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Grain rearrangements during superplastic deformation

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Current models for obtaining large superplastic flow without change of grain size are two-dimensional; they therefore involve rearrangement of grains without increasing the surface area of the specimen as it deforms. A new model is proposed in which grain-boundary sliding (GBS) in a group of grains is accommodated by a grain emerging from the next layer of grains, giving the correct increase in surface area. This also produces curved grain boundaries and there is some rotation of grains involving plastic flow in a zone along grain boundaries (the "mantle") of predictable width. Grains do not have to be uniform and regular for the process. Characteristic configurations of marker lines are produced by the deformation. All these features are shown to have been observed in the literature. The model does not predict a threshold stress. It can be linked with a previous constitutive equation based on the climb and glide of dislocations in the grain mantles.

1. Introduction

During superplastic deformation grains apparently move past one another without permanent changes in size, although there are characteristic changes in shape. A satisfactory theory for superplasticity must therefore start with a model which has geometrical attributes which predict these topological features correctly and then leads on to a constitutive equation which gives the correct rates of strain for various conditions of stress, grain size and temperature.

Ashby and Verrall [1] put forward a theory, involving diffusion-accommodated flow, based on a model in which grains were rearranged through a neighbour-switching process and claimed that it met the above conditions. Although this theory has been very widely quoted, it is increasingly evident that the predictions of the rate equation are not in good agreement with experimental results. Nevertheless, the neighbour-switching model continues to be accepted by many authors, partly at least because no other gives so specific a means of attaining large strains without changing grain shape or size.

It is the purpose of this paper to re-examine the Ashby and Verrall (A & V) theory, noting some other problems with it and then suggesting a new model which overcomes these and accords well with several kinds of experimental observation. This model can be linked with constitutive equations already developed and thus match results for much of superplastic behaviour.

2. Ashby and Verrall's theory

2.1. The rate equation

Strain rates predicted by the A & V theory are almost always much too low, except occasionally at the lowest stresses [2]. The theory also gives strain rate $\dot{\epsilon}$ depending upon $\sim\sigma/d^3$ (σ is the applied stress and d the grain size) under the conditions usually applicable to superplastic deformation when grain-boundary diffusion dominates; experimentally a dependence of $\sim\sigma^2/d^2$ is found. The grain-switching event gives rise to a threshold stress, because significant energy is required to change grain-boundary surface area during this process. This threshold stress is identified by A & V with the low-stress regime I of the sigmoidal plot of log $\dot{\epsilon}$ against log σ. Their equation does not predict this regime well [1, 2]. More importantly, it attributes to this regime an activation energy equal to that for grain-boundary

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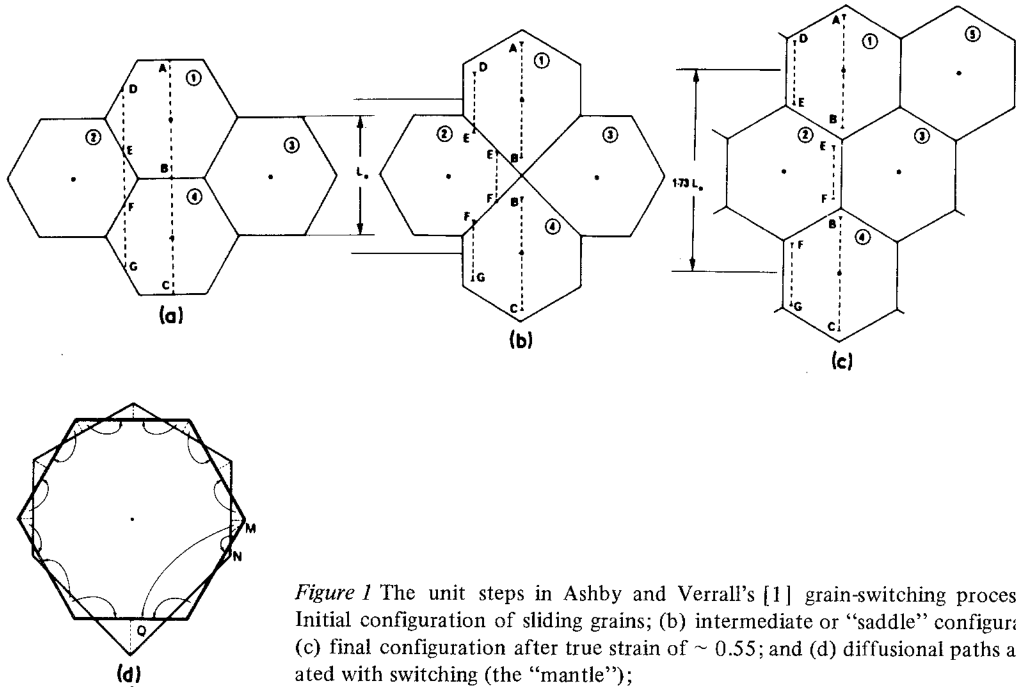


Figure 1 The unit steps in Ashby and Verrall's [1] grain-switching process. (a) Initial configuration of sliding grains; (b) intermediate or "saddle" configuration; (c) final configuration after true strain of ~ 0.55; and (d) diffusional paths associated with switching (the "mantle");

self-diffusion, whereas recent results make it clear that it should be close to that for lattice self-diffusion [3].

A & V also predict that the strain rate should be lower (approximately equal to that for grain-boundary diffusion creep) at low strains, only rising to the rate predicted by their equation after the grain-switching strain of 0.55 (true strain). There is no evidence to support this. This cannot be explained away, as they suggest, by supposing that there are groups of grains at all stages of the switching process at all strains, because there must be sliding over a distance of ~0.9 of the grain edge before any switching can occur.

2.2. The geometrical model

The A & V grain-switching model is illustrated in Fig. 1. The four grains 1 to 4 in the initial position, Fig. 1a, move by GBS along the inclined boundaries to an intermediate saddle position, Fig. 1b, the shapes of grains 1 and 4 having been changed by diffusion in the mantle region to avoid formation of voids.

The area of each grain remains constant throughout the process, although the grain-boundary area increases at the saddle position. Further GBS and diffusion accommodation, together with grain-boundary migration, allows the grains to move to the final position, Fig. 1c, the whole process generating a true strain of 0.55 (≡ 73%). The key to the grain-switching event is the decay of the quadruple node in Fig. 1b to two triple nodes in Fig. 1c. It is also during this process that work is done in creating and then losing additional grain-boundary area, giving rise to the threshold stress.

2.2.1. Diffusional paths

The diffusional process is sketched in Fig. 1d, the paths shown in the left-hand side of the diagram being those given in the A & V paper. The diffusional paths are short compared with those involved in normal diffusion creep and it is for this reason that A & V were able to derive a strain rate faster than that for diffusion creep. In fact, the situation is not quite as simple as this, because the triangles concerned in the change of shape are of unequal areas in the lower half of the diagram; diffusion is not then limited to exchange between neighbouring areas. Some material from triangle M has to diffuse to Q as well as the neighbouring N. The path MQ is equivalent to the path in normal diffusion creep and it would follow that the strain rate from the grain-switching process would not be much greater than that for diffusion creep. This would still further widen the disagreement between experimental rates and those computed from the A & V equation.

2.2.2. *Initial and final groupings of grains*

It should be noted that the final position of the grains is such that for a new cycle of grain switching to occur, the grains have to be regrouped. This can be done by taking, for example, grains 1, 2, and 3 with a fifth grain adjacent to 2 and 3. The sliding boundaries for this grain switching sequence are then at 30° to those of the original set. This was not taken into the rate equation, but would probably not affect it if, as A & V claim, the power used to drive GBS is negligible. However, this claim rests on using Ashby's [8] viscous sliding equation which may not be appropriate [9]. Particularly if Regime I is identified with GBS, then at lower stresses in Regime II, GBS may consume significant power in its operation.

2.2.3. *Surface area of specimens*

This model was developed from observations of an emulsion forming an array of "grains" which served as a topological analogue to the superplastic case. This followed an earlier, similar, model described by Rachinger [7] and his recognition of the occurrence of grain switching. These emulsions, and the models based on them are two-dimensional. Ashby and Verrall were quite aware of this and mentioned that their model "was not expected to reproduce exactly the topological changes in a real polycrystal", also that in practice – as Rachinger first pointed out in 1952 [7] – "sub-surface grains appear at the surface or surface grains disappear below the surface" during deformation involving GBS without change of grain size. They claim, however, that "this does not involve any new phenomena – the essential step is still that shown" e.g. that in Fig. 1.

The fact remains that as it stands the A & V model gives extension without any increase in surface area, such as normally accompanies extension. With a two-dimensional array of grains, *there is no other way in which strain can be generated than by the rearrangement of grains, that is by grain switching* (provided, of course, the grains do not permanently change shape or size). If superplastic specimens do increase in surface area during extension, and we shall see that they do, then a significant part of the process is left unexplained in the two-dimensional model, because a true strain of 0.55 normally requires an area increase of 31.6%. It is not sufficient to claim, as A & V do, that this is taken care of by the same grain-switching process (presumably acting through groups of four grains inclined to the surface) because that does not explain how the increase is 31.6% and not some other amount*.

2.2.4. *Other theories*

Other theories based on dislocation motion have been put forward which do give the σ^2/d^2 dependence [2, 4, 5], the stress term arising from the stress concentration due to dislocation pile-ups of some kind. These dislocation models do not automatically give large strains. Indeed, the earlier two theories [4,5] postulate large amounts of dislocation movement across the grains and thus require some further mechanism to maintain equiaxed grains. The third theory [2] confines dislocations to the "mantles" of the grains and thus can avoid change of grain shape.

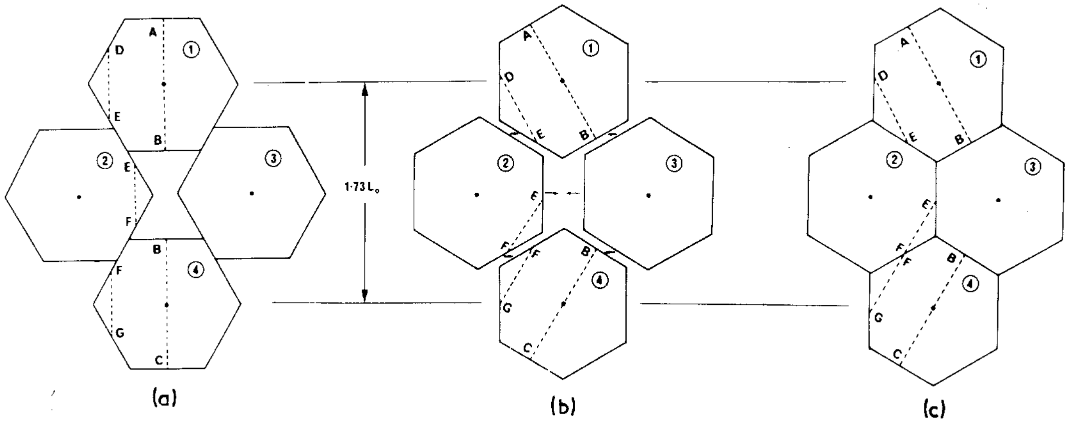
One other recent theory put forward by Padmanabahn [6] claims to give σ^2/d^2 and to allow grain-boundary sliding to continue indefinitely without accommodation being necessary. As will be shown elsewhere the σ^2/d^2 dependence is open to considerable doubt, but it is more relevant to the present argument to note that – as will be shown later in Section 2.3 – the model does not avoid accommodation problems.

The position is therefore that no present theory combines a geometrical model giving large strains with a constitutive equation giving good predictions.

2.3. Rotation and sliding

The solution can be approached by considering, in Fig. 2, the attainment of a strain of 0.55 by grain switching with the formation of voids. In Fig. 2a the four grains have moved by GBS to increase the area by ~31.6% in effect, two voids of trapezoidal section being formed as shown. In Fig. 2b the grains have been rotated, thus distributing the void as channels between the grains. The grains

*This problem of increase in surface area and its solution by movement from neighbouring layers of grains has also been discussed by Hazzledine and Newbury in "Grain-boundary Structure and Properties", edited by G. A. Chadwick and D. A. Smith (Academic Press, London, 1976) p. 243.



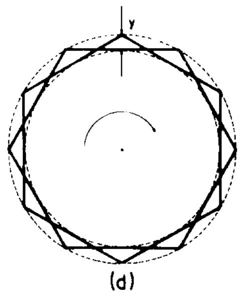


Figure 2 Alternative (notional) steps to attain grain-switching as in Fig. 1 but here with the creation of voids, the initial position as in Fig. 1a. (a) Sliding to create a void; (b) rotation of grains; (c) grains close up to final position, identical to that in Fig. 1c; and (d) showing zone swept out by rotation of apices of grains – the "mantle".

can then be moved, as indicated by the arrows, to reproduce in Fig. 2c the same final configuration as in the A & V model.

The total effect in Fig. 2 is equivalent to that of the A & V model and would be identical if the grains *rotated as they slid.* This would require accommodation in the mantle defined by the paths swept out by the apices and midpoints of the sides of the rotating grains (Fig. 2d), which is almost the same mantle as in the A & V model. The width y of this mantle is given by

$$y = (d/2)(1 - \cos 30°) = 0.07d \qquad (1)$$

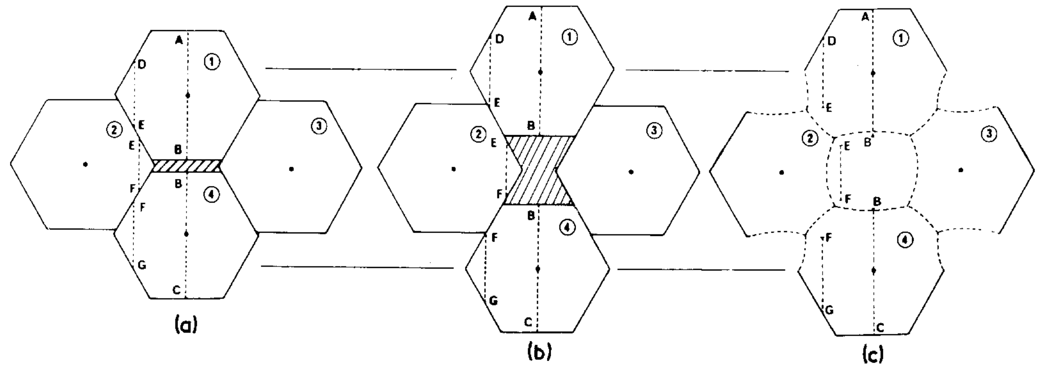
As A & V have noted, y becomes smaller the smaller the grain size.

This zone is required for the operation of Padmanabahn's [6] mechanism, which involves GBS occurring through the shear of disordered groups of atoms in the grain boundary (a notion first put forward to explain internal friction results [10]). He claims that this mechanism avoids the necessity for accommodation of GBS at triple edges, which is only true for the case sketched in Fig. 2. As his model stands, however, it postulates this flow to be in the grain boundary itself, not the mantle, which means in a zone ~1 nm wide instead of one equal to $y = 0.14\,\mu$m required for a grain size of 1 μm. It is for this reason that Padmanabahn's *model* is inadequate.

Superplastic specimens do increase in surface area during deformation. This has been shown by measurements on lead–thallium specimens which had deformed to a strain of ~0.1 in the superplastic regime (i.e. deformed by GBS without change of grain size in the regime where $\dot{\epsilon} \propto \sigma^2/d^2$ [9]). The increase in area for these specimens was just that required by such a strain. No voids were formed internally. The specimens thus seem to conform more to Fig. 2a than to Figs. 1b or c.

3. A new model

A means of achieving the required changes without creating voids is shown in Fig. 3. As the sliding grains (Fig. 1a) begin to open up a void, Fig. 3a, a grain (shaded) begins to move from the next layer to fill the gap. Initially this probably means that a shallow fissure is formed on a free surface, (Fig. 3a) but as the gap increases, Fig. 3b, the emerging grain fills the void. However, this involves a grain-boundary network which is unstable, and migration occurs to adjust to the correct dihedrals, Fig. 3c. This tends to curve the boundaries of the emerging grain and, to a lesser extent, the boundaries of the original four grains become



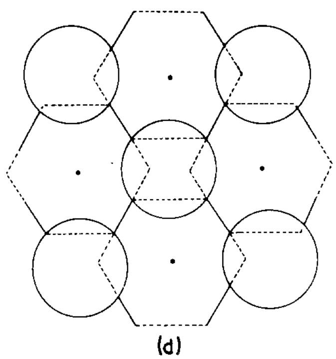


Figure 3 Specimen elongation by GBS and accommodation by movement of grains from one layer to the next – "emerging" grains. (a) After a small amount of deformation, a small narrow fissure forms; (b) this gap is enlarged and filled by an emerging grain; (c) the grain-boundary network adjusts to maintain correct dihedral angles. (d) The unit of five grains shown as part of a repeated pattern for the whole specimen. However, note that the process does not necessarily require a symmetrical, repeatable unit as its basis.

curved as shown in Fig. 3c. This is the situation for a group considered in isolation. If the whole specimen is considered to be made up of repeat units of this kind, the final configuration would be typified by Fig. 3d and the majority of boundaries would show curvature. In practice, because of the variation in both true and apparent grain sizes, the situation would be between the two cases shown.

Although Fig. 3 has been drawn to represent the situation at a true strain of 0.55 in order to make comparison with Fig. 1 easy, it is important to note that the emerging grain will begin to round off and give the characteristic pattern of the model at all strains except those small enough to give rise to the pattern in Fig. 3a.

3.1. Problems of symmetry

It is worth noting at this point that a problem with repeat units arises in the A & V model, which with its initial and final configurations implies a specimen made up of repeated groups of four grains. The saddle position (Fig. 1b) then becomes impossible, because this group of four grains will not repeat to give a specimen without voids or some major adjustment of the outer boundaries of each group. No doubt this can be countered by claiming a real specimen to have a variety of units, rather than one standard grouping repeated, but this underlines the difficulties of making such models. If they are so simplified to make the geometry and resultant mathematics easy to handle, then predictions of what might be observed on real specimens are unrealistic.

This kind of difficulty is greatly diminished if not entirely eliminated with the model sketched in Fig. 3, for although it has been presented there in terms of uniform hexagonal prisms (to facilitate comparison with Figs. 1 and 2) *the grains need be neither hexagonal nor uniform, nor does the group have to consist of four grains for the operation of the grain-emerging mechanism.* All kinds of sizes and shapes and of local associations can be orchestrated into the general pattern by the conditions of stability of grain size and shape and of increasing the number of grains in each layer. It is indeed a feature of real specimens that, on the surface at least, groups of grains move together and rise above the general level or drop below it, in addition to individual movements.

It is also a feature of the ideal, uniform, model involving emerging grains that triple-edge accommodation at the lines of emergence is attained without the necessity of moving material around the triple edge or shearing of the third grain of a group. Instead material has to be moved in the

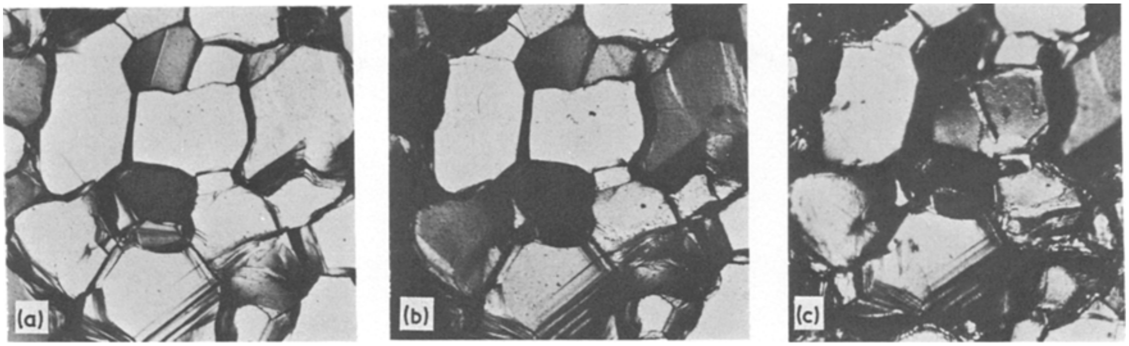


Figure 4 Movement of grains in a Pb–Tl specimen extending in Regime II (superplastically) reproduced from [11]. After creep of (a) 13% (243 days); (b) 18% (351 days); and (c) 38% (757 days). (× 145).

mantle (width $\sim 0.07\,d$) of the emerging grain to overcome locking of grain corners. Triple-edge accommodation might still be required at other places to allow whole groups of grains to co-operate in the grain-emerging process. Thus the behaviour of a particular grain will be complex and difficult to predict: the model attempts an average view. This also means that although the details of the geometry have been changed from the previous model [2], the overall accommodation problem remains that of moving material in a mantle of width $0.07\,d$. Again, in the idealized case, this accommodation does not necessarily produce axial strain.

4. Marker-line configurations

The various models presented in Figs. 1 to 3 give characteristic patterns for marker lines after reaching strains equivalent to that for the grain-switching event. These have been shown in the figures for inert marker lines, such as would be obtained with internal strings of oxide particles or precipitates. For surface scratches there would be gaps other than those shown, where grain-boundary migration would obliterate the marker – for example, the segment EF in the new grain in Fig. 3c would probably be lost. Under good conditions it should be possible to deduce the mechanism operating from observation of marker-line configurations.

5. Experimental observations

5.1. Surface fissures

At low strains the emergence of grains is limited (Fig. 3a) to strip-like areas between grains which are moving apart. As suggested in Section 2.3, these may then develop as shallow fissures, the emerging grain not completely filling the void created. Examples can be seen in Fig. 4a (which has previously been published [11]). As deformation proceeds, these fissures can be seen to become wider (see Figs. 4b and c). It was fissures of this kind which were found recently when a specimen was examined for evidence of diffusion creep during superplastic flow [9]. Double marker-lines, as described by Aigeltinger and Gifkins [12], were made on a Pb–Tl specimen which was extended $\sim 10\%$ at the lower-stress end of Regime II. Configurations which *could* be interpreted as the accretion of material by diffusion creep (see Fig. 5) were found on 13 out of 86 boundaries showing GBS. In most of these 13 cases there was a shallow fissure. The marker-line configuration can therefore be attributed to accretion of material, but by emerging grains rather than by diffusion creep: no examples of the marker line configuration associated with *loss* of material by diffusion creep were found.

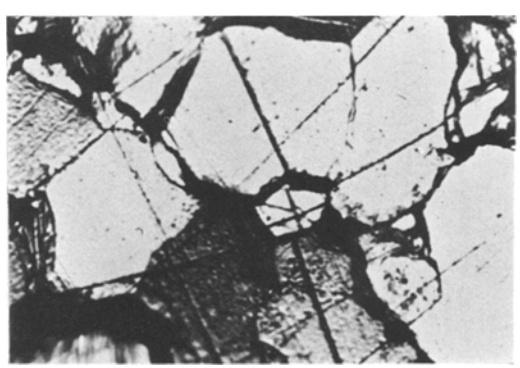


Figure 5 Marker-line configurations indicating the development of shallow fissures between sliding grains (cf. Fig. 3a). Pb–Tl specimen after 10% extension (× 195).

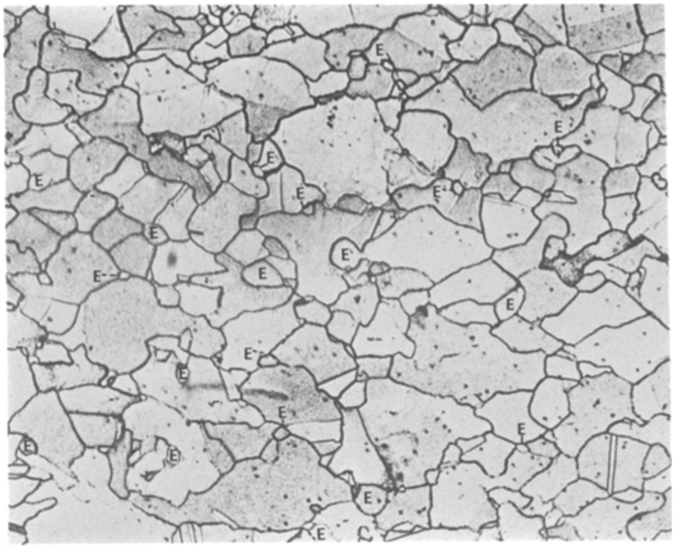


Figure 6 Specimen of Pb–Tl alloy repolished after extension to 372% in 221 days, showing rounded grains identified here as emerging grains (E); reproduced from [13] (× 140).

5.2. Rounded grains

Fig. 6 originally published in a note in 1952 [13] shows the grain structure on a Pb–Tl specimen repolished after ~400% extension. A number of grains (marked E) almost circular in section can be seen in this micrograph, matching the configuration shown in Fig. 3b and suggesting that these grains are emerging from neighbouring layers.

It will be seen in Fig. 6 that a number of the larger grains have been plastically deformed to unusual, irregular shapes; this was the main point in the original note [13]. This could have resulted from their being too large to take part in the general sliding movement involving groups of grains and therefore to their having to deform throughout their volumes by dislocation movement. It also appears that some of these large grains may have amalgamated with other grains through rotation and migration. This kind of growth could also occur in two-phase materials and has been noted by Naziri *et al.* [14] in their Fig. 7.

5.3. The work of Naziri *et al.* [14]

Naziri *et al.* [14] followed selected areas of a zinc–aluminium alloy deforming superplastically in the 1 MV electron microscope. They reproduced two sets of micrographs – their Figs. 8 and 9 – which show changes which they claim confirm the A & V neighbour-switching process. There is no doubt that this claim is well sustained for their Fig. 9. Calculation shows, however, that these photographs were taken at strains such that their specimen was then *less* than 2 to 3 grains thick at the beginning of this particular series and 1 to $1\frac{1}{2}$ at the end. In other words, the specimen was essentially two-dimensional whilst the grain switching was taking place and, as we have seen there is no other way it could extend whilst keeping grains unchanged in area and shape other than by grain switching. The series in Fig. 8 shows, in their description, "grains A and B are moving away from each other... whilst grain F appears to be coming up from below and moving between A and B". The point of importance here is that in this sequence the strains were such that the number of grains in the specimen thickness was four. Thus the grain-switching process is not essential and that of grain emergence (our Fig. 3) can take over and indeed the evidence shows it to be doing so.

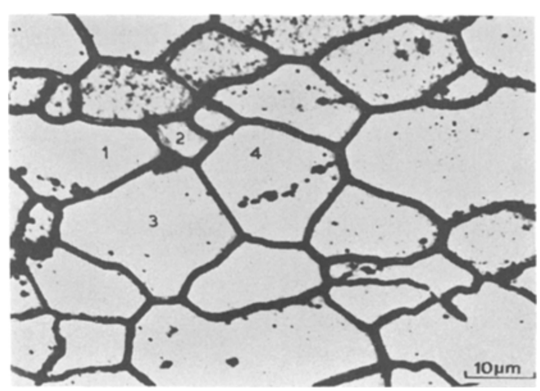


Figure 7 Internal marker lines in an Al–Zn–Mg alloy after 100% extension, reproduced from [15]. It is suggested that grain "2" is an emerging grain cf. Fig. 3c.

5.4. The work of Matsuki *et al.* [15]

Matsuki *et al.* [15] have reported grain movements and marker-line configurations on a superplastic alloy (Al–9 Zn–1 Mg) which they claim support the A & V grain-switching model, although they modified this model to some extent to match observations of the way grains were oriented.

In their Fig. 9 they show a series of micrographs of the same area in which grains appear to slide as in Fig. 1a here, and then become separated by dark areas which conform to our Fig. 3 – i.e. support the idea of emerging grains. A similar set of micrographs was published in 1963 [11] showing grains of a Pb–Tl alloy separating longitudinally, here reproduced as Fig. 4.

Matsuki *et al.* also show in their Fig. 7 a "neighbour-switching event revealed by relative translation of internal marker lines", here reproduced as Fig. 7. It will be seen that this configuration is better matched by the grain-emerging model, Fig. 3c, than the A &V model, Fig. 1c, although the marker lines have been rotated as well. Since the strain was 100% it might be expected that flow in the mantle and grain rotation in the manner of Fig. 2 has also occurred to a significant extent, so that the resulting configuration is a blend of Figs. 2c and 3c.

Their Fig. 4 – reproduced here as Fig. 8 – also gives evidence for the grain-emerging model. It will be seen that marker lines begin by showing offsets at lower strains, indicating sliding but with some breaks in the marker where grains have begun to emerge but not persisted (Fig. 8a) and increasingly at higher strains show marker lines in alternate grains, in conformity with Fig. 3c or d.

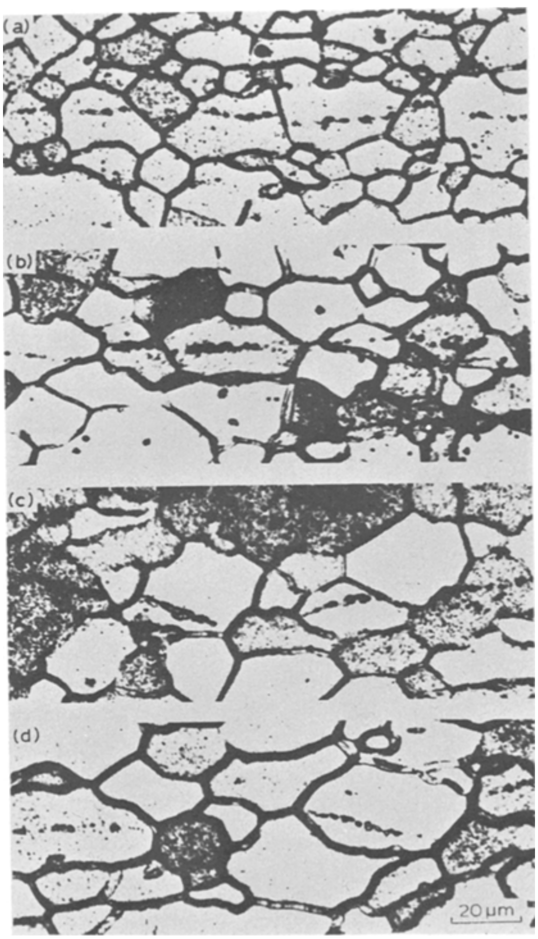


Figure 8 As for Fig. 7 [15] strains of (a) 30% (b) 60% (c) 100% and (d) 200%, showing configurations compatible with Fig. 3.

5.5. "Thickened" grain boundaries

Another feature of the micrographs in the paper by Matsuki *et al.* is that the grain boundaries of specimens repolished after deformation tend to etch as thick lines (see Figs. 7 and 8). This also occurs with the very pure single-phase Pb–Tl alloys, as shown in Fig. 6 here and in the illustrations to a previous paper [16]. The boundaries in Fig. 8 are particularly interesting, because they are thicker after larger strains, when the grain size is noticeably larger.

An explanation of this phenomenon can be given on the basis of Fig. 2d. If accommodation is occurring in the mantle defined by the rotation of grains, this involves transfer by diffusion, whether it is by dislocation climb [2] or simple vacancy–atom diffusion. This would tend to modify the composition of the mantle with respect to the core (since it is the matrix atoms which diffuse) in a manner analogous to the denuded zones found in diffusion creep [17] – although in a different geometrical pattern to this case.

On this basis, the "thickened" boundaries ought to be $2y$ wide and in the illustrations shown they are indeed approximately in agreement with this prediction. The increase in thickness between Figs. 8a and d, associated with an increase in grain size, is of particular relevance.

5.6. Apparent contribution of GBS

The results of Matsuki *et al.* [15] give a maximum value of ϵ_{gb}, determined from internal marker lines, of $0.63\,\epsilon_t$ at $\epsilon_t = 0.60$. They do not state what value of the geometrical constant they used to convert sliding measurements to ϵ_{gb}; the number of readings of offsets taken was on the low side ("over 200") and they did not make any allowance for the marked amount of grain rotation. Their result therefore compares reasonably with the value $\epsilon_{gb} = 0.52\ (\pm 0.06)\ \epsilon_t$ found [9] for a Pb–Tl alloy at $\epsilon_t = 0.10$.

These values of ϵ_{gb} are therefore such as to account for about half of the total deformation in the superplastic range. At higher stresses, in Regime III, $\epsilon_{gb} \simeq 0.3\ \epsilon_t$ for the Pb–Tl alloy and $0.42\ \epsilon_t$ for the Al–Mg–Zn alloy. In Regime I the latter gave $0.26\ \epsilon_t$ but the Pb–Tl alloy gave $0.44\ \epsilon_t$, a value that is barely significantly below the value for Regime II.

If all offsets in a longitudinal line are recorded, it might be expected that $\epsilon_{gb} = \epsilon_t$, but in a model based on hexagons oriented as in Figs. 1 to 3, half of all possible intersections of marker lines with grain boundaries do not become offset and thus $\epsilon_{gb} = 0.5\ \epsilon_t$. It is not clear how this effect will operate for less regular grain shapes.

The accommodation of GBS by emerging grains does not contribute to the strain, although it is rate controlling. This is for the ideal case depicted in Fig. 3. The situation is very similar to that in diffusion creep, where the conventional *measurement* gives $\epsilon_{gb} \simeq 0.5\ \epsilon_t$ [18] even though this cannot be taken to mean that GBS independently contributes half the strain: it is a matter of definition of how the measurements are made [19].

In the present case not all accommodation will be by simple emergence of grains and some strain-producing accommodation at triple edges will be present. The value of ϵ_{gb} will also be affected by grain rotations, but unless some process operates to bias this in one rotational sense, it would seem unlikely to *reduce* the net value of ϵ_{gb} significantly.

Thus the expected value of ϵ_{gb} is between $0.5\ \epsilon_t$ and ϵ_t and – if the analogy with diffusion creep is accepted – the lower value of $0.5\ \epsilon_t$ might be expected [18, 19].

5.7. Rate equations

If the conclusion of the last section is accepted, then the rate equation already developed [2] for GBS accommodated by dislocation climb and glide in the mantle is appropriate, namely

$$\dot{\epsilon} = 64\, b^3 D_{gb}\, \sigma^2 / GkTd^2 \qquad (2)$$

where b is the Burgers vector, D_{gb} the grain-boundary diffusivity, G the shear modulus, k Boltzmann's constant, and T the absolute temperature.

This equation implicitly contains $\epsilon_{gb} = 0.5\ \epsilon_t$ based on the geometry of accommodation of GBS and with this assumption gives excellent fit to a number of results [2, 9]. If $\epsilon_{gb} = \epsilon_t$, the constant 64 would have to be changed towards 32 and the agreement with experiment could be less good; however, a factor of two is easily introduced one way or the other in selecting values of D_{gb} and G, so this source of disagreement is not too serious.

When the stress is high enough, the model changes to one of accommodation of GBS by triple-edge folds (Regime III) and the value of ϵ_{gb} falls to $\sim 0.3\ \epsilon_t$ for sufficiently fine-grain material. The grain emerging mechanism is then lost and attainable superplastic strains consequently diminished. The equation for this regime, which also matches a wide range of experimental results [2, 20] is

$$\dot{\epsilon} \simeq 10^{21}\, b^3 D \sigma^n / G^{n-1} kTd \qquad (3)$$

where D is the lattice diffusivity, n a constant usually of value 4.5 to 5, G the shear modulus and d the grain size in cm.

5.8. The low-stress Regime I

There is no specific change in grain-boundary area in the grain-emerging mechanism and therefore the prediction of a threshold stress is not part of this model. However, the model remains linked to the concept of GBS accommodated in various ways and thus the low-stress Regime I can be identified with rate control by GBS itself (or with GBS controlled by barriers other than triple edges). A previous model [2] for GBS (Regime I), although meeting several of the experimental criteria, does not readily lead to prediction of recent values of activation energy for this regime: experimentally these are found to be approximately equal to those for lattice self-diffusion [3], whereas the model would suggest a value no greater than that for boundary self-diffusion. This means there is no acceptable model for Regime I extant. Nevertheless, it is likely that the general physical basis of the previous model [2] is appropriate – namely the movement of grain-boundary dislocations impeded by elements of the structure of the grain boundary itself.

6. Discussion and summary

It has been shown that there are difficulties with all the existing theories for superplastic deformation and, in particular, that the model used in the A & V theory as well as the resulting constitutive equation have serious difficulties.

A new model has been put forward, as follows. GBS occurs on the boundaries of a group of grains, as in the A & V model, but probably by the movement of grain-boundary dislocations rather than by viscous flow. (Further work is required to elucidate the mechanism of GBS). The sliding produces stress concentrations at the triple edges and thereby gives rise to the power term (σ^2) for stress. To accommodate the GBS several processes occur. Material flows in a mantle of width $\sim 0.07\,d$ allowing grains to rotate (or to appear from their geometry to do so) and, at the same time, grains move from one layer to the next so that a fifth grain emerges in the middle of the original four. This maintains the correct surface area of the specimen and requires less movement in the mantles of grains than transfer of material around triple edges, as previously postulated in an earlier model [2]. Some groups of grains may still require triple-edge accommodation because of the detailed local topography of the specimen. The accommodation is, however, always restricted to the mantle and takes place by dislocation climb and glide.

This model in association with an earlier theory [20] can lead to rate equations for Regimes II and III which agree well with a wide variety of results [2, 9] but even if these equations are not accepted the model may be judged by itself: it gives predictions concerning microstructure which are in good agreement with experiment, as shown in Section 5. These are summarized as follows:

(1) GBS is the only strain-producing mechanism (except in the larger grains of the population);

(2) there is grain rotation;

(3) interaction with GBS by grain rotation, emerging grains and triple-edge accommodation leads to marker-line measurements giving, apparently, $\epsilon_{gb} < \epsilon_t$;

(4) small rounded grains (the emerging grains) develop into normal grains as strain proceeds;

(5) other grains also develop curved boundaries to maintain correct dihedral angles with the emerging grains;

(6) the width of the mantle in which accommodation occurs is determined by grain rotations and is $\simeq 0.07\,d$;

(7) the mantle may develop compositional differences from the core which allow it to be revealed by etching;

(8) there is limited grain-boundary migration;

(9) longitudinal separation of grains occurs;

(10) marker-line configurations after deformation have characteristics which distinguish the mechanism from others (particularly the A & V process);

(11) the surface area of specimens increases, and

(12) the process is continuous, i.e. there is not a critical strain below which the characteristic changes are limited.

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