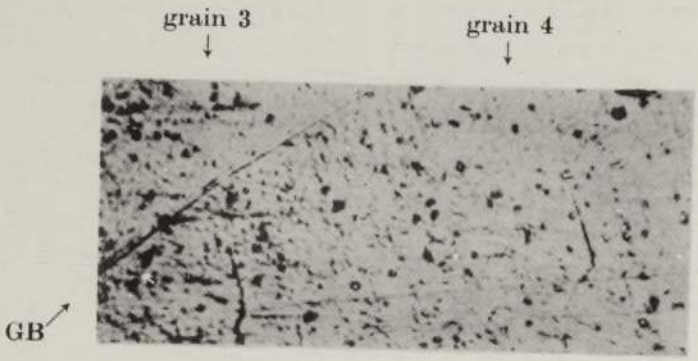
Before a new attempt to calculate the stress-strain curve can be made, the conditions prevailing at the grain boundaries have to be established. Certainly the slip is not homogeneous within a crystal, and it seems even to be doubtful whether slip is sufficient to explain the observed deformation. According to geometrical considerations any arbitrary deformation of a crystal, for instance, the deformation of a crystal in an aggregate, requires the occurrence of slip along at least five systems. Experimentally only single and double slip have been observed in our aggregates. Further, Barrett has shown that the change in orientation is not always such as would result if five-fold slip took place. Since contact at the grain boundaries is maintained slip cannot be the only mechanism of deformation operating in the crystals of an aggregate.

It appears that the deformation tends to be continuous at the boundaries, and if the deformation is entirely due to slip this implies quite different stresses on the two sides of the boundary where crystals of different orientations adjoin. Because of the principle of action and reaction the stress normal to the boundary and the shear stresses in the boundary must be continuous. Hence the mechanism of deformation must be such as to allow the deformation to be continuous, although the stresses are the same on the two sides of the boundary. In addition to the slip observed there must be another process for which the stress-strain relationship is different. The closer the approach to the boundary the greater is the relative proportion of the second process, although under favourable conditions more slip takes place near the boundaries than at the centre.

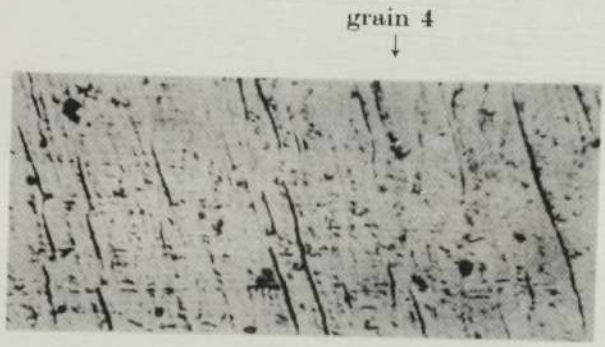
If five-fold slip were to operate at the beginning of plastic deformation the critical shear stress would have to be obtained on all five slip systems. The external stress necessary would be much higher than that which gives rise to the critical shear stress on the most favourable system for slip. It is suggested that non-slip deformation takes place at an external stress smaller than that necessary to initiate slip on the less favourably orientated of the five systems. No suggestion as to the nature of the non-slip deformation can yet be made from the experimental evidence.

Although in the present experiments only comparatively small deformations were used, it is considered that at higher deformations the non-slip mechanism will become increasingly important. The inhomogeneity observed for small deformations will penetrate further into the crystal as deformation proceeds, and at higher deformations the extent of the non-slip process will become greater. With smaller grain size the effect will be more pronounced. It has already been suggested by Chalmers (1940) that a type of plasticity similar to amorphous flow becomes preponderant at high deformations.

The results of this investigation were obtained from measurements on the surfaces of specimens. A crystal in the interior of a polycrystalline specimen will be still more



a



b

c

FIGURE 3

(*Facing p.* 96)

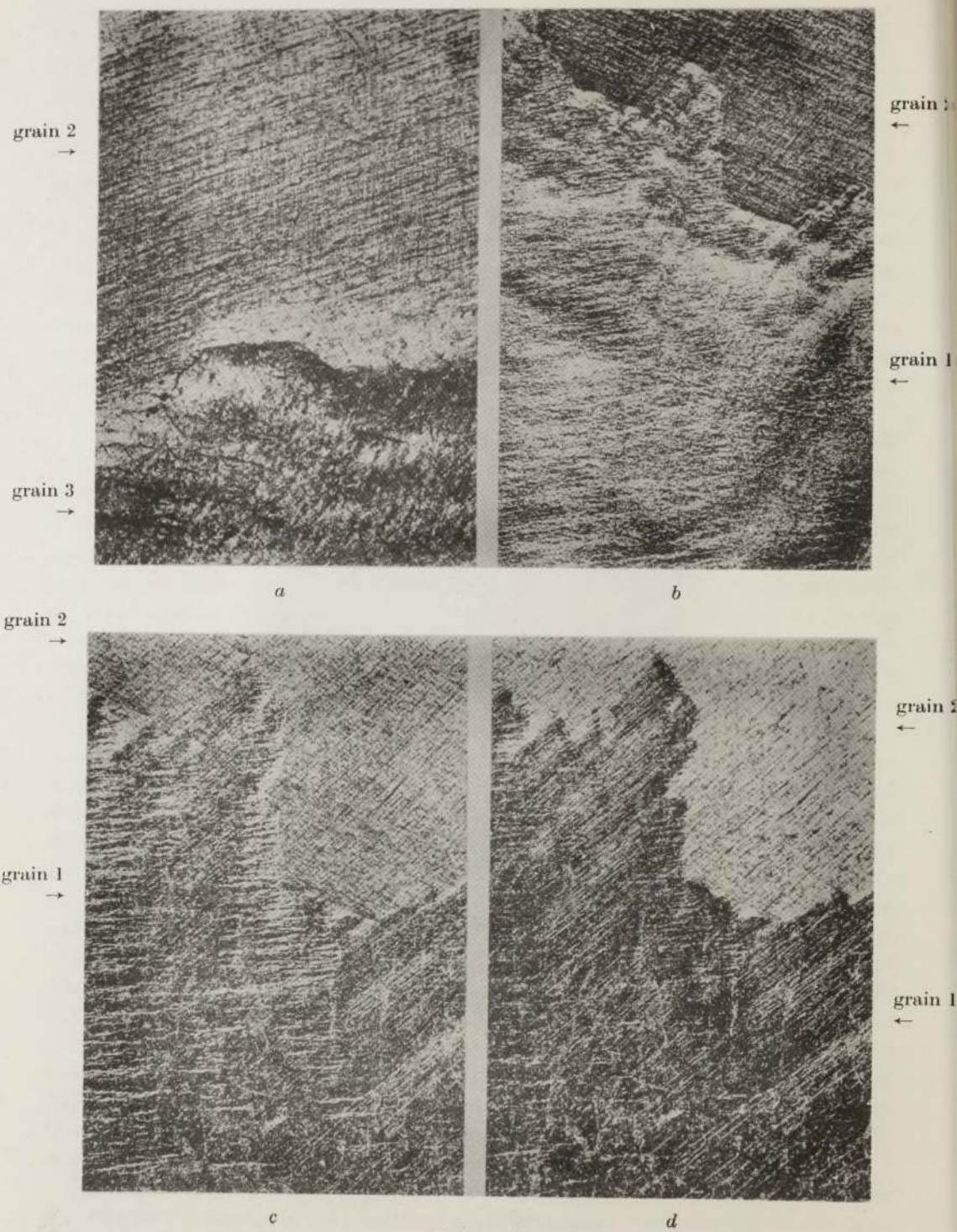


FIGURE 4

restricted in its deformation, since it is not allowed the freedom in deformation at the free surface (observed as surface rumpling) and has a larger grain-boundary area relative to its volume. For such a crystal the non-slip mechanism will therefore play a greater role than for a surface crystal. The continuity of deformation may then even extend throughout the crystals, and it is conceivable that the strain will become uniform in a small-grained specimen in agreement with Taylor's assumption. This uniformity, however, would be the result of the non-slip process.

This work forms part of a general programme, carried out by the Section of Tribophysics, Council for Scientific and Industrial Research, Australia. We wish to thank Professor E. J. Hartung for laboratory facilities in the Chemistry School, University of Melbourne, Professor H. K. Worner for the use of equipment in the Rosenhain Memorial Laboratory, and the staff of the Munitions Supply Laboratories Maribyrnong, for carrying out spectrographic analyses and help in the use of equipment.

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Description of Plates 1 and 2

Plate 1

Figure 3. Variation of slip line density in grain 4 of specimen 5 after 5 % elongation. Compare with figure 1*b*. *a*, boundary area grains 3 and 4 (× 250). *b*, centre of grain 4 (× 250). *c*, boundary area grains 4 and 5 (× 250).

Plate 2

Figure 4. Slip lines in grain-boundary areas of specimen 19 after 5 % elongation. Compare with figure 1*a*.

a, boundary between grains 2 and 3. No double slip in grain 2 near the boundary (× 23).

b, boundary between grains 1 and 2. Mainly single slip and surface rumpling in grain 1. Double slip in grain 2 (× 6).

c, *d*, portion of the area shown in *b*, at higher magnification (× 15). The same area is shown under different illumination in (*c*) and (*d*).

c, note the second slip system near the boundary in grain 1 in addition to the principal seen in *b*.

d, the extent of the second slip system in grain 1 is more apparent than in (*c*). The slip lines of this second system are almost parallel to those of one of the systems in grain 2.