# Orientation dependent slip in polycrystalline titanium

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The factors determining the active slip systems in cold-rolled polycrystalline titanium sheet were investigated. The texture of such a sheet has an important role in determining the active slip systems. Equi-Schmid factor lines for different slip modes were calculated, and transmission electron microscopy proved that pile ups of dislocations of the predicted systems are formed. The active primary slip system was found to be the prismatic ***a*** type slip $\{1\bar{1}00\}\langle 11\bar{2}0\rangle$ while the secondary system is either prismatic or pyramidal type I $\{10\bar{1}1\}$. Basal slip of ***a*** dislocations could in certain orientations of load direction be the primary slip systems. Dislocations of the (***c*** + ***a***) type play no significant role in the plastic deformation of polycrystalline titanium sheet.

## 1. Introduction

Electron microscopy of titanium has demonstrated the existence of three types of dislocation [1]. Dislocations of the ***a*** type $-\langle 11\bar{2}0\rangle$ were found to be the most active, while the *c*-[0001] and the $(\boldsymbol{c}+\boldsymbol{a}) - \langle 11\bar{2}3\rangle$ types were rarely found [1-3], though persistently sought by several investigators. Dislocations of the ***a*** type can slip on three families of planes: prismatic type I $\{10\bar{1}0\}$, 1st order pyramidal type I $\{10\bar{1}1\}$ and the basal (0001) plane. Contrast analysis in the electron microscope has proved that prismatic slip is preferred followed by pyramidal slip. Basal slip has rarely been reported [10]. The critical resolved shear stress (CRSS) at room temperature for prismatic $\{1\bar{1}00\}\langle 11\bar{2}0\rangle$ slip has variously been reported as 5 kg mm$^{-2}$ [4] and 2 kg mm$^{-2}$ [5], while for basal (0001) $\langle 11\bar{2}0\rangle$ slip the values 11 kg mm$^{-2}$ [4] and 8 kg mm$^{-2}$ [5] were found by the same workers. CRSS for pyramidal slip of ***a*** type dislocations as well as that for ***c*** and (***c*** + ***a***) dislocations was not reported. This communication is aimed at clarifying the factors determining the active slip systems in commercial polycrystalline titanium sheet.

## 2. Results and discussion

### 2.1. Competition between slip systems

In polycrystalline metals of cubic symmetry the large number of possible slip systems with identical CRSS ensures that deformation occurs on many systems in each individual grain, in response to the compliance of the neighbouring grains. On the other hand, hexagonal metals, such as titanium, have a limited number of slip systems with large differences in CRSS between systems. For these metals it might be expected that the active slip systems in any individual grain would be primarily determined by the uniaxial tensile stress applied to the specimen. At the same time, the strong texture in the case of polycrystalline titanium sheet should further reduce the effect of complex triaxial stresses introduced into each grain by the compliance of its neighbours, so that, to a good approximation, the active slip systems in each grain of the sheet are then determined by the applied tensile stress and the direction of this stress in relation to the orientation of the grain.

Based on this approximation, an insight into the relative incidence of the various slip systems in titanium is provided by considering the Schmid factor, given by $\sigma_s/\sigma_n = \cos\phi \,.\, \cos\lambda$, where $\sigma_s$ is the shear stress on the system, $\sigma_n$ is the applied tensile stress, $\phi$ is the angle between the stress axis and the slip plane normal and $\lambda$ is the angle between the stress axis and the slip direction [6].

Fig. 1 shows the directions of the applied stress for which the Schmid factor reaches the

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values of 0.1 to 0.5 for ***a*** type dislocations slipping on a prism plane [7], that is the systems $(\bar{1}100)$ $[\bar{1}\bar{1}20]$, $(\bar{1}010)$ $[\bar{1}2\bar{1}0]$ and $(0\bar{1}10)$ $[\bar{2}110]$, two of which are independent. It is seen that as the stress axis moves gradually from [0001] to cross $[\bar{1}010]$, the resolved shear stress on the systems $(01\bar{1}0)$ $[\bar{2}110]$, and $(\bar{1}100)$ $[\bar{1}\bar{1}20]$ increases. On this zone the ratio of shear stress to normal stress reaches a maximum value of 0.433 for both the systems $(0\bar{1}10)$ $[\bar{2}110]$ and $(\bar{1}100)$ $[\bar{1}\bar{1}20]$ when the tensile axis is $[\bar{1}010]$, while for the third system $(\bar{1}010)$ $[\bar{1}2\bar{1}0)$ the Schmid factor is always zero. We would thus predict for this zone duplex slip on two prismatic slip systems. If, on the other hand, the applied stress lay between the $[\bar{1}010]$ and $[\bar{2}110]$ directions there is a possibility that all three slip systems will be activated, the primary system being $(\bar{1}100)$ $[\bar{1}\bar{1}20]$.

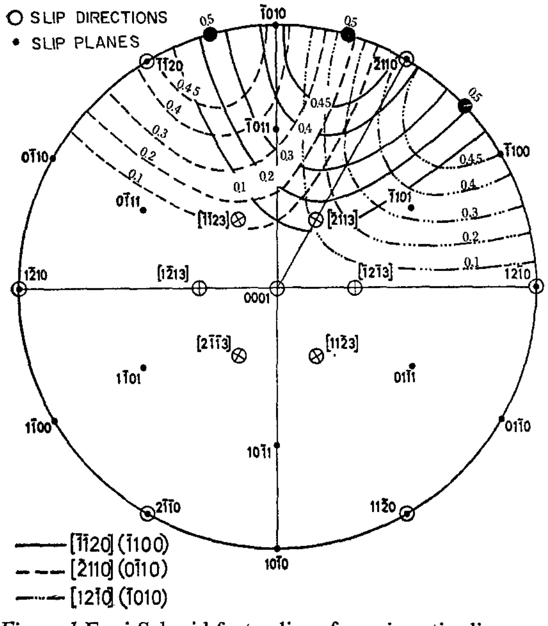


*Figure 1* Equi-Schmid factor lines for prismatic slip.

The standard stereographic triangle created by the intersection of the three planes (0001) $(01\bar{1}0)$ and $(1\bar{2}10)$ contains all the necessary information, and it is not necessary to use the full projection. Equi-Schmid factor curves for pyramidal slip $\{1\bar{1}01\}\langle 11\bar{2}0\rangle$ are shown in Fig. 2a. This type of slip can occur on six systems, four of which are independent. The curves for the systems $(\bar{1}10\bar{1})$ $[\bar{1}\bar{1}20]$, $(0\bar{1}11)$ $[\bar{2}110]$, $(\bar{1}011)$ $[\bar{1}2\bar{1}0]$ and $(\bar{1}101)$ $[\bar{1}\bar{1}20]$ show

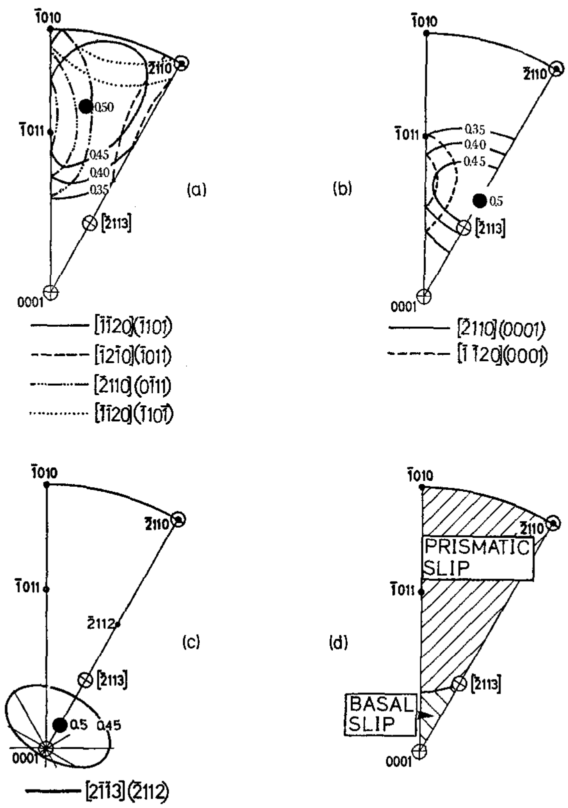


*Figure 2* Equi-Schmid factor lines for (a) pyramidal slip, (b) basal slip, (c) (***c*** + ***a***) slip on the $(\bar{2}112)$ plane, (d) predicted slip systems as a function of external load direction (excluding ***c*** + ***a*** slip).

that a relatively high shear stress may exist for one, two and even three pyramidal systems simultaneously, the activity of the fourth system being restricted by a low Schmid factor.

Fig. 2b shows equi-Schmid factor lines for basal slip – (0001) $\langle 11\bar{2}0\rangle$. This mode of slip occurs on three systems, two of which are independent. Geometrical conditions for basal slip may exist for two systems simultaneously, but the third one is very unlikely to be activated. Equi-Schmid factor lines for (***c*** + ***a***) dislocations slipping on the system $(\bar{2}112)$ $[2\bar{1}\bar{1}3]$ are shown in Fig. 2c. To activate this system, the external stress must be oriented very near the [0001] axis in which case all six possible systems (five of which are independent) have high Schmid factors ($\sigma_s > 0.45\ \sigma_n$).

The final mode of slip, for which the Burgers' vector is ***c***, has rarely been reported and is not considered to play an important role.

### 2.2. Critical resolved shear stress

The data given by Levine [5] show that the CRSS for basal slip of $\boldsymbol{a}$ type dislocations is four times that needed for prismatic slip. It follows that the Schmid factor for basal slip must exceed four times that for prismatic slip before basal slip can occur and, therefore, there is a rather definite direction along which the external load must be applied in order to activate basal slip. This direction is within a solid angle of about 30° around the [0001] direction, and, in any other direction, prismatic slip will be the primary mode (Fig. 2d). The data given by Anderson *et al* [4] lead to similar conclusions.

It is known that the CRSS for pyramidal slip is higher than that for prismatic system, although its numerical value has not yet been determined. An attempt to evaluate the CRSS for the pyramidal mode of slip will be discussed below.

### 2.3. Electron microscopy

In order to observe the slip mode as a function of the direction of the external load, specimens made from cold-rolled and annealed polycrystalline titanium strip (Ti-35A) were loaded to near the flow stress. The composition of the titanium (wt %) was 0.07 $O_2$, 0.07 Fe, 0.01 $N_2$, 0.004 $H_2$ and 0.023 C. Thin foils were prepared by standard methods [8], and marked to define the load axis in the plane of the specimen when in the electron microscope. Contrast analysis based on double $\boldsymbol{g} \cdot \boldsymbol{b}$ analysis was used to identify slip vectors and slip planes [9]. The general dislocation arrangement consisted of pile-up groups on well defined planes, together with more random arrangement of single dislocation loops and dipoles (see Fig. 3).

In all cases the predicted prism slip systems were the ones activated. For example, in Fig. 3 the calculated Schmid factors are 0.14 for $(0\bar{1}10)$ $[\bar{2}110]$, 0.35 for $(1\bar{1}00)$ $[\bar{1}\bar{1}20]$ and 0.46 for the system $(\bar{1}010)$ $[1\bar{2}10]$, while the observed primary system is $(\bar{1}010)$ $[1\bar{2}10]$. Although $(\boldsymbol{c} + \boldsymbol{a})$ dislocations were observed occasionally they were always present in network which appeared to be non-glissile.

Pyramidal slip has been reported in titanium by some investigators [1, 2] and was observed

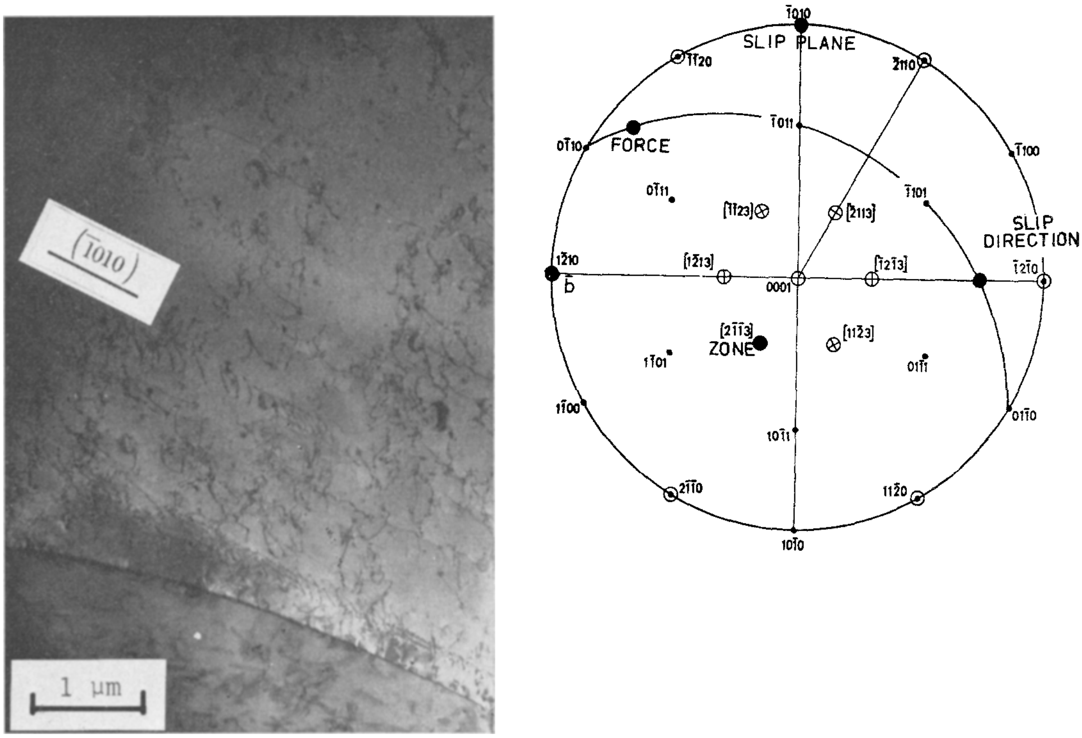


*Figure 3* Activity of a single prismatic slip system. The line of intersection of the slip plane with the foil is indicated.

also in this study. In Fig. 4 three slip systems are active, one of which is pyramidal. In this example, the Schmid factor for the primary prismatic system is 0.47, for the secondary prismatic system 0.2, and for the pyramidal system the Schmid factor is 0.45. The simultaneous activity of the last two systems enables the ratio of the CRSS for pyramidal to prismatic slip to be estimated as approximately 2.3. This is in fair agreement with the results of Cass [2], who observed that in a titanium single crystal loaded along the $[1\bar{1}04]$ direction, simultaneous prismatic and pyramidal slips were activated. In this orientation the ratio of ths Schmid factors for the two systems is 2.7. There is, therefore, *no* direction along which a tensile stress will activate pyramidal slip as the primary system in titanium. Indeed, all the pyramidal slip activity observed in the present work was found to be secondary slip, while the primary mode was always prismatic. We conclude that primary slip may be prismatic but not pyramidal (Fig. 2d). However, there are directions in which the applied tensile stress necessary for pyramidal slip is only slightly higher than that for prismatic slip and in such cases, because of easy cross-slip (the stacking-fault energy of titanium is of the order of 300 erg $cm^{-2}$) multiple slip occurs and extensive dislocation debris is formed. It is also possible that primary basal slip will occur. However, the

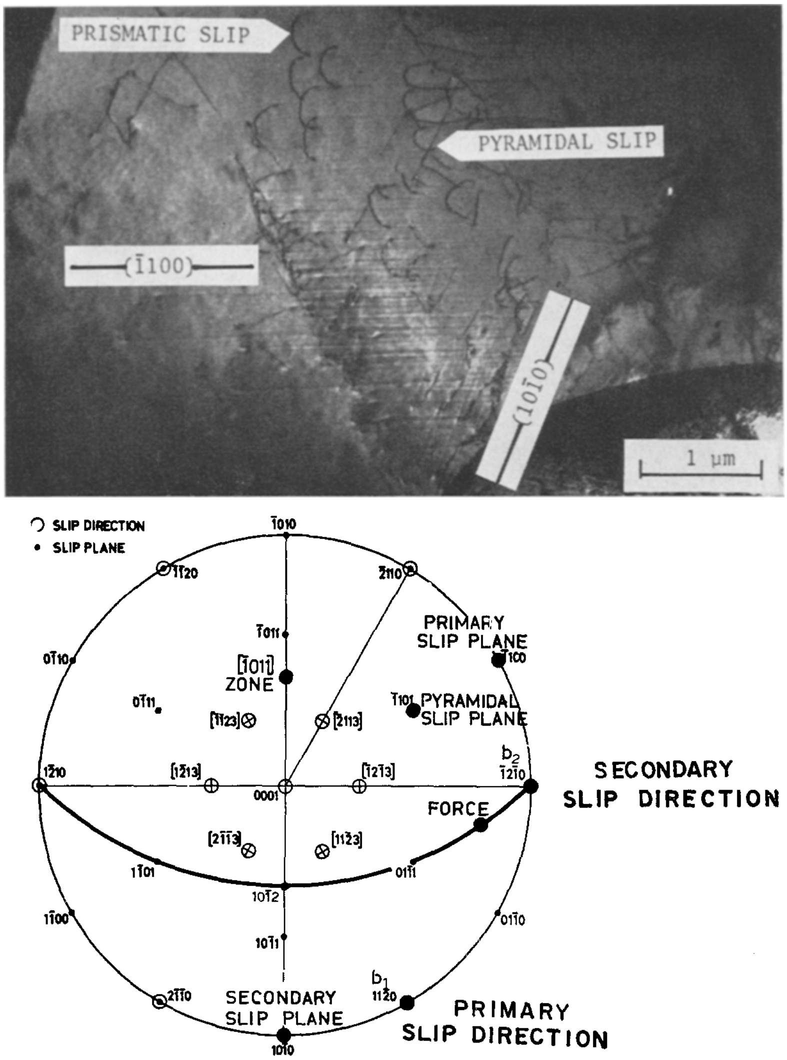


*Figure 4* Simultaneous activity of prismatic and pyramidal slip systems.

texture of the material examined in this study precluded the detection of such slip.

### 2.4. The role of texture

Both the cold-rolled and the hot-rolled texture of polycrystalline titanium have been studied by several investigators [10, 11]. The common result of all the studies is that in hot-rolled titanium the [0001] poles tend to lie within a solid angle of 30° from the normal to the sheet, while in cold-rolled sheet there is a tendency for these poles to spread in the transverse direction.

The spread of the zone axes of electron diffraction patterns from the grains analysed in the present work is shown in Fig. 5. The results are completely consistent with the known texture as determined from X-ray data; most grain normals lying within the solid angle of 30° to the [0001] pole, with a small proportion at 90° to this pole. As a result of this texture, prismatic slip is dominant and the basal system will rarely be activated (compare Fig. 2d).

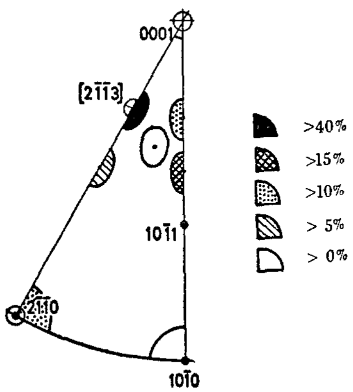


*Figure 5* Distribution of zone axes for diffraction patterns from individual titanium grains. (Shaded areas represent the possible variations in sheet normals.)

The CRSS for all the ***a*** type systems is low relative to the flow stress of the polycrystalline titanium (36 kg mm$^{-2}$ in the present case). Dislocations are, therefore, found to exist on many of the possible slip planes. However, gross plastic deformation by slip can occur only by the development of dislocation pile-ups on prismatic planes in grains oriented to give a high Schmid factor on these planes and stresses well above the CRSS are needed to generate these pile-ups. In other grains, twinning may be responsible for the plastic deformation, and can contribute to the plastic shear component perpendicular to the basal plane.

## 3. Conclusions

1. The slip systems responsible for plastic deformation in polycrystalline titanium can be predicted with fair accuracy from a knowledge of the Schmid factor and the critical resolved shear stress for each system.
2. Primary slip in titanium can occur on the prismatic or basal planes, leading to pile-ups of ***a*** type dislocations on these planes.
3. Pyramidal slip can only occur on a secondary system, normally by cross-slip from the prismatic planes. The CRSS for pyramidal slip is approximately 2.5 times that for prismatic slip.
4. The common texture in cold-rolled polycrystalline titanium sheet effectively ensures that primary slip is confined to the prismatic slip systems, while secondary slip occurs in both the prismatic and the pyramidal systems. Basal slip is very rarely observed.
5. Dislocations of Burgers' vector ($\boldsymbol{c} + \boldsymbol{a}$) play no significant role in the plastic deformation of such polycrystalline titanium sheet.

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