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Plasticity in the compression stress state

ABSTRACT

The sequence of deformation path in compressed aluminium single crystals (99.992%) and its conformity with the slip activity predicted by Bishop–Hill method was investigated. The monocrystals with the orientation of sample axes parallel to the $[\bar{1}25]$ direction were compressed to different degree of plastic strain ($\varepsilon = 0.05–0.65$). The slip trace analysis was performed and results were compared with the calculated slip activity by Bishop–Hill method. It was found to be in good agreement between the observed and predicted slip planes in the range of large deformations ($\varepsilon > 0.4$). However, at the early stages of deformation, the unexpected slip systems appeared or lack of some systems were found, which show a significant influence of the latent hardening on the activation of slip systems.

INTRODUCTION

Latent hardening has a significant effect on the flow stress at low strains [1,2]. In the latent hardening test, secondary samples are cut at various angles from the predeformed parent crystals and submitted to secondary deformation. As a result, the new slip systems will be activated. Similar effect of activation of new slip systems occurs, when orientation of the deformed sample changes due to the rotation of axis. However, the interpretation of this phenomenon is not simple because of the local stress concentrators, which can have additional influence on the set of active slip systems [3]. For this reason in the real deformation conditions, assumption about the equal stress on at least 5 slip systems is not always fulfilled especially in the early stages of deformation [4]. Some unexpected slip systems can appear or lack of some slip systems may be found.

An interpretation of crystal plasticity on the background of Bishop–Hill method should be carried out carefully taking into consideration different additional factors, which can influence the deformation mechanisms. In spite of some simplifications the Taylor [5] and the Bishop–Hill [6,7] theories on plasticity are still fundamental. They join the slip behaviour with the macroscopic parameters of deformation.

In the Taylor model of deformation, it is assumed that all grains are deformed by the same strain. The critical resolved shear stress for slip is the same for all equivalent systems. At least 5 independent slip systems have to be activated to satisfy the yield criterion.

The set of active slip systems can be determined by the Taylor's minimum work analysis or by the Bishop–Hill criterion of maximising the external work [6,7]. Both solutions are equivalent and give the same results. However, the Bishop–Hill method is simpler.

The Bishop–Hill analysis indicates that only a limited number of stress states are capable to activate 5 independent slip systems without violating the yield criterion. For cubic metals which slip on $\{111\}\langle 110\rangle$ slip systems, Chin et al. [8] obtained a list of 28 stress states which satisfy the condition of the same stress for all activating systems. Each of 28 stress states is associated with the Taylor factor M given by the equation:

$$M = \frac{\sum \gamma_i}{\varepsilon_{xx}} = \frac{\sigma_{xx}}{\tau^x} \quad (1)$$

It is necessary to calculate the 28 orientation factors (from M1 to M28) for the applied external stress state associated with the yield criterion on the 5 independent slip systems. The orientation factor with maximal value, M–max, points the set of active slip systems [8].

The aim of this work is to analyse slip development in compressed aluminium monocrystals on the basis of Bishop–Hill method.

EXPERIMENTAL PROCEDURE

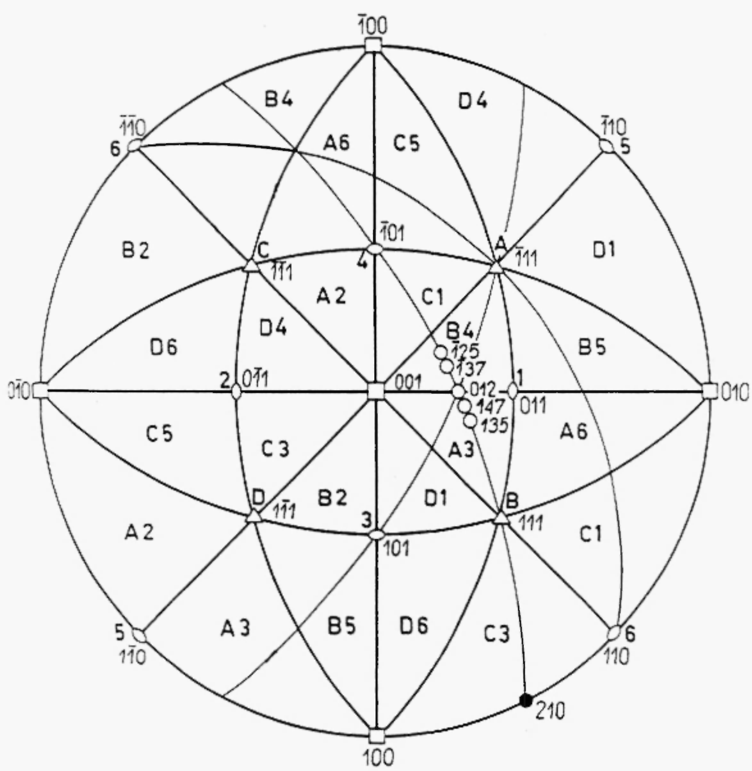
The investigations were performed on aluminium monocrystals (99.992%). The crystals were grown in the vertical, natural temperature gradient furnace in the Division of Structure and Mechanic of Solids, University of Mining and Metallurgy, Cracow. The crystals were cylindrical in shape, 10 mm in diameter and longitudinal axes were parallel to the $[\bar{1}25]$ direction. The samples of 8 mm in height were compressed by the MTS testing machine with the strain rate $\dot{\varepsilon} = 1.2 \times 10^{-3} s^{-1}$ to the following value of true strains: 0.05; 0.09; 0.12; 0.25; 0.4; 0.65. They were then cut along the sample axes in the middle sections, electrolytically polished and additionally compressed to approximately 0.01 of true strain. This allowed observation of the topography of slip events on polished sections of samples. The orientation of sample axes and the cross section planes were identified by X-ray diffraction technique performed by TZ6 texture appliance mounted on the IRIS5 X-ray equipment with numerical measurement of the diffraction intensity. The indices of the sample axes and cross section planes were calculated applying the orientation distribution function (ODF). The ODF was calculated according to three pole figures of the {111}, {200} and {220} planes which were determined by means of the Schul'z reflection technique.

The calculations by the Bishop–Hill method were executed according to the procedure showed by Chin et al. [8]. The orientations of samples were referred to the [001]-[011]-[$\bar{1}$11] basic triangle. The slip planes and slip systems were designated according to this notation (Schmid and Boas notation).

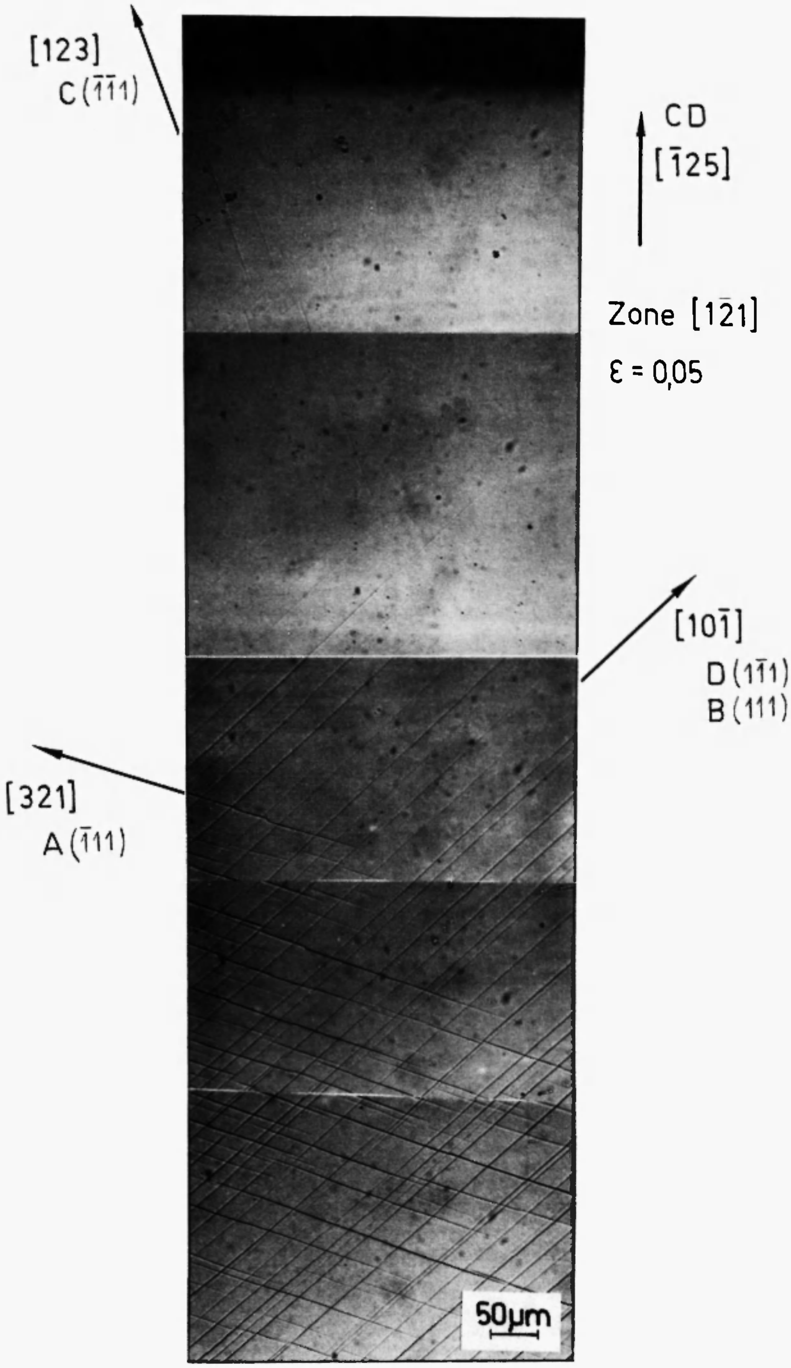
RESULTS

The orientations of the axes of all deformed samples are placed on the great circle of the (1$\bar{2}$1) plane (Fig. 1).

After deformation to 0.05 of true strain the sample axis has the [$\bar{1}$25] orientation. The structure is observed on the (1$\bar{2}$1) plane (Fig.2). Traces of the following slip planes are visible:



1. The evolution of sample orientation in the compression test



2. The traces of active slip planes, observed on the ($1\bar{2}1$) plane in the sample deformed to the 0.05 of true strain

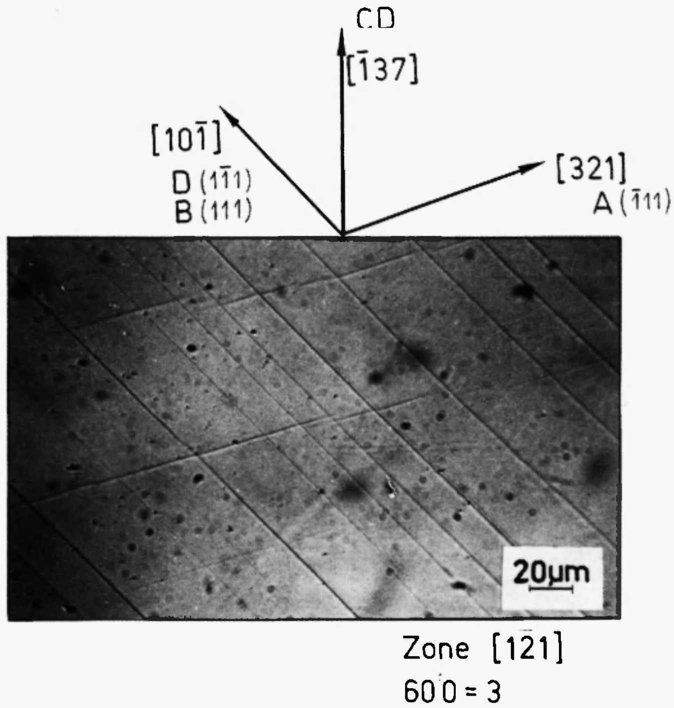
B-(111) and D-($\bar{1}11$) associated with the direction [$10\bar{1}$], A-($\bar{1}11$) associated with the direction [321] and C-($\bar{1}\bar{1}1$) associated with the direction [123].

Structural observations and slip trace analysis do not allow recognition of the active slip systems. However, this is possible by applying the Bishop–Hill method. This method requires data on the crystal orientation and external state of stress exerted on it. To predict the set of active slip systems the calculations of 28 orientation factors (M1 to M28) has to be performed. The factor M with the maximum value indicates the seeking set of slip systems [8].

Calculations done on the data of sample deformed to 0.05 of true strain show two factors of the same maximal value. M7 and M27. Following systems, common for both factors, are most probably active: B4 and B5 (a2 and a3 in the B–H notation) on the B-(111) slip plane, CI and C5 (b1 and b3 in the B–H notation) on the C- ($\bar{1}\bar{1}1$) plane and D1 and D4 (d1 and d2 in the B–H notation) on the D-($\bar{1}11$) slip plane. The activation of slip on the A-($\bar{1}11$) slip plane, revealed in the structure, is not predicted.

This indicates that probably the stress state is not so simple as it was assumed in the calculations. The latent hardening phenomenon, especially in the earlier stages of deformation, plays an important role in the plasticity development [1,2]. In such conditions, it is very possible that some slip systems can appear although they were not predicted by the theoretical analysis. Some simplified assumptions included in the theoretical analysis generate disagreement between the real deformation and theoretical predictions.

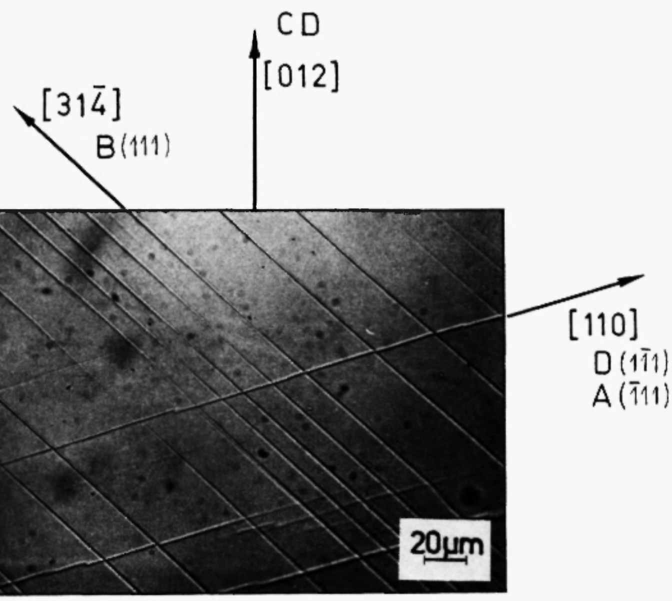
In the crystal compressed to 0.09 of true strain the orientation of the sample axis shifts to the [$\bar{1}37$] orientation. The cross plane is the same as in previous sample, i.e. ($1\bar{2}1$). The following traces of three slip planes have been observed: B-(111), D-($\bar{1}11$) and A-($\bar{1}11$) (Fig.3). The two



3. Slip traces after deformation to the 0.09 of true strain

calculated factors: M7 and M27 have the same maximal value. Common to both factors active slip systems are: B4, B5, C1 and D4 (a2, a3, b1, d2 in the B–H notation). The observed traces of slip on the plane A-($\bar{1}$11) are not confirmed by computations as well as the calculated slip related with the C-($\bar{1}\bar{1}$1) plane is not revealed in the structure.

After deformation to 0.12 of true strain, traces of the B-(111), A-($\bar{1}$11) and D-(1$\bar{1}$1) slip planes are observed on the (2$\bar{2}$1) side plane of the sample (Fig.4). The sample axis is rotated to the [012] direction. In this case the calculations show three factors of the same maximal value: M1, M14 and M16. After elimination of the collinear slip systems we can obtain a set of active slip systems in the sample: B4, C5, A2, A3, D1 and D6 (a2, b3, c1, c2, d1, d3 in B–H notation). They agree with the observed traces of the slip planes except of the C5 slip system on the C-($\bar{1}\bar{1}$1) slip plane which is not revealed in the structure.



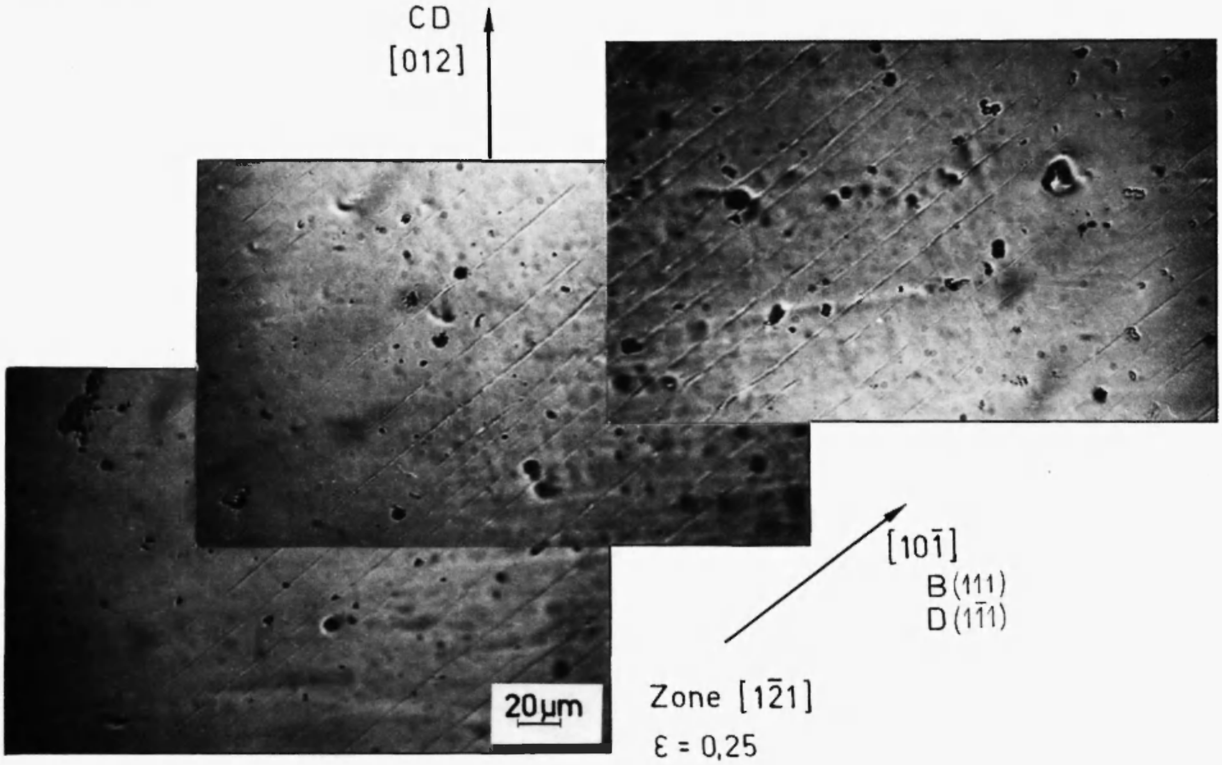
Zone [2$\bar{2}$1]

ε = 0,12

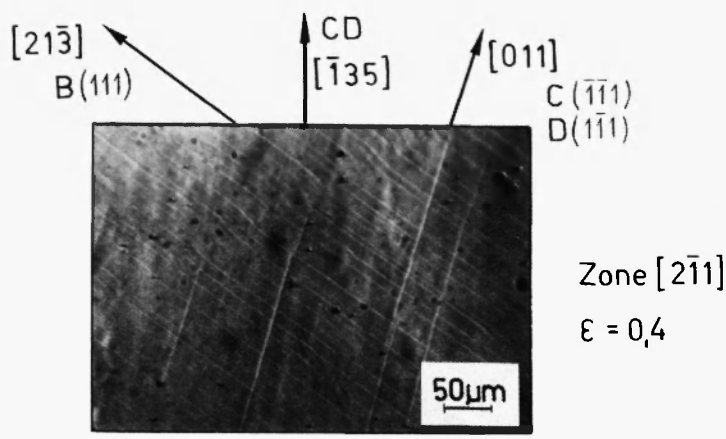
4. Slip traces after deformation to the 0.12 of true strain

In the sample deformed to 0.25 of true strain the [012] orientation of axis and the (1$\bar{2}$1) orientation of the side plane has been found. The traces of B-(111) and D-(1$\bar{1}$1) slip planes have been observed (Fig.5). The calculations show that, similar to the previous case, same three factors M1, M14 and M16 have maximal value. That is the same set of slip systems should be activated: B4, C5, A2, A3, D1 and D6 (a2, b2, c1, c2, d1, d3 in the B–H notation). However, differences between the observed traces of slip planes and the predicted set of slip systems have been found. The traces of C-($\bar{1}\bar{1}$1) and A-($\bar{1}$11) planes have not been revealed.

After compression to 0.4 of true strain, traces of the three slip planes B-(111), C-($\bar{1}\bar{1}$1) and D-(1$\bar{1}$1) are observed on the (2$\bar{1}$1) side plane of the sample (Fig.6). The orientation of sample axis is [$\bar{1}$35]. The factor M27 gets the maximal value and is associated with the set of: B4, B5, C1, C5,



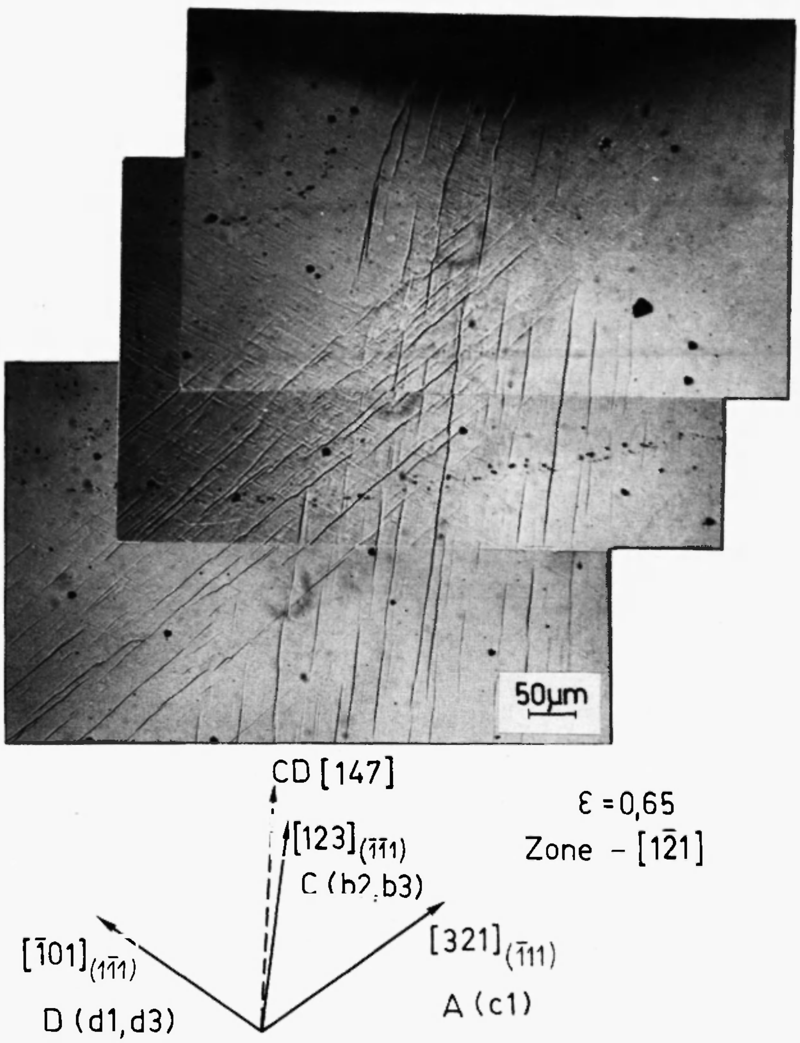
5. Slip traces after deformation to the 0.25 of true strain



6. Slip traces on the (2$\bar{1}$2) plane in the sample deformed to the 0.4 of true strain

D1 and D4 slip systems (a2, a3, b1, b3, d1, d3 in the B–H notation). In this case, the observations of the slip traces in the structure agree with the predicted set of slip systems.

In the crystal deformed to 0.65 of true strain, traces of B-(111), C-($\bar{1}\bar{1}1$), A-($\bar{1}11$) and D-($1\bar{1}1$) are observed on the ($12\bar{1}$) side plane of sample with the [$\bar{1}47$] orientation of the sample axis (Fig.7). In the computations, M16 factor gets the maximal value, associated with the following set of slip systems: C3, C5, A2, A3, D1 and D6 (b2, b3, c1, c2, d1 and d3 in the B–H notation). Comparing the predicted set of active slip systems with the observed traces of slip planes, we can see that [$\bar{1}01$] direction is the common trace of two slip planes, B-(111) and D-($1\bar{1}1$). The



7. Slip traces after deformation to the 0.65 of true strain

calculations show that the activation of D-($\bar{1}11$) slip plane is more probable. This sample, similar to the previous one, shows a good agreement between the revealed and predicted traces of slip planes.

CONCLUSIONS

The results show the significant influence of the latent hardening in crystal plasticity during the earlier stages of deformation. In those stages, some unexpected slip systems were observed while some predicted slip systems did not appeared. Similar results were observed in the work of Franciosi et al. [4], performed on the Al and Cu monocrystals. In the range of large deformations above approximately ε=0.4 of true strain, good agreement between the observed and predicted sets of active slip planes has been found. This suggests that the assumption about the equal stress on at least 5 slip systems is more realistic in the range of large deformation, where the influence of the latent hardening is not very distinct [1,2].

REFERENCES

1. P. J. Jackson, Z. S. Basinski, Can. J. Phys. 45 (1967) 707-735
2. D. Jull Jensen, N. Hansen, Acta Metall. Mater. 38, 8 (1990) 1369-1380
3. M. Szczerba, A. Korbel, Arch. Hutnictwa, 31, 1 (1986) 43-56
4. P. Franciosi, M. Berveiller, A. Zaoui, Acta Metall. 28 (1980) 273-283
5. G. Y. Chin, "The Role of Preferred Orientation in Plastic Deformation" in "The Inhomogeneity of Plastic Deformation", (edited by R. E. Reed-Hill), ASM, Metals Park, Ohio (1973), pp. 83-112
6. J. F. W. Bishop, R. Hill, Phil. Mag. 42 (1951) 414-427
7. J. F. W. Bishop, R. Hill, Phil. Mag. 42 (1951) 1298-1307
8. G. Y. Chin, E. A. Nesbitt, A. J. Williams, Acta Metall, 14 (1966) 467-476