JOURNAL OF MATERIALS SCIENCE 17 (1982) 2618–2624

Crystallographic effects in metal cutting

J. A. WILLIAMS
Cambridge University Engineering Department, Trumpington Street, Cambridge, UK

J. G. HORNE
Teknekron Inc., Berkeley, California 94704, USA

In the machining of coarse grained metals the thickness of the ribbon of material removed may be comparable with the grain size. Previous work on the microtoming of single crystals of copper has shown that the resolved shear stress exhibited during cutting is dependent on crystallographic orientation. Other results reported in the literature on the cutting of aluminium show no such effect. Here we describe a series of experiments on copper and aluminium which confirm both these sets of observations and suggest an explanation in terms of dislocation mobility. Some further work on single crystals of magnesium show that in some circumstances it is possible for the machined chip to be longer than the surface from which it was produced.

1. Introduction

Many attempts have been made and are currently being pursued to apply the principles of continuum mechanics to the process of metal cutting [1, 2]. The failure so far to achieve a satisfactory predictive model is usually attributed to the significant differences between the deformation involved in other metal working operations, where these methods have been notably more successful, and that in cutting, namely, that the shear strains are very large (1 to 5), the strain rates are very high (10^5 to 10^7 sec^{-1}) and the constitutive material behaviour equations are still unclear in this region. In addition the boundary conditions are complicated by a free surface and the important frictional conditions between the chip and the rake face of the tool are imperfectly understood. One other significant difference between machining and bulk plastic forming processes is one of scale. The plastic zone in machining at a depth of cut of 0.1 mm is typically 100 μm deep × 10 μm wide. These dimensions may be comparable with the grain size of the material and so one may therefore ask whether the usual assumptions of homogeneity and isotropy should be assumed to apply. The observation that the macrostructure of metals may be developed by machining is evidence of non-isotropic behaviour and has been noted in the case of a number of fcc metals [3, 4]: Fig. 1 shows the cut surface of a coarse grained specimen of commercially pure aluminium produced by orthogonal planing. It can be seen that certain grains are covered by strong surface markings running perpendicular to the direction of relative motion of the tool. These markings are regularly repeated within any given grain, although their severity and spacing varies from one grain to another. Since the marks do not extend across the whole of the workpiece, meeting the edges only where the grain meets one or both sides, they cannot be attributed to tool movements but rather must have some direct crystallographic origin in the region close to the cutting edge. A similar pattern is seen on the upper surface of the chip and this morphology is echoed by the dislocation structure within the bulk of the chip.

The origin of these features has been discussed elsewhere [4, 5]. In addition the forces associated with the machining operation have been reported when cutting both single crystals of copper of known orientation [6] and specimens of coarse grained aluminium where the orientation of individual grains relative to the geometry of the cutting tool was known [7]. In these latter experiments Ramalingam and Harza [7] obtained results on commercially pure aluminium indicating that

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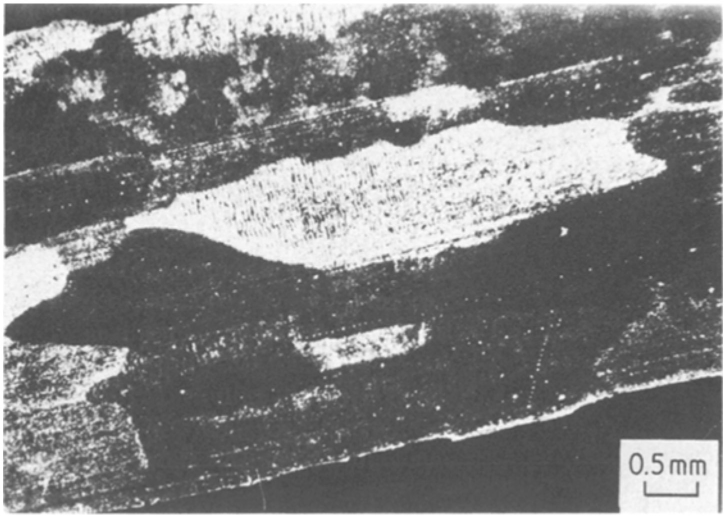

Figure 1 Machined surface of a coarse grained aluminium workpiece.

the resolved shear stress (RSS) on the shear plane has a constant value, although the shear plane angle may vary with orientation over a wide range (from 14.6° to 41.7° in their results). They consider that the shear in cutting occurs on a crystallographic plane of non-specific Miller indices by the operation of multiple slip on a number of slip systems. The variations of cutting forces with crystal orientation are due to the variations in the angle of the most favourable shear plane; the RSS is an invariant material property. The depth of cut in these experiments was 127 μm.

Williams and Gane [6] in their study of the microtoming of pure copper crystals of two known orientations, with a typical depth of cut of 10 μm, found that the RSS was dependent on orientation having a lower value when a slip plane was aligned with the shear plane. The shear stress on the shear plane was estimated to be some 30% lower in the "favourable" crystal orientation compared to that in the "unfavourable" orientation, and further, the RSS in the "unfavourable" orientation was close to that for a polycrystalline specimen cut in similar conditions.

2. Experimental procedure

In the experiments described in this paper both aluminium and copper single crystals have been cut in the same experimental arrangement and in a number of orientations. Great care was taken to obtain an accurate value of the cutting ratio and hence of the shear plane angle. In addition we describe some results of the cutting behaviour of a single crystal of magnesium.

The single crystal specimens were grown from a high purity melt using seed crystals and subsequently checked for orientation by X-ray diffractometry. Each workpiece was 3 mm thick, 20 mm wide by about 80 mm long. Copper crystals of $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 112 \rangle$ orientations and aluminium of $\langle 100 \rangle$ and $\langle 112 \rangle$ were prepared. The $\{110\}$ $\langle 112 \rangle$ crystals being unsymmetrical were cut in two directions; the various orientations and positions of the most favourably inclined $\{111\}$ slip planes in each situation are indicated in Fig. 2. The arrangement designated (110) $[001]$ corresponds to the "favourable" orientation I, and (111) $[\bar{1}\bar{1}2]$ to the "unfavourable" orientation II of Williams and Gane [6].

All cuts were made using high speed steel tools with a rake angle of 40° and a speed of 20 mm sec^{-1} with a depth of cut of nominally 100 μm. (This was checked for each run by weighing the resulting chip.) The experimental planing machine used in this investigation has been described elsewhere [8]. The machine was intended primarily to examine the effects of cutting lubricants and was capable of operating under a good vacuum (approximately 10^{-6} Torr); under these circumstances using high-speed steel tooling to machine copper and aluminium the chip–tool frictional forces are reduced [8, 9]. In this study experiments were carried out both *in vacuo* and in the presence of laboratory air. In every case but one the shear angle *in vacuo* was greater than that in air indicative of the reduced friction forces.

The values of the shear plane angle (ϕ) and RSS on the primary shear plane for the single crystal experiments and those for a fine grained annealed polycrystal of similar purity are presented in

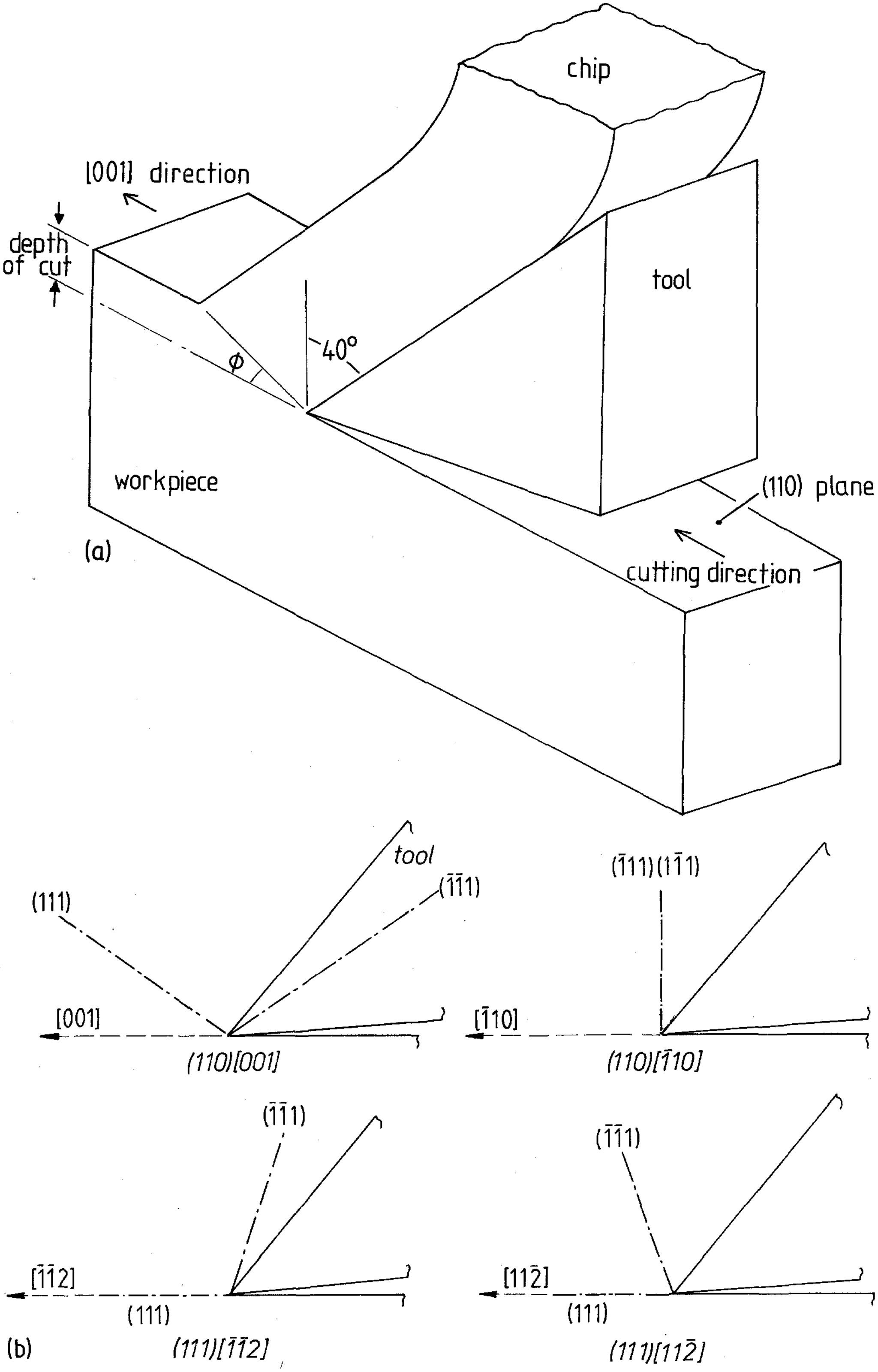

Figure 2 (a) General arrangements of cutting geometry for copper and aluminium single crystals. (b) Crystal orientations used when cutting copper and aluminium single crystals: position of $\{111\}$ planes seen on side view of the specimen.

TABLE I Copper single crystal cutting. Shear angle ϕ and resolved shear stress k on the shear plane as a function of crystal orientation and cutting environment

Orientation	Air		Vacuum	
	ϕ (°)	k (N mm^{-2})	ϕ (°)	k (N mm^{-2})
Polycrystal	16.6 ± 0.5	298 ± 7	20.5 ± 1.1	297 ± 1.1
(110) [001]	13.0 ± 0.7	288 ± 9	14.3 ± 0.6	257 ± 12
(110) [$\bar{1}$10] (a)	5.9 ± 0.4	230 ± 8	8.0 ± 0.5	221 ± 9
(110) [$\bar{1}$10] (b)	30.1 ± 2.5	286 ± 15	24.1 ± 1.0	284 ± 20
(111) [$\bar{1}\bar{1}$2]	22.2 ± 1.3	320 ± 5	25.1 ± 2.2	333 ± 5
(111) [11$\bar{2}$)	36.3 ± 0.9	261 ± 11	45.2 ± 1.6	221 ± 4

Tables I and II. The errors quoted refer to scatter in the data. In the case of the copper (110) [$\bar{1}$10] and the aluminium (111) [11$\bar{2}$] specimens the shear plane angle was able to take up one of two values with corresponding changes of chip thickness: this switching from one geometry to another could occur two or three times in the course of one cut of 80 mm. In each case the higher shear angle was associated with a greater RSS on the shear plane. However, when allowance is made for the different lengths of the two shear planes the highest shear plane angle is seen to occur in conjunction with a reduced shear *foce.*

The single crystals of magnesium were of similar dimension to those of copper and aluminium, each had a {10$\bar{1}$0} face and were cut with the basal slip plane (0001) making various angles with the cutting direction as shown in Fig. 3. A fine grain polycrystalline specimen was also included. Not only the cutting force but also the mode of chip formation was found to vary dramatically with orientation. The behaviour varied from cutting with a continuous chip, which when unwound was longer than the surface from which it had been cut (Fig. 4), to the situation where no chip was formed and the tool dug in as fractures propagated along the (0001) plane. The observations are summarized in Table III.

3. Discussion and conclusions

Copper was found to exhibit variations in RSS with orientations as reported previously, although the average increase between the (110) [001] orientation and the (111) [$\bar{1}\bar{1}$2] at 20% is rather lower than that found in the microtoming experiments. The polycrystal has an RSS between the two single crystal values instead of equivalent to the "unfavourable" orientation as found previously. This discrepancy is almost certainly due to the difference in scale between the planing and the microtoming experiments in relation to the grain size and dislocation microstructure. The new orientation used provides further evidence of the dependence of cutting stress on orientation. In the case of the (110) [$\bar{1}$10] crystal there appears to be two possible shear geometries. The higher angled shear plane operates at an RSS similar to the (110) [001] and polycrystalline specimens. The lower angled shear plane leads to high cutting forces but the RSS is low although the precise value of this figure should be treated with caution bearing in mind the difficulty of measuring a small shear plane angle accurately. It is proposed that the switching behaviour is due to variations in the rake face fractional force. Increased resistance to chip flow would favour the operation of the lower shear plane but should the resistance to chip movement fall – possibly as a result of the effect of interfacial conditions on the mode of secondary deformation within the chip – there is a return to the higher plane. The fact that shear plane angles of intermediate values are not observed,

TABLE II Aluminium single crystal cutting. Shear angle ϕ and resolved shear stress k on the shear plane as a function of crystal orientation and cutting environment

Orientation	Air		Vacuum	
	ϕ (°)	k (N mm^{-2})	ϕ (°)	k (N mm^{-2})
Polycrystal	9.2 ± 0.3	101 ± 4	10.8 ± 0.2	93 ± 2
(110) [001]	9.2 ± 0.3	95 ± 3	10.4 ± 0.3	94 ± 2
(111) [$\bar{1}\bar{1}$2]	7.3 ± 0.2	98 ± 4	7.6 ± 0.2	94 ± 1
(111) [11$\bar{2}$] (a)	8.6 ± 0.2	98 ± 1	17.7 ± 0.2	85 ± 3
(111) [11$\bar{2}$] (b)	–	–	31.1 ± 1.6	93 ± 3

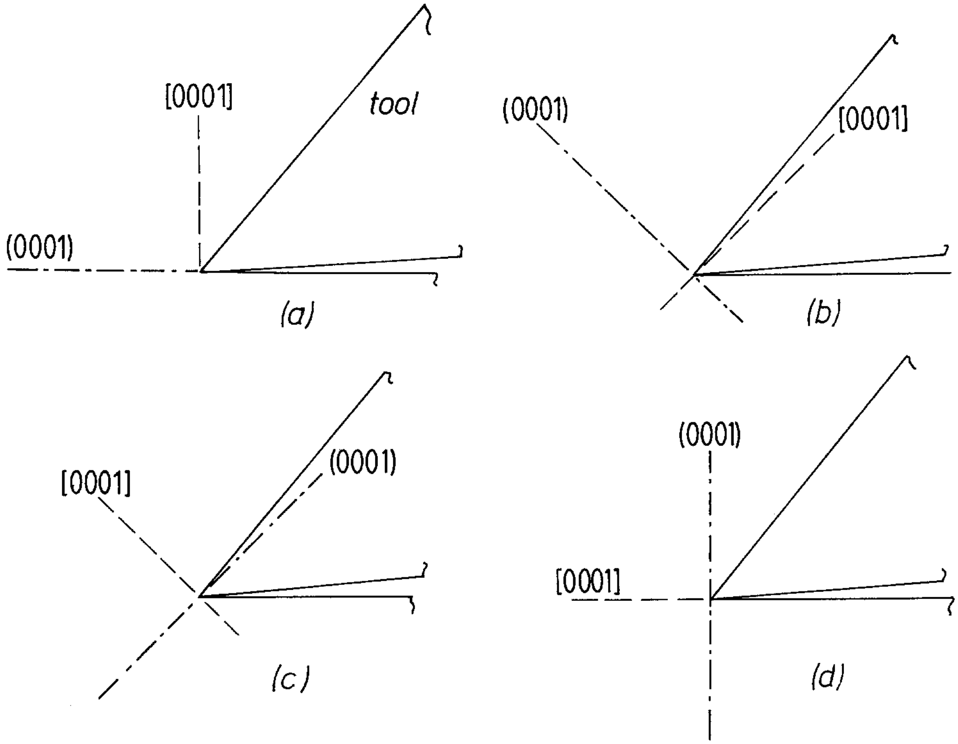

Figure 3 Orientations used in studying the cutting behaviour of magnesium single crystals showing the position of the (0 0 0 1) plane.

presumably because they involve greater cutting force, offers further evidence for the concept of "easy" shear directions.

The $\{1\,1\,1\}\langle 1\,1\,2\rangle$ orientations not used previously give the most striking demonstration of a reduced RSS in a favourable crystal geometry. Rotating the specimen from the (1 1 1) $[\bar{1}\bar{1}2]$ to the (1 1 1) $[1\,1\,\bar{2}]$ position reduces the RSS by an average of more than 25% and in this second orientation the RSS is some 20% less than that for the polycrystal.

The experiments on aluminium also confirm the previously published work. Variations in the shear plane angle have been observed as well as the switching from one value of ϕ to another, although only *in vacuo* where the friction forces are smaller. However, there is no marked dependence of the magnitude of the RSS on crystal

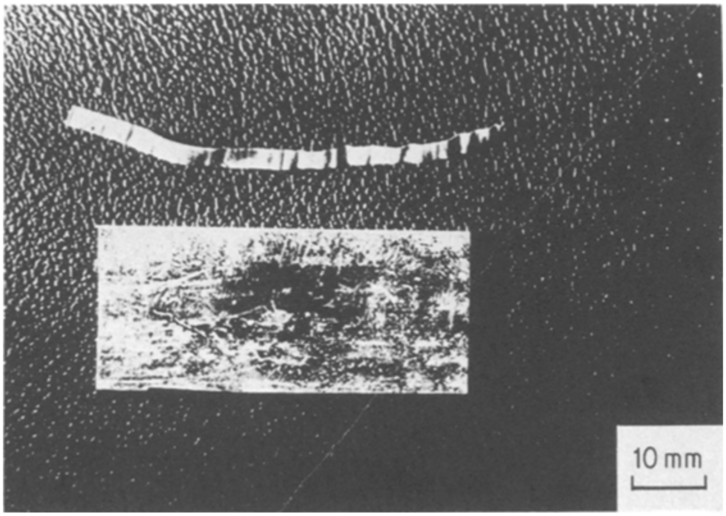

Figure 4 Chip (uncurled) from single crystal magnesium specimen cut from the same orientation as Fig. 3d showing that the chip is longer than the workpiece.

TABLE III Cutting behaviour of magnesium single crystals

Orientation	(0001) plane angle	Mode of chip formation	ϕ (°)	k (N mm^{-2})
(a)	0	Discontinuous	54	89
(b)	45	Continuous segmented no curl	43	53
(c)	−45	No chip tool digs in	–	–
(d)	90	Continuous tight curl	79	43
Polycrystal	Varies	Discontinuous	54	91

orientation, in fact the scatter is rather less than that given by Ramalingam and Harza [7]. Thus the apparent contradiction in the published work on single crystal cutting appears not to be due to differences in the cutting configuration but to a real difference in behaviour between copper and aluminium demonstrated when they are cut under identical circumstances. Copper displays a dependence of RSS on $\{111\}$ plane orientation, aluminium does not.

The difference between these two materials must relate to the processes of dislocation movement that contribute to the shear process as cutting proceeds. In particular the ability of an individual dislocation to glide on more than one $\{111\}$ plane, i.e. the process of cross-slip, is of significance here. Consider the dislocation $\frac{1}{2}[1\bar{1}0]$ (111), it is free to move on the $(11\bar{1})$ plane some 70° away. However, it may also dissociate into partials,

$$\tfrac{1}{2}[1\bar{1}0]\ (111) \rightarrow \tfrac{1}{6}[1\bar{2}1] + \tfrac{1}{6}[2\bar{1}\bar{1}]. \quad (1)$$

These will repel each other as a result of their elastic interaction and as they separate a sheet of stacking fault is formed between them. The stacking fault energy associated with this region leads to a constant force pulling the partials together and hence results in an equilibrium spacing between them. Glide of the extended dislocation is thereby confined to the (111) plane as it cannot cross-slip. However, if a local constriction in the ribbon of stacking fault occurs then the dislocation resulting at the point of the constriction is one more free to move out of the plane of the faulted region. A certain amount of energy is needed to form such a constriction and this will depend on the width of the stacking fault. Materials of high stacking fault energy, having low equilibrium spacing, should thus undergo cross-slip more readily than those of low stacking fault energy.

TABLE IV Stacking-fault energies

Material	Stacking-fault energy ($\times 10^{-3}$ Jm^{-2})	Equilibrium spacing atom distances
Copper	55	10–15
Aluminium	200	2

The stacking gault energies and equilibrium spacings for copper and aluminium are shown in Table IV [10] and it can be seen that cross-slip should occur much more readily in aluminium. Small local fluctuations in the stress field around a pair of partials, due to the presence of nearby dislocations, solute particles, precipitates or grain boundaries, frequently cause constriction and recombination. This is much less likely with copper and most dislocations whould therefore be confined to one glide plane. (In fact, some pairs of partials in copper can also interact with one another to form "locks", e.g. the Lomer–Cottrell lock $\frac{1}{6}[110]$, which are unable to glide at all.) We suggest that the apparent conflict between the results of previous work may be the effect of stacking fault energy. The same processes of dislocation mobility that contribute to the low strength of pure aluminium cause its flow stress in machining to be substantially constant with workpiece orientation. Since dislocations are less mobile in the stronger copper favourable orientation of a glide plane reduces the resolved shear stress.

The experiments on the single crystals of magnesium show that in this case fracture as well as shear can play a part in cutting. Forces and chip morphology are highly orientation dependent. When the major slip plane is coincident with the cutting direction dislocation glide does not significantly contribute to material removal: chips are formed by fracture along the direction of maximum shear stress. Plastic flow becomes possible when the specimen is rotated so that the slip plane makes an acute angle with the cutting direction, as in Fig. 3b. The RSS required to produce the chip is reduced by this change of mechanism although fracture would seem to be still involved as the chip is of segmental form. However, if the slip plane is rotated to such a position as shown in Fig. 3c then cleavage along this plane results in the tool digging in and no steady-state cutting condition is achieved. The basal plane can act either as a preferred cleavage or slip plane. If the slip plane is aligned perpendicular to the cutting direction (Fig. 3a) then somewhat surprisingly a tightly curled continuous chip is produced which, when straightened out, is longer than the surface from which it was generated (Fig. 4), the RSS on the shear plane being further reduced. The polycrystal forms chips by a combination of shear and fracture at an RSS comparable to that of the 0° specimen. Fracture and cleavage play an important part because only a few grains are appropriately aligned for shear.

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Received 22 December 1981
and accepted 1 February 1982