heavy particles saturates. The same effect is indicated for electrons, but due to the uncertainty of the magnitude of the back diffusion effect in this case no quantitative statement can be made. However, we do not believe that the different results for electrons and heavy particles could be a result of surface effects and back diffusion alone, since the experiments with the 27-kev x-rays, which produced electrons inside the crystal, gave data in agreement with the above results.§

VII. ACKNOWLEDGMENTS

The authors are grateful to Professor F. Seitz for stimulating discussions concerning the interpretation of the data. They wish to thank A. L. Atkins, R. O. Kerman, and W. E. Kreger who determined the cyclotron beam energy. The valuable assistance of Mr. Chester Lob and the use of facilities of the Tube Laboratory of the Electrical Engineering Department in performing the electron experiments are deeply appreciated. The authors also would like to thank W. G. Cross of Chalk River Laboratory who kindly sent them his data prior to publication.

§ *Note added in proof:*—J. B. Birks, Phys. Rev. 84, 364 (1951), has recently used the exciton theory to explain the general features of these results.

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Investigation of the Gliding Process in Ionic Crystals by Prismatic Punching

Alexander Smakula* and Myron W. Klein
Engineer Research and Development Laboratories, Fort Belvoir, Virginia

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The prismatic punching method applies a unidirectional stress on a very small surface (approximately 0.001 square centimeter) of a crystal lying on a support which is softer than the crystal itself. The method is very convenient for low and high temperature and for small samples. The glide system of thallium bromoiodide crystals determined by the prismatic punching method contains dodecahedron planes (110) as glide planes and cubic planes [001] as glide directions. The width of the glide bands ranges from 1 to 5 microns. The stress-strain curve shows a linear relation between the shear angle δ and the applied stress σ ($\delta=a'\sigma+b$). The creep takes place according to the exponential law ($\delta=at^m$). The glide bands have to be displaced a distance of about 100 ions at room temperature and about 15 ions at -190°C before rupture takes place (plastic limit). Prismatic punching on sodium chloride crystals produces gliding along dodecahedron planes (110) in [1$\bar{1}$0] direction. Apparent cleavage of sodium chloride crystals along dodecahedron planes and normal cleavage along cubic planes are explained as ruptures between neighboring glide planes.

I. INTRODUCTION

GLIDING is the basic process in the plastic deformation of crystals. Although numerous investigations have been made in this field, many problems are still unsolved. There exists a great need for new experiments which may contribute to their solution. Great progress has been achieved in the study of the gliding process, mainly by investigations of single metal crystals.[1] Nonconducting crystals as compared with metals have some advantages. Since most of them are transparent, they permit study of the gliding process in their interior by observation between crossed polarizers.[2] On the other hand, nonconducting crystals have the disadvantage of a very narrow plastic range; therefore, the method for studying the gliding process must be very sensitive. However, there exist a few ionic crystals which possess plastic properties resembling metals. Those crystals are the silver and thallium halides which can be easily grown in large sizes. As pure silver and thallium halides are very soft, they require special care when specimens are being prepared. Mixed crystals of thallium halides are almost ideal for gliding studies as their hardness is considerably greater than that of their pure components. Thallium bromoiodide crystals of the composition 41.7 percent TlBr+58.3 percent TlI by weight have been used in this investigation.

The methods generally used for investigation of the gliding process are based on the study of shear stress-strain curves. The simplest conditions exist when pure shear stress is applied. Under tension or volumetric compression, however, no pure shear stress is present. The same is true of torsion method. The Bausch method,[3] which claims to give a unidirectional stress, gives no uniform shear stress, as has been shown by Read.[4] In addition, all these methods require large crystal specimens which are seldom obtainable; other disadvantages which should also be mentioned are the variable influence of the specimen surface on the stress-strain and the multiple gliding along different glide planes.

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* Now at Laboratory for Insulation Research, Massachusetts Institute of Technology, Cambridge 39, Massachusetts.

[1] For general summary and references see: *A Symposium on the Plastic Deformation of Crystalline Solids*, Mellon Institute, Pittsburgh 19, 20 May 1950.

[2] E. Schmidt and W. Boas, *Kristallplastizitaet* (Verlag-Springer, Berlin, 1935).

[3] K. Bausch, Z. Physik. 93, 479 (1935).

[4] W. T. Read, see reference 1, p. 111.

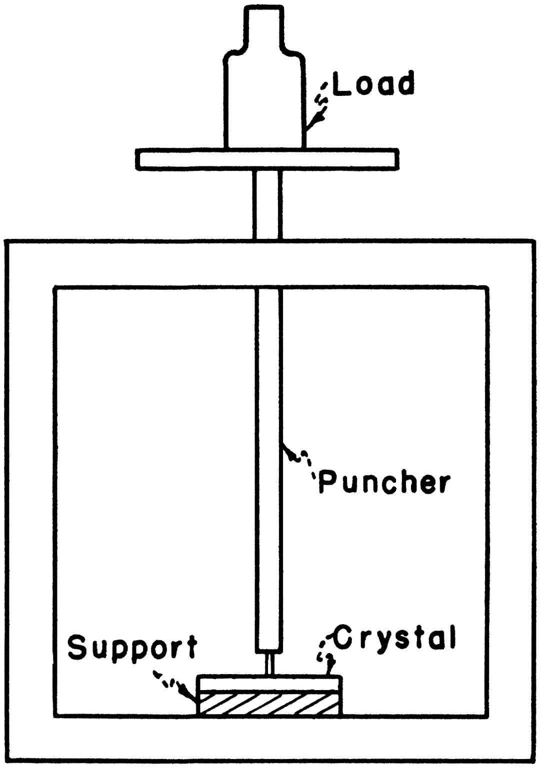

FIG. 1. Schematic diagram of punching apparatus.

II. EXPERIMENTAL METHOD

Some disadvantages mentioned in the preceding paragraph can be eliminated by using the prismatic punching method which already has been used for the determination of crystal orientation.[5] The method involves the application of a force on a prismatic puncher with a square or circular cross section which compresses a small part of a thin crystal specimen lying on a support which is softer than the crystal itself. The method is actually static and, therefore, the word "punching" is somewhat misleading but already accepted in the literature. The puncher is merely pressed into the surface as the load is slowly applied. The compressed part of the crystal under the puncher glides through the crystal in the glid direction along the glide planes. On the side opposite the punch point one or more elevated mounds appear. With increase of stress, the height and the lateral dimensions of the mound increase. The gliding parts of the crystal carry along their adjacent layers, thus forming glide bands. From the dimensions and the structure of the mounds one can obtain information about the gliding process.

The prismatic punching method essentially resembles the hardness test of Vickers. It differs, however, in two points. Whereas the indenter of the hardness tester of Vickers has the shape of a four-sided pyramid, the prismatic punching method uses a cylindrical indenter to provide a constant stress cross stress section regardless of the depth. (For qualitative investigation a conical indenter may also be used.) The other point concerns the method of observation. In hardness measurements only the dimensions of the indentation are determined, whereas in gliding measurements by the prismatic punching method, the elevated mound on the opposite side of the indentation is measured.

The cross section of the puncher is not important. However, for practical reasons it is convenient to use small cross sections, so that the load and the crystal specimen may be small. The punchers used here had cross sections of about 0.03 cm×0.03 cm. The optimum thickness of the crystal specimens is a few tenths of a centimeter. It is important that the dimensions of the sample surface be at least two times greater than the thickness; otherwise, the gliding may take place in the direction of the shortest distance. This effect has already been observed in single aluminum crystals by Wu and Smoluchowski.[6] The crystal specimens used had surfaces of a few square centimeters, so that many punch points could be obtained on the same sample. The thickness was between 0.1 and 0.2 cm. The samples were cut with proper orientation, then ground and polished as described in a previous paper.[7] The apparatus used is shown in Fig. 1.

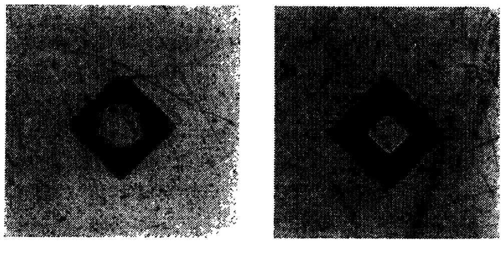
(a) (b)

FIG. 2. Punch patterns on a cube face [100], puncher cross section 4.2×10^{-4} cm^2, load 1.27 kg, crystal thickness 0.118 cm; (a) punched surface; (b) opposite surface; magnification 50×.

III. RESULTS

(A) Glide Planes and Glide Directions

The glide planes and glide directions of thallium bromoiodide have already been determined.[8] The glide directions are perpendicular to the cubic faces [100] and the glide planes are dodecahedron faces (110). In Fig. 2(a) is shown the pattern on the top surface obtained by punching the cubic face [100] with a circular puncher. The bright circle in the middle of the pattern indicates the cross section of the puncher. The dark square surrounding the bright circle is the indented portion outside of the actual punched area. This surface,

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[5] A. Smakula and M. W. Klein, J. Opt. Soc. Am. 30, 445 (1949).

[6] T. L. Wu and R. Smoluchowski, Phys. Rev. 78, 468 (1950).

[7] A. Smakula and M. W. Klein, J. Opt. Soc. Am. 40, 748 (1950).

[8] See Smakula and Klein, reference 5.

in the figure shown, is 2.5 times larger than the cross section of the puncher. The indented area does not depend on the shape of the puncher cross section. It is always limited by four straight sides. On the surface opposite the punch point a truncated pyramid appears [see Fig. 2(b)]. The sides of the pyramid are not planes but slightly curved surfaces. The base of the pyramid is larger than the indented area on the opposite side. The top of the pyramid is smaller than the actual punched area on the opposite surface. The relation between the applied stress and the dimensions of the pyramid is treated later.

Punching on a dodecahedron face [110] produces an indentation on the top surface under the puncher and, in addition, an elevation in the form of two wings, as shown in Fig. 3(a). The wings are formed by the gliding of plastic deformed crystal parts in [100] directions along (110) glide planes. On the opposite side two rhombic truncated pyramids appear displaced 45° from the punch direction and pointing toward [100] directions [see Fig. 3(b)]. Their linear distance depends on the thickness of the sample.

Punching on an octahedron face [111] produces around the punched surface three wings directed toward [100] planes [see Fig. 4(a)]. On the opposite side three pyramids appear which are rotated 60° with respect to the wings on the top surface [see Fig. 4(b)]. The pyramids may be considered as projected patterns from cubic faces onto octahedron faces.

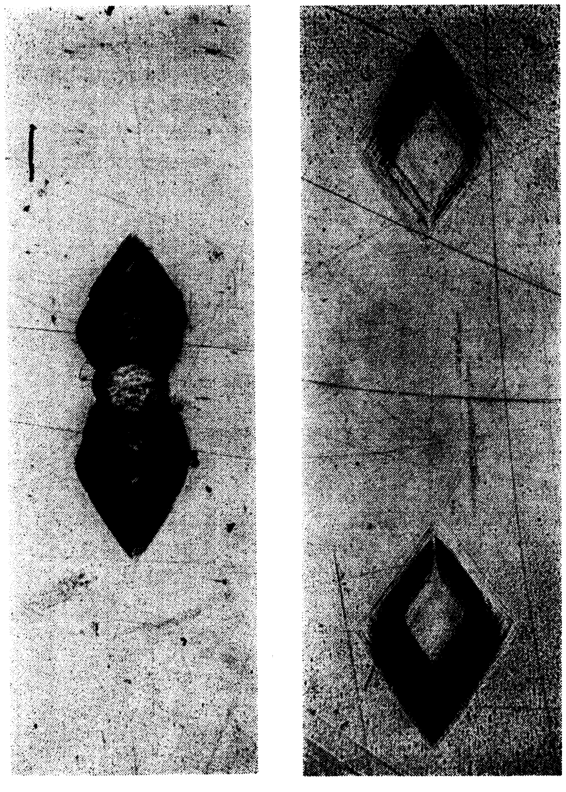
(a) (b)

FIG. 3. Punch patterns on a dodecahedron face [110], puncher cross section 4.2×10^{-4} cm^2, load 2.53 kg, crystal thickness 0.136 cm; (a) punched surface; (b) opposite surface; magnification 50×.

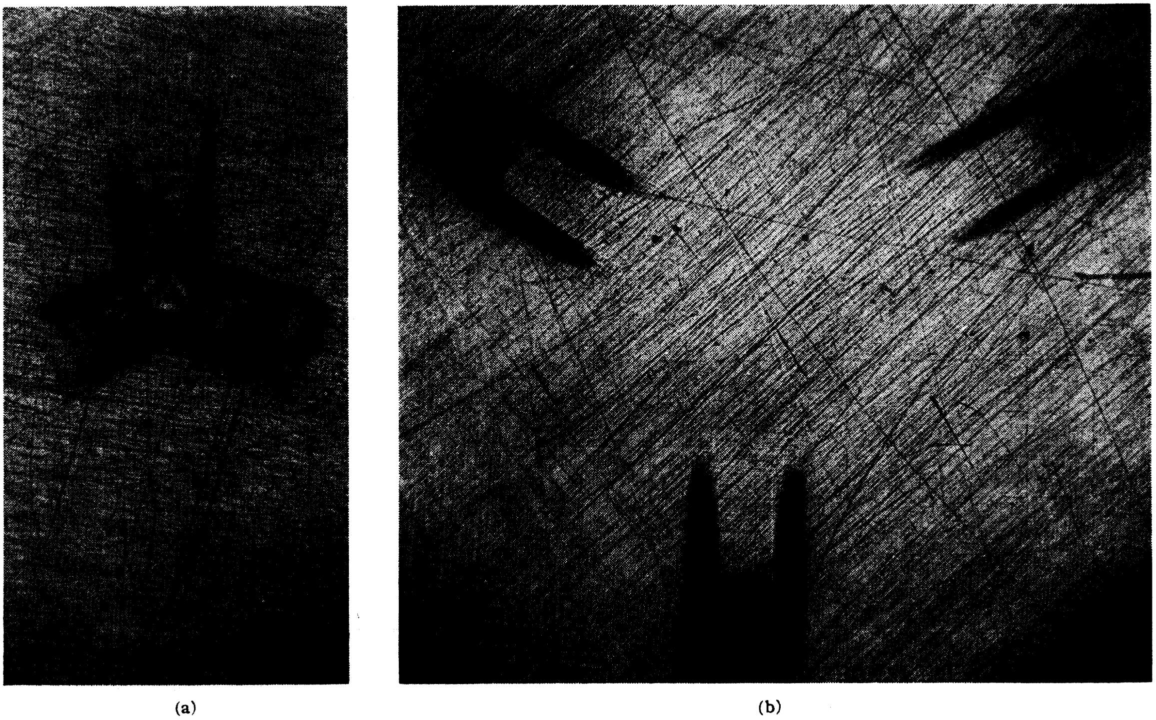
(a) (b)

FIG. 4. Punch patterns on an octahedron face [111], puncher cross section 4.2×10^{-4} cm^2, load 3.83 kg, crystal thickness 0.125 cm. (a) Punched surface. (b) Opposite surface. Magnification 50×.

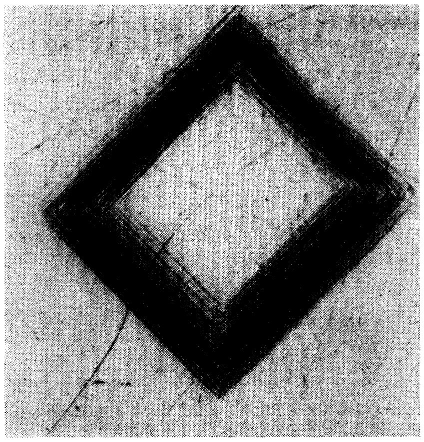

FIG. 5. Glide bands on a cubic face, magnification 100×.

(B) Glide Bands

The sides of the elevated pyramids shown in Figs. 2 through 4 are not smooth, but have a steplike structure, called glide bands. Such glide bands are shown in Fig. 5. The formation of the glide bands takes place quite uniformly. If the puncher has a square shape and its edges coincide with the directions of the glide planes, that is, cubic faces, the first bands appear directly under the edges of the puncher. If the cross section of the puncher is circular, or if the edges of a square puncher do not coincide with the directions of the glide planes, the elevated mound will still have a square shape with dimensions corresponding to the puncher dimensions in the direction perpendicular to the glide planes. If a circular puncher is used, the square mound circumscribes the puncher circle. This result indicates that the gliding is transmitted outside of the stress area until two perpendicular glide bands meet each other. If the stress increases, new glide bands develop on both sides of the bands already present. As a consequence, the base of the pyramid increases, and the top surface decreases. The distance between the glide bands varies from 1 to 5 microns. An average of 25 bands has been found to be 3.36 microns apart. It is probable that narrower bands exist which might not have been resolved by the microscope used. A Bausch and Lomb metallographic microscope has been used for all strain measurements. The glide bands can reach a height of about 1 to 2 microns before a rupture takes place. When glide bands are produced at low temperature (−190°C) they are much sharper than those produced at room temperature, but their widths and heights seem to be independent of the temperature.

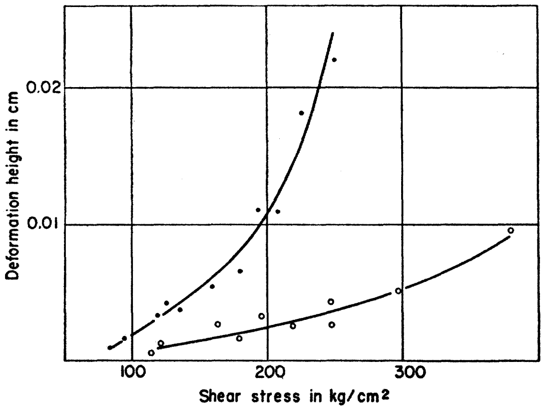

FIG. 6. Strain-stress curve in terms of the height of the elevated pyramid on a cube face. The dots represent room temperature values. The open circles represent values at −190°C.

(C) Stress-Strain Curve

The stress-strain curve represents the relation between the applied force and the resulting deformation. When the punch method is employed, the deformation may be estimated from the dimensions of the elevated mound. Both the height and the width of the mound are measured. Since punching on the cubic face produces the simplest conditions, it has been used for the quantitative study. Application of different amounts of stress on a crystal by the punch method changes the dimensions of the elevated mound. In Fig. 6 the height of the pyramid *versus* stress is shown. The curve has a parabolic shape. With an increase of stress the lateral sides of the mound change, as shown in Fig. 7. The lateral increase of the mound is linear with the stress.

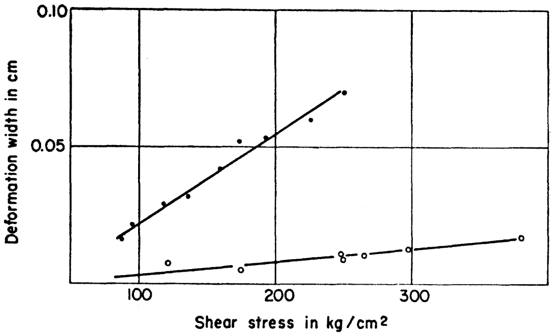

FIG. 7. Strain-stress curve in terms of the strained width of the elevated pyramid on a cube face. The dots represent values at room temperature. The open circles represent values at −190°C.

The influence of stress on the dimensions of the mound at a temperature of −190°C is similar to that at room temperature. The only difference is that at low temperature a considerably higher stress is necessary to produce the same sized mound.

Neither the height nor the width of the elevated pyramid gives a complete relationship between shear stress and shear strain. If the direction of applied stress is parallel to the glide planes, the strain may be expressed by the shear angle δ. It can be expressed

$$\delta = \text{arc tg}(h/w),$$

where h = the height of the elevated pyramid and w = the width of the strained pyramid sides. In the elastic range, δ is directly proportional to the applied stress σ. We have a linear relation in the plastic range too, as can be seen in Fig. 8 where the shear angle δ is plotted *versus* applied stress σ. The relatively wide scattering of experimental points might be caused partly by not uniformly applying the stress and partly by the inaccuracy of microscopic readings. The remarkable result is that the points obtained at low temperature (−190°C) coincide with those at room temperature. This indicates that the ratio of the height of the pyramid to the strained width does not depend on temperature.

The strain-stress curve of Fig. 8 may be represented by

$$\delta = a'\sigma + b,$$

where a' and b are constants. The linear relation has already been found for other body-centered cubic and hexagonal crystals and the parabolic relation for face-centered cubic crystals.[9] In the transition region between the elastic and plastic range we may expect in thallium bromoiodide a parabolic relation too.

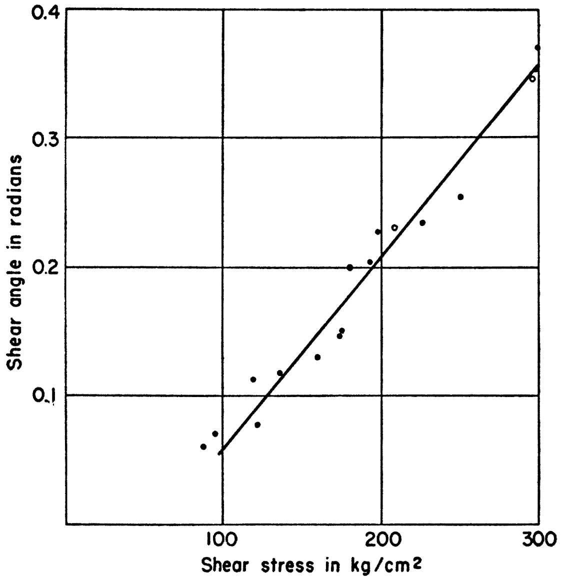

FIG. 8. Strain-stress curve in terms of the shear angle of the elevated pyramid on a cube face. The dots represent room temperature values. The open circles represent values at −190°C.

(D) Strain-Time Curve (Creep, Plastic Flow)

There are two kinds of creep: transient creep which occurs at the moment when the stress is applied and quasi-viscous creep which continues to extend under constant stress. The transient creep obeys the law

$$\delta = at^m,$$

and the quasi-viscous creep

$$\delta = kt,$$

where t is time, a and k are coefficients of flow and m is creep exponent.[10,11]

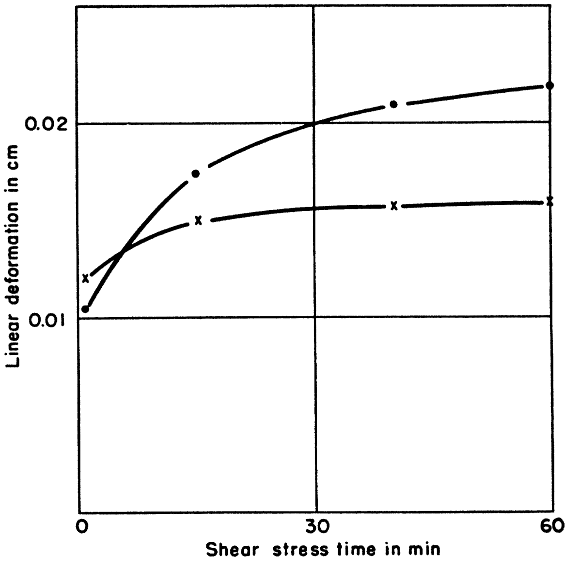

FIG. 9. Plastic flow of the elevated pyramid on the cube face. The dots represent height, and the crosses represent the strained width.

All our results so far have been obtained by applying the stress for 5 seconds. Figure 9 shows the change of the width w and the height h of the elevated pyramid extending the stress time up to one hour. Both increase with time at a decreasing rate. The height is influenced by time more than the width. In Fig. 10 is plotted $\log\delta$ *versus* $\log t$. The straight line indicates that the exponential law of transient creep is valid for thallium

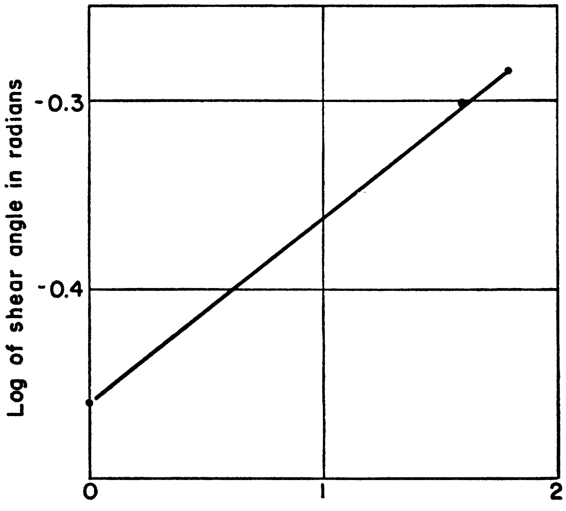

FIG. 10. Plastic flow of the elevated pyramid on the cube face in terms of shear angle.

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[9] G. I. Taylor, Proc. Roy. Soc. (London) **145**, 362 (1934).

[10] E. N. Andrade, Proc. Roy. Soc. (London) **A84**, 1 (1910); and **A90**, 392 (1914).

[11] E. P. T. Tyndall, see reference 1, p. 49.

FIG. 11. Punch pattern on a dodecahedron face [110] of NaCl, surface opposite to the puncher, puncher cross section 8.1×10^{-3} cm^2, crystal thickness 0.2 cm, magnification 50×.

bromoiodide crystals. If t is given in minutes, $a=0.44$ min^{-1} and $m=0.095$ for a stress of 200 kg/cm^2 and room temperature. The coefficient a depends on the applied stress, while m seems to be constant. The influence of the temperature has not yet been studied.

(E) Elastic and Plastic Limits

The elastic limit of thallium bromoiodide produced by pure shear stress has not yet been determined. The apparent elastic limit estimated by torsion is 163 kg/cm^2.[12] The first visible deformation which takes place on the punched surface occurs at a stress of about 100 kg/cm^2. The glide bands inside of the crystal can already be seen at even lower stress. The formation of the elevated mound on the opposite side depends on the stress and the crystal thickness. For thickness smaller than 0.05 cm the glide bands can be transmitted through the whole thickness. If the thickness is greater than 0.05 cm, the upper part of the crystal directly under the puncher is distorted beyond the plastic limit before the mound on the opposite side appears. With increased stress the mound becomes wider and higher (see Figs. 6 and 7), until finally it breaks. The maximum height which the mound may obtain at room temperature is about 0.02 cm and the width 0.07 cm. At a temperature of −190°C the maximum height obtained is 0.003 cm and the width 0.01 cm. The corresponding total shear stress of the plastic limit is about 250 kg/cm^2. The maximum shear angle (the slope of the sides of the mound) is about 20°. If we consider that the nearest glide bands are about 1 micron apart, we obtain a maximum glide of one band $=3\times10^{-6}$ cm. This indicates that a lattice plane must be shifted about 100 atoms until the binding force is broken.

(F) Gliding in Sodium Chloride Crystals

The glide system (glide planes and directions) in thallium bromoiodide are of the highest possible symmetry; there are four glide planes parallel to one glide direction. The punched part, therefore can be pushed through the crystal as a prism. It is quite interesting to see what happens if some of the glide planes are not parallel to the glide directions. This is so in sodium chloride crystals where the glide planes are dodecahedron planes (110) and the glide directions are perpendicular to dodecahedron planes $[1\bar{1}0]$.[13] The simplest gliding conditions exist when the punch direction coincides with the glide direction. This is true when we punch a sodium chloride crystal on a dodecahedron plane, that is, [110]. Only the two planes $(01\bar{1})$ and $(0\bar{1}1)$ are parallel to the glide direction. The other four

FIG. 12. Glide bands in NaCl as seen between crossed polarizers produced by punching on a cube face at 350°C, magnification 100×.

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[12] Combes, Ballard, and McCarthy, J. Opt. Soc. Am. 41, 215 (1951).

[13] Under certain conditions sodium chloride may glide also along (100) planes. See: M. J. Buerger, Am. Mineral. 15, 174 (1930).

are at 45° angles. Sodium chloride crystals are too brittle for punching at room temperature. Therefore, the experiments have been carried out at a temperature of 350°C. The result of punching on the [110] plane is shown in Fig. 11. The elevated mound is limited only on two sides by glide bands. The other two sides of the mound show a diffuse transition between the mound and the undeformed crystal surface. From this result we may conclude that if the glide planes are not parallel to the glide direction, no glide bands are formed.

Punching on a cube face [001] of sodium chloride produces gliding along four adjacent dodecahedron planes (101), (011), $(\bar{1}01)$, and $(0\bar{1}1)$. We should expect four mounds similar to the one shown in Fig. 11. The glide bands formed inside the crystal by punching on a cubic face are shown in Fig. 12. Since a conical puncher has been used in this experiment the two bands do not split into two components. On the punched cubic surface of sodium chloride four cracks appear along dodecahedron planes (Fig. 13). This effect is already known and is called an "apparent cleavage" in contrast to the normal along the cubic planes. Both cleavages have actually the same cause. If a stress is applied on a point or small surface of the cubic plane, the material glides in four different directions and the cracks appear along the boundaries of the glide planes. To cleave a crystal along a cube face, a stress must be applied on a line parallel to a cube face. The crystal is forced to glide along two dodecahedron planes only, and the crack appears along the boundary between those two glide planes. Hence, the cleavage in sodium chloride can be explained as a simple separation of glide planes.

IV. DISCUSSION

A mechanism of plastic deformation produced by punching has been described by Seitz.[14] According to Seitz, spirals or rings of dislocation are generated along the periphery of the contact area between the indenter and crystal surface in the manner of Frank-Read mechanism.[15] These dislocation rings or spirals can move along the glide planes in glide direction through the crystal sample. It is generally assumed that the shearing stress, determined by stress-strain measurements, corresponds to the production or liberation of the dislocations from some stable array and not to their movement in the crystal. This conclusion has been drawn indirectly from the smallness of the shearing stress and from the strong influence of impurities. We can give a direct proof from our experiments for this mechanism. As it has been shown under III-A there can be produced one, two, or three mounds depending on the crystal orientation. It is very surprising that the necessary stress is the same whether we produce one, two, or three mounds of the same size. This experimental fact can be explained only by the assumption that the shearing stress is used only to start the deformation.

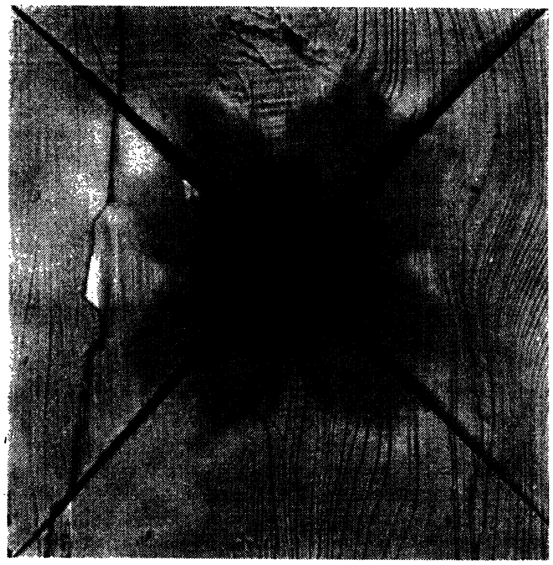

FIG. 13. Apparent cleavage of NaCl produced by punching on a cube face at room temperature, magnification 100×.

V. CONCLUSIONS

One can see from the results of the experiments presented in this paper that prismatic punching is a very convenient method for study of plastic deformation. The linear dimensions of the crystal specimen may be as small as 0.1 cm or even smaller. The high or low temperature study is very simple since the punching only is made at desired temperatures and the subsequent microscopic measurements are carried out at room temperature. The surface influence of the specimen is eliminated in the prismatic punching method since the crystal is forced to deform in that area where the stress is applied. The formation of glide bands in space and time can be studied easily. Crystals with low plastic properties such as sodium chloride can be studied easily by the punching method at higher temperatures.

ACKNOWLEDGMENT

The authors are indebted to Professor F. Seitz for reading the manuscript and for his valuable comments.

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[14] F. Seitz, Phys. Rev. **79**, 723 (1950).

[15] F. C. Frank and W. T. Read, Phys. Rev. **79**, 722 (1950).

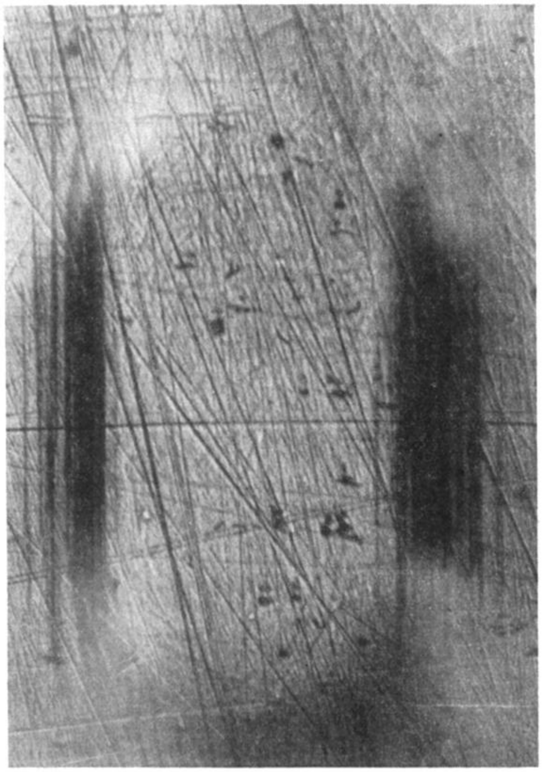


FIG. 11. Punch pattern on a dodecahedron face [110] of NaCl, surface opposite to the puncher, puncher cross section 8.1×10^{-3} cm^2, crystal thickness 0.2 cm, magnification 50×.

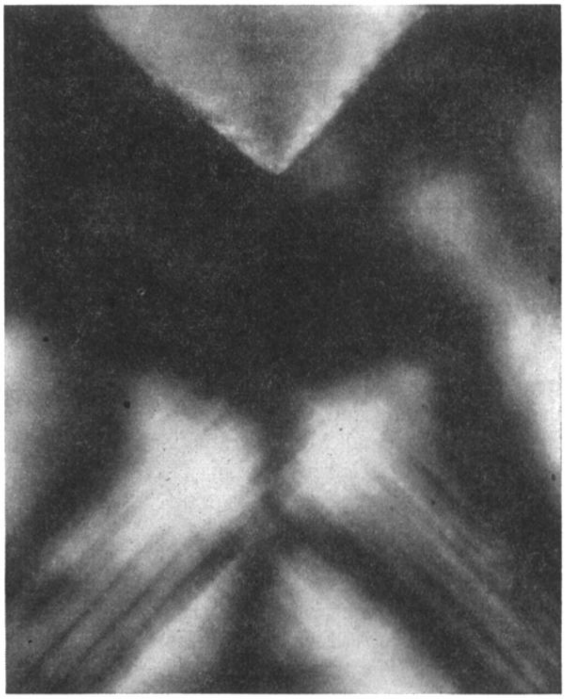


FIG. 12. Glide bands in NaCl as seen between crossed polarizers produced by punching on a cube face at 350°C, magnification 100×.

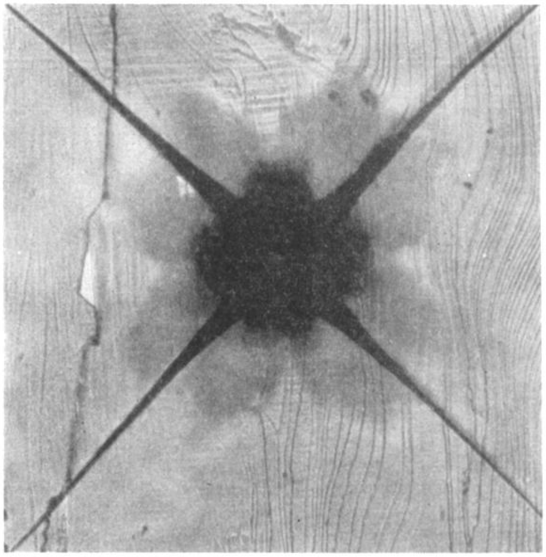


FIG. 13. Apparent cleavage of NaCl produced by punching on a cube face at room temperature, magnification 100×.

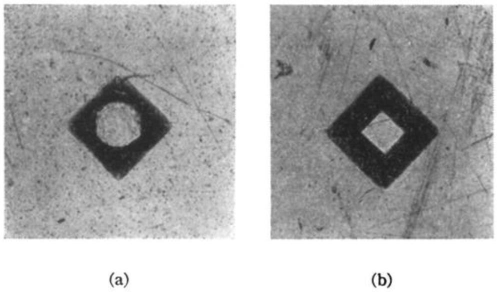

(a) (b)

FIG. 2. Punch patterns on a cube face [100], puncher cross section 4.2×10^{-4} cm^2, load 1.27 kg, crystal thickness 0.118 cm; (a) punched surface; (b) opposite surface; magnification 50×.

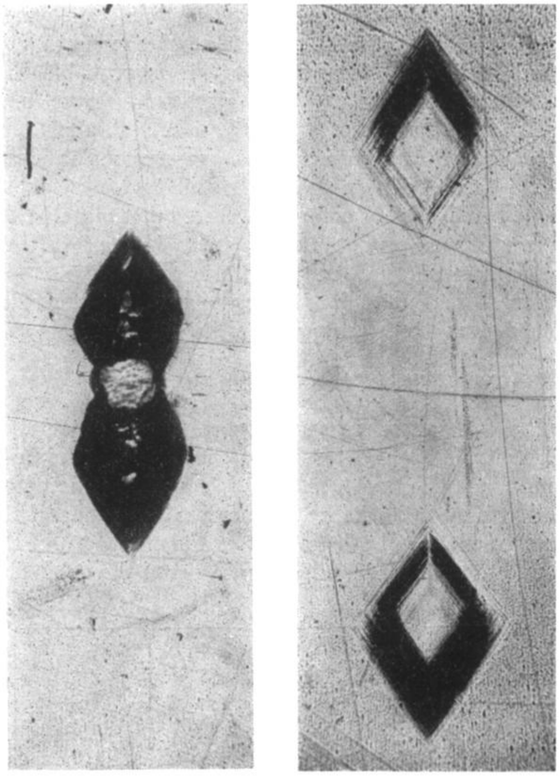
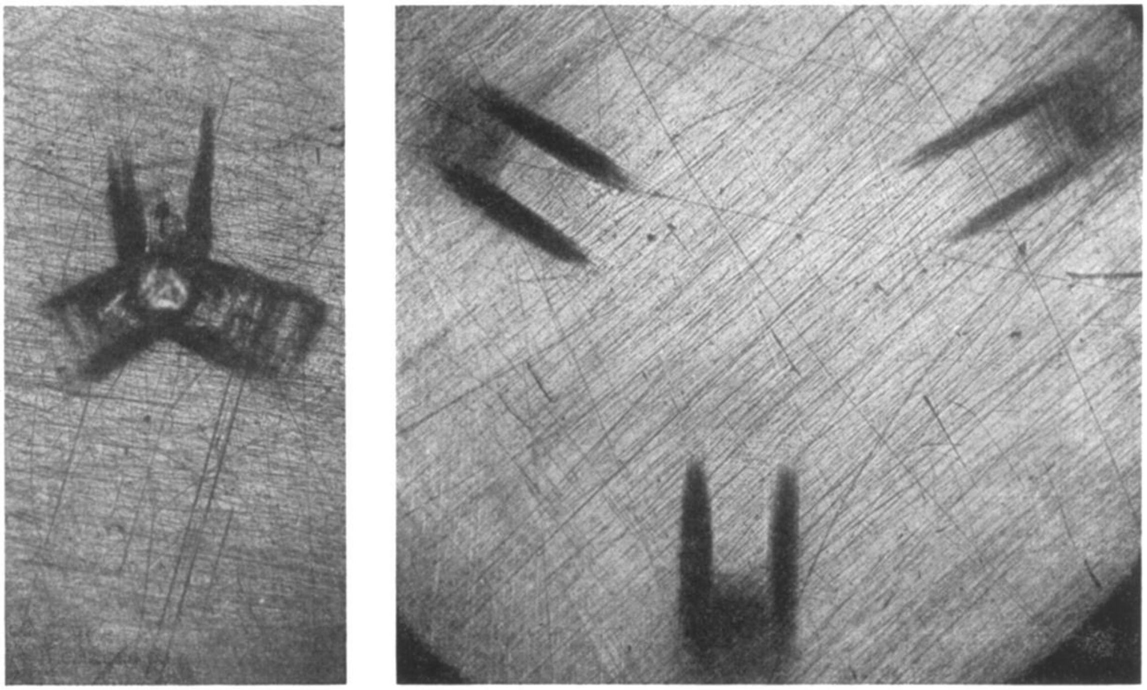

(a) (b)

FIG. 3. Punch patterns on a dodecahedron face [110], puncher cross section 4.2×10^{-4} cm^2, load 2.53 kg, crystal thickness 0.136 cm; (a) punched surface; (b) opposite surface; magnification 50×.



(a) (b)

FIG. 4. Punch patterns on an octahedron face [111], puncher cross section 4.2×10^{-4} cm^2, load 3.83 kg, crystal thickness 0.125 cm. (a) Punched surface. (b) Opposite surface. Magnification 50×.

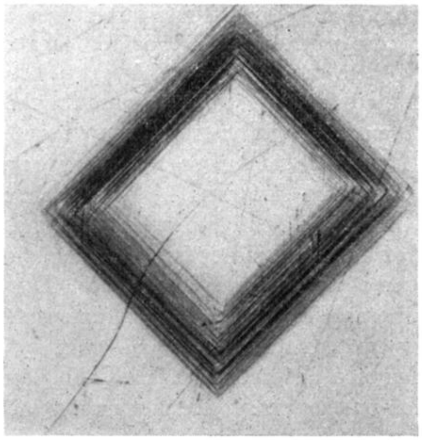


FIG. 5. Glide bands on a cubic face, magnification 100×.