Moderator's Comment

E. Kröner

► To cite this version:

E. Kröner. Moderator's Comment. Revue de Physique Appliquée, 1988, 23 (4), pp.513-518.
10.1051/rphysap:01988002304051300 . jpa-00245798

HAL Id: jpa-00245798

<https://hal.science/jpa-00245798>

Submitted on 1 Jan 1988

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Moderator's Comment

E. Kröner

Institut für Theoretische und Angewandte Physik, Universität Stuttgart und Max-Planck-Institut für Metallforschung, Stuttgart, F.R.G.

Preliminary remarks

As all the previous sessions, so also the present one shows that plasticity belongs to the most complex phenomena in the scientific world. This has the consequence that all existing theories in our field, if they can predict something, have a rather limited range of application. A theory which covers the whole plasticity (or viscoplasticity) would be by far too complex to be of any use. This state of affairs should cause us to give as precisely as possible the limits of any theory in our field. Above all, this means that all assumptions and simplifications need to be precisely stated and always kept in mind. Clearly, when the theory is tested on the experiment, this should match the underlying assumptions of the theory. If the result of such testing is positive, then this is a necessary condition for the theory to be acceptable. It is by far not a sufficient condition.

As has often been emphasized, plasticity can be described at various spatial levels. In the phenomenological, or macro, approaches suitable variables, which satisfy certain field equations, are introduced and constitutive equations formulated. In the "macro-macro" approach, as Cailletaud [1] calls it, the constitutive equations are found from experiments between which interpolations are allowed (criterion: the success). In the "micro-macro" approach the constitutive equations are derived by some synthesis of the mechanisms occurring on smaller scales. Clearly the predictive power of a theory increases if it starts from smaller levels. The corresponding theoretical effort, however, increases.

It is particularly valuable when certain general features and the pertaining principles can be detected which are valid for wider clas-

ses of materials. As well-known examples I mention the volume conservation, the Schmid law of critical shear stress, valid for instance for fcc crystals, and the formation of cell structures, at the time being a more qualitatively explored feature. The laws of volume conservation and critical shear stress have a good theoretical basis so that also deviations from them, as the failure of Schmid's law in bcc crystals, can be well explained. As emphasized by Hansen and Leffers [2], the principles underlying the formation of cell structures are more complex, a fact which is also reflected by a certain variety of internal cell boundary structures. There is a large experimental body on this, out of which I would like to mention the work of Mughrabi [3], who reports among other things that the cell walls approach ideal low-angle boundary configurations both at higher temperature and, less pronounced, at extensive deformation. Obviously, dislocation dipoles, present in the original walls, can relax in such situations, leaving behind in the wall dislocations of one sign in an ideal low-angle (= low energy) configuration. Thus, although internal stresses build up due to the constraints implied by the existence of only a few slip systems, there will always be a tendency to get rid of these stresses. Hence rearrangements of the dislocations can always be expected when the dislocations gain new mobility, in our case assisted by temperature or by large stress.

I shall now give four comments which are related to the lectures and posters of this session.

Formation of cell boundaries

The importance of this phenomenon was stressed by Hansen and Leffers [2] as well as by Canova [4]. Some quantitative results were presented by Kratochvil [5], Kubin [6] and Rey [7]. It seems to be appropriate to discuss this topic in terms of dislocation walls. Recall the three important types of edge dislocation walls:

a) $\vdash \vdash \vdash \vdash \vdash \vdash$:

low-angle grain boundary wall (low energy)

b) $\top \top \top \top \top \top \top \top$:

long-range internal stress wall (high energy)

c) $\begin{array}{cccccccc} \perp & \perp & \perp & \perp & \perp & \perp & \perp & \perp \\ \top & \top & \top & \top & \top & \top & \top & \top \end{array}$:

dipole wall, often more irregular (moderate energy).

Note that for instance a wall of form $\angle \angle \angle \angle$ is macroscopically equivalent to a superposition of walls of type a and c. In a similar manner different walls can be constructed with screw dislocations.

Most important for the formation of cell boundaries are the geometric boundary conditions which have to be fulfilled in addition to the usual stress boundary conditions. Although it is seldom stated in terms of dislocation walls, those of type b are excluded by most workers in the field (see e.g. the old work by Livingston and Chalmers [8] and the newer work by Kocks and Canova [9], Rey [7] and by Berveiller and Bouaouine [10]). The exclusion of the b-walls, though probably approximate, seems to be justified since the tendency is towards low internal strain energy.

The cell walls form under the impact from loading and under the restriction of mobility due to the discrete nature of the slip systems. These two influences determine largely the motion and mobility of the dislocations. Berveiller and Bouaouine define a habit plane as a plane where a macrostress-free dislocation wall can build up, given the possible slip systems around that plane. According to this theory the observed cell walls should lie in the habit planes.

The calculations of the mentioned authors combine macro- and micro-considerations. In fact, the boundary conditions are formulated in the macrolanguage, although the physical mechanisms concern the motion of dislocations, i.e. phenomena on the microscale. Thus this seems to be an example where the micro- and macrodescription have indeed come closer together, even though we do not know how to express our knowledge on cell structures in terms of yield surfaces and hardening laws.

3-level description of polycrystal plasticity

A length scale can not only be attributed to the grain structure of a polycrystal, but also the cell structure occurs on a typical length scale. Let the characteristic lengths of these two scales be $l(II)$ and $l(III)$ respectively. The corresponding levels of description may be called mesoscopic and microscopic. If we add a macroscopic length scale with characteristic length $l(I)$, considered large compared to $l(II)$ and $l(III)$, then we arrive at a 3-level description of polycrystal plasticity.

This description corresponds to the well-known 3-level description of the internal stresses (see e.g. ref. [11]). $l(I)$, $l(II)$ and $l(III)$ can now be understood as distances over which the internal stresses of the three kinds are essentially homogeneous. Although this classification matches well the physical situation, it is now seldom mentioned. It should perhaps be noted that Orłowska [12] has developed some formalism to treat multilevel systems of the kind considered here. Further work in this direction seems desirable.

Self-consistent scheme

Contrary to other theoretical approaches this scheme handles the development of residual (or internal) stresses due to inhomogeneous plastic strain in polycrystals. In particular, the stresses of the IIInd kind which vary from grain to grain are treated. The plastic behaviour of a grain (also called inclusion) of average shape (e.g. sphere) in the matrix of the other grains is calculated (approximately) as a function of orientation. The self-consistence implies that the plastic behaviour of the inclusion averaged over all orientations equals that of the matrix. With certain approximations one obtains

$$\sigma(\text{incl}) - \bar{\sigma} = -2\mu\alpha(1-\beta) (\epsilon(\text{incl}) - E) \quad (1)$$

where σ^I and $\bar{\sigma}$ are the mean (deviatoric) stresses of inclusion and whole body, ϵ^I and E the pertaining plastic strains, μ the shear modulus and β a geometric factor $\approx 1/2$. For various values of the scalar factor α one obtains formulae which have appeared already in other theories, namely in those of Sachs ($\alpha = 0$), of Zaoui and Berveiller ($\alpha < 1$, decreasing with increasing deformation), of Kröner ($\alpha = 1$, the first to use an equation like (1) [13]), of Lin ($\alpha = 1/(1-\beta)$) and of Taylor ($\alpha = \infty$). This sequence of numbers suggests that the theories of Sachs and Taylor could perhaps represent lower and upper bounds to the real behaviour. A good proof for the reality of this suggestion seems to be missing. The predictions of the above mentioned theories are compared by Hansen and Leffers [2] who report that the required number of slip systems is the same for all models covered by eq. (1), except that of Sachs which by definition works with only one system.

According to Hihi et al. [14] the observed decrease of α (till $\alpha \approx 0,02$) is due to plastic accommodation which means that slip in one grain may initiate slip in a neighboring grain if the relative orientation is favorable. This effect has been studied many times by means of bicrystals. It can be included into the self-consistent scheme if instead of a single grain a double grain is taken as the inclusion, and the result is also averaged over all relative orientations of the grains in the double grain thus incorporating the plastic accommodation. The result of such a calculation, which still has to be done, would be a more realistic factor α in eq. (1).

Statistical approaches

Bretheau et al. [15] emphasize that the theories mentioned so far fail to account for effects which result from the spatial distribution of phases or, more generally, from the distribution of the local elastoplastic properties. They propose to study such influences on two-phase materials and present interesting results on heterogeneous iron-silver compounds. Now, in a sense, elasticity

theory is a limiting case of elastoplasticity. It should, therefore, be possible to draw some conclusions about elastoplasticity from the well-developed stochastic theory of elastic polycrystals.

For instance, the elastic theory has rigorous results on bounds and self-consistent values for effective elastic moduli. The latter results should come out as limiting cases of a well-formulated self-consistent theory of elastoplasticity. Now the self-consistent elastic moduli represent, what is not well-known, the rigorous effective moduli of polycrystalline aggregates only in the case of "perfect disorder", a notion defined by the requirement that no principle of order exists in the distribution of grain shapes and sizes and of lattice orientations. What are principles of order in this sense? For instance, when in average distinguished grain shapes exist, when in average lengthy grains are harder than compact grains and when the orientations of neighboring grains are correlated. Applied to plasticity the latter principle of order can mean, that for instance flow in one grain induces correlated flow in the neighbor. It is clear that such correlations do, in fact, build up during plastic deformation which is accompanied by changes of grain shape and orientation.

In elasticity, deviations from perfect disorder shift the effective behaviour towards the bounds of Voigt or Reuss, which can be far apart. It depends on the elements of order created, which direction (Voigt or Reuss) is preferred. Taylor's theory is often compared with the Voigt bound. Both Hansen and Leffers [2] and Canova [5] in their lectures emphasize that the Taylor model predicts well the deformation texture in copper and aluminum at large deformations: "which brought a great success to that model" (Canova). But we have also heard from Jonas [16] that in other cases (brass) the Sachs model, the other extreme, seems to be more successful. It appears to me that the real success would be a theory which explains why in one case Taylor-like, in a second case Sachs-like and in some other cases still other behaviours are observed. It is believed that this has to do with the stacking fault energy (Hansen and Leffers [2]), which is a decisive factor for the dislocation mobility, and, therefore, also for the formation of the dislocation cell structure. This is a good example of the interconnection between many effects which makes the phenomenon of plasticity so complex.

These considerations show that it is desirable to take into account correlations from grain to grain. This is also suggested by the fact that the crystallites are often highly anisotropic. For instance, the shear modulus of crystalline copper depends on the orientation and varies by a factor of 3. In order to select the active slip systems, it would, therefore, help if not only the stress averaged over all grains, but also that averaged over the grains of a given orientation (and, if possible, grain shape) were known. The theory of random elastic media allows us to calculate such conditional averages.

References

1. G. Cailletaud, this volume
2. N. Hansen and T. Leffers, this volume
3. H. Mughrabi, this volume
4. G.R. Canova, this volume
5. J. Kratochvil, this volume
6. L. Kubin, this volume
7. C. Rey, this volume
8. J.D. Livingston and B. Chalmers, *Acta Met.* 5, 322-327 (1957)
9. U.F. Kocks and G.R. Canova, *Proc. 2nd Risø International Symp. on Deformation of Polycrystals, Mechanics and Microstructures*, N. Hansen ed., 1981, p. 135
10. M. Berveiller and H. Bouaouine, *Arch. Hutnictwa, Polish Acad. Sciences*, 1987, in press
11. A. Kochendörfer, *Plastische Eigenschaften von Kristallen und metallischen Werkstoffen*, Springer-Verlag, Berlin 1941
12. B. Orłowska, On a multilevel model of residual stresses, *Z. Ang. Math. Mech.*, 1987 or 1988, in press
13. E. Kröner, *Acta Met.* 9, 155-161 (1961)
14. A. Hihi, M. Berveiller and A. Zaoui
J. Méc. Theor. Appl. 4, 201-221 (1985)
15. T. Bretheau, D. Caldemaison, A. Feylessoufi and A. Zaoui, this volume
16. J.J. Jonas, this volume