

$\phi'$  et  $U$  sont donnés par les expressions (9) où les produits scalaires  $\mathbf{sy}_i$  prennent la forme

$$(\hbar\mathbf{b}_1 + k\mathbf{b}_2 + l\mathbf{b}_3 + \epsilon)\Delta_i.$$

Cette répartition n'est symétrique que si l'ensemble  $\alpha_i(\Delta_i)$  est centro-symétrique.

Dans ce dernier cas  $\phi'$  ne peut être que 0 ou  $\pi$ . Pour  $\phi'=0$ , un maximum de  $G$  se trouve sur le nœud du réseau réciproque et les minima de  $G$ , à partir du second, coïncident avec les maxima secondaires de  $(\sin^2\pi L\epsilon)/(\pi\epsilon)^2$ : la réflexion est moins diffuse que dans un domaine ordonné isolé; elle est d'autant moins diffuse que  $U$  est plus près de l'unité et que  $M$  est plus grand. Pour  $\phi'=\pi$ , le nœud du réseau réciproque se trouve sur un minimum de  $G$ . Les maxima de  $G$  se produisent pour  $\epsilon = \pm\left(\frac{1}{2L}, \frac{3}{2L}, \frac{5}{2L}, \dots\right)$  et coïncident, à partir du second, avec les maxima secondaires de  $(\sin^2\pi L\epsilon)/(\pi\epsilon)^2$ .

La réflexion comporte deux maxima principaux placés symétriquement par rapport au nœud du réseau réciproque.

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## Fractography as a Technique in Crystal Chemistry\*

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'Fractography' is the technique recently developed in metallurgical fields for studying the patterns found on nascent fracture surfaces at high magnifications of the optical microscope. It is applied here to cleavages of non-metallic crystals to demonstrate its usefulness in disclosing deformation and cleavage mechanisms and in displaying intracrystalline structures, particularly imperfection structures. As with metals, numerous informative patterns are readily found which serve to distinguish crystal types, to reveal the history of growth of the individual crystal, and to provide direct visual evidence for the much-discussed mosaic constitution of the solid state.

### Introduction

A few years ago a new micrographic technique was discovered which allowed a direct study at high magnification of unetched and unpolished nascent fracture surfaces (Zapffe & Moore, 1943). The technique was developed into a practicable laboratory procedure (Zapffe & Clogg, 1945*a*), particularly designed for the study of metals (Zapffe & Clogg, 1945*b*; Zapffe, 1947*a*), and was later explored intensively in the senior author's laboratory under contract with the Office of Naval Research (Zapffe, 1946*a,b,c*, 1947*b*, 1948; Zapffe & Landgraf, 1948*a,b*; Zapffe, Landgraf & Worden, 1948*a,b,c,d*; Zapffe, Worden & Landgraf, 1948, 1949).

Although many chemists and mineralogists have probably studied cleaved crystal surfaces at high magnifications under the microscope, only an occasional earlier investigator can be found who so studied metals, notably Howe (1916), Goetz (1930) and Schilling (1934)—undoubtedly because of the forbidding nature of metallic fractures when considered for magnifications beyond a few diameters.

By means of the recently developed 'fractographic stage' (see Fig. 1), the study of most fracture surfaces is now readily accomplished; and the numerous developments in metallurgical thought which have followed from an intensive study of cleavage markings suggest that the cleavage surfaces of non-metallic materials should be reinvestigated in the light of those developments. Markings may be discovered with the new

\* From research conducted in the laboratory of the senior author under contract with the Office of Naval Research.

technique which have not been observed before; and perhaps new importance can be attached to markings which have been observed before.

As for the operation of the stage shown in Fig. 1, a small specimen containing the desired surface is mounted in a built-in plasticene cup; and the fracture face is brought approximately into the equatorial plane (lower face of the stage) of the two concentric upper hemispheres by movement of a polar axis, which then locks and holds the field at the approximate center of the spherical motion. This permits maintaining a rough focus on the mass of individual cleavage facets, while their orientation is being modulated by rocking the outer movable hemisphere upon the surface of the inner fixed one.

When a single cleavage facet or local cleavage area is thus oriented perpendicular to the light beam, a bright flash is observed from the reflection. The motion is then stopped, and the field is brought into focus. Lenses of higher magnification may now be inserted; and other optical changes may be made as desired, for the selected facet remains oriented and subject to direct observation until the position of the fractographic stage is changed. When other individual facets are later sought, the lateral movements of the microscope stage bring a new area into the field; and the described movements of the fractographic stage subsequently orient it. The principals of orientation are essentially those of other standard devices, the novelty of the technique consisting more in the general procedure of successfully observing difficult fracture faces at high magnification, using oblique illumination to provide a sense of texture and depth of focus, and relating the observed structures on the cleavage facets to important characteristics of the material, which in many cases has already opened promising new fields for study. Further details on the procedures of fractography can be found in the ample bibliography appended to this paper.

Consequently, to call the attention of investigators in the general field of non-metallic crystal chemistry to the fractographic technique is the principal purpose of the present manuscript. The research which is described is exploratory, not exhaustive. The full significance of the individual patterns is accordingly often left undeveloped and requiring further study. The important message is that one can find on the

individual cleavage facets of metallic and non-metallic materials alike a detailed record of (1) the imperfection structure of the crystal, (2) the crystallographic mechanisms involved in deformation and fracture, (3) the path of the cleavage traverse as influenced by crystallography, imperfection structures, and local stress resolutions, and (4) other phenomena relating to both intergranular and intragranular characteristics of the grain or crystal.

### Structures in bismuth

In the field of metallurgy, constitutions are occasionally observed which are semi-metallic or non-metallic in nature. Since these come close to the category under discussion, they may provide useful introductory examples in aiding the interpretation of fractographs of non-metallic materials in terms of the better-established metallic patterns.

Two fractographs in Fig. 2 illustrate the point. The specimen is pure bismuth metal in Fig. 2(a), and bismuth alloyed with 1.7% antimony in Fig. 2(b). These and all following specimens are described in Table 1.

From previous detailed studies of bismuth\* (Zapffe, 1946a), the facets in both fractographs of Fig. 2 are known to be basal (0001) cleavages. The broad dark bands are registrations of twinning on  $\{10\bar{1}4\}$ , accentuated here by oblique illumination—a standard procedure in the technique. In Fig. 2(a) the bands are remarkably regular in spacing and in width, and strictly regular in orientation. Their complete traverse of the field proves this to be a single grain (crystal) that is being observed.

Very close examination of Fig. 2(a) will also reveal an overlying network of fine striae disposed exactly along three directions at  $60^\circ$  to one another (possibly difficult to see in the reproduction). These have a significance not yet fully determined. Other markings have the nature of fissures, lamellar profiles, and undulations. The interactions of these categories on one another can be studied in the fractograph to disclose both their nature and the order of their occurrence during deformation and fracture. Thus, this material is found to respond to deformation first by twinning,

\* A series of three papers on the fractography of the bismuth-antimony system is to be published shortly.

Table 1. *Description of specimens*

Specimen no.	Type	Remarks
I	Bismuth (Bi)	C.P. lump, as purchased
II	Bismuth alloy (with 1.7% Sb)	C.P. Bi and Sb melted at $700^\circ\text{C}$ ., furnace-cooled, condition: as-cast
III	Molybdenum (Mo)	Electric-melted, vacuum-cast by Climax Molybdenum Corp. process; oxygen content too high to be forgeable
IV	Potassium dichromate ( $\text{K}_2\text{Cr}_2\text{O}_7$ )	†Specially grown single crystal
V	Sodium chloride (NaCl)	†Single crystal grown from a seed in saturated solution of NaCl + 1% KI in distilled water at $50^\circ\text{C}$ .
VI	Copper sulphate ( $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ )	C.P. reagent, as purchased
VII	Nickel sulphate ( $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$ )	C.P. reagent, as purchased
VIII	Iodine	C.P. reagent, resublimed

† Produced by the Crystal Section of the Naval Research Laboratory. See acknowledgement.

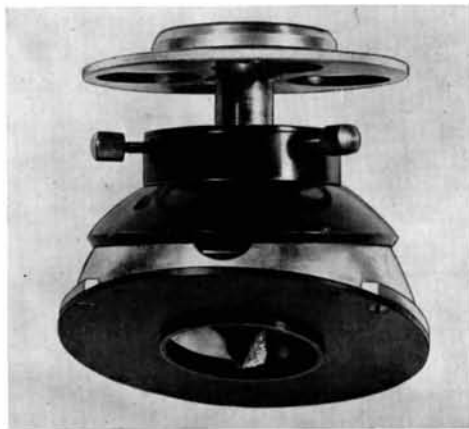


Fig. 1. The fractographic stage. This stage, in process of manufacture by the Bausch and Lomb Optical Company, consists of two concentric hemispherical domes containing a plasticene cup for holding odd-shaped specimens, and a polar axis attached to this cup by means of which the fracture face can be brought into the equatorial plane so that subsequent orienting movements will not importantly change the focus.



Fig. 2. Basal cleavage (a) in pure bismuth ( $225\times$ ) and (b) in bismuth containing 1.7% antimony ( $175\times$ ).



Fig. 3. Fractograph of cast molybdenum fractured intergranularly to show a granular growth of oxide (lower portion of figure) invading and destroying a field of carbide 'feathers' (upper portion).  $287\times$ .



Fig. 4. Fractograph of copper sulphate, showing a predominating hackle pattern.  $187\times$ .

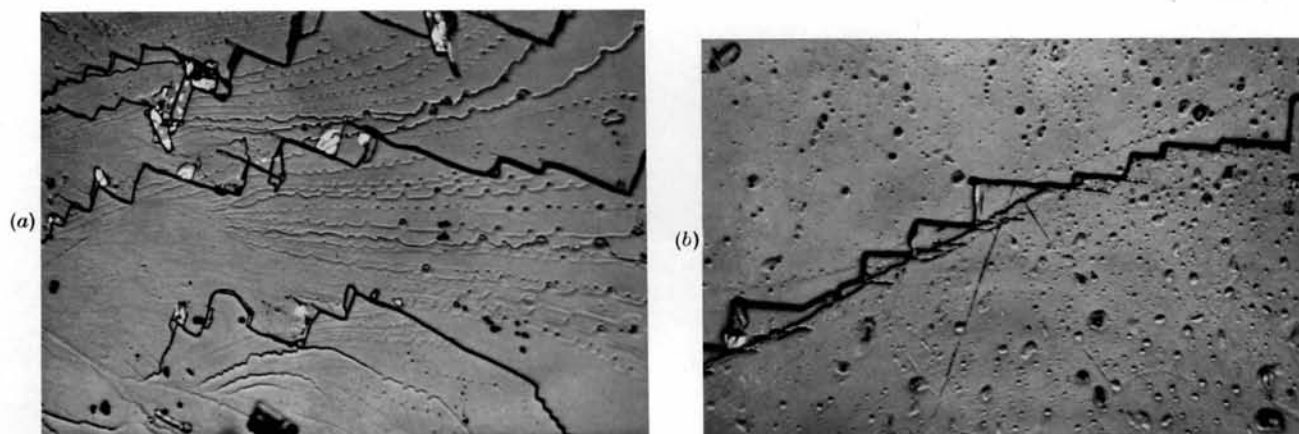


Fig. 5. Fractographs of nickel sulphate, showing crystallographic markings, block structures, lineage traces, and impurities. 225  $\times$ .

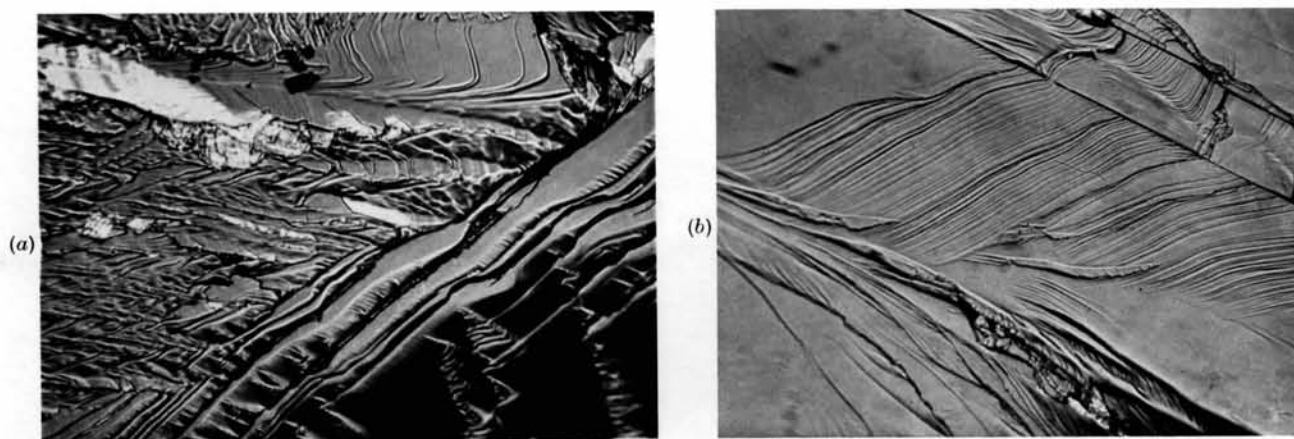


Fig. 6. Fractographs of potassium dichromate showing complex markings, certain of which are probably related to crystal structure and to imperfections in crystal growth. (a) 237  $\times$ ; (b) 105  $\times$ .

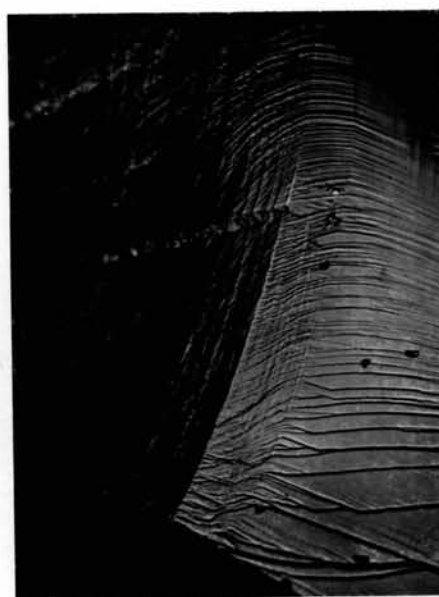


Fig. 7. Fractograph of potassium dichromate indicating a lamellar imperfection structure. 162  $\times$ .

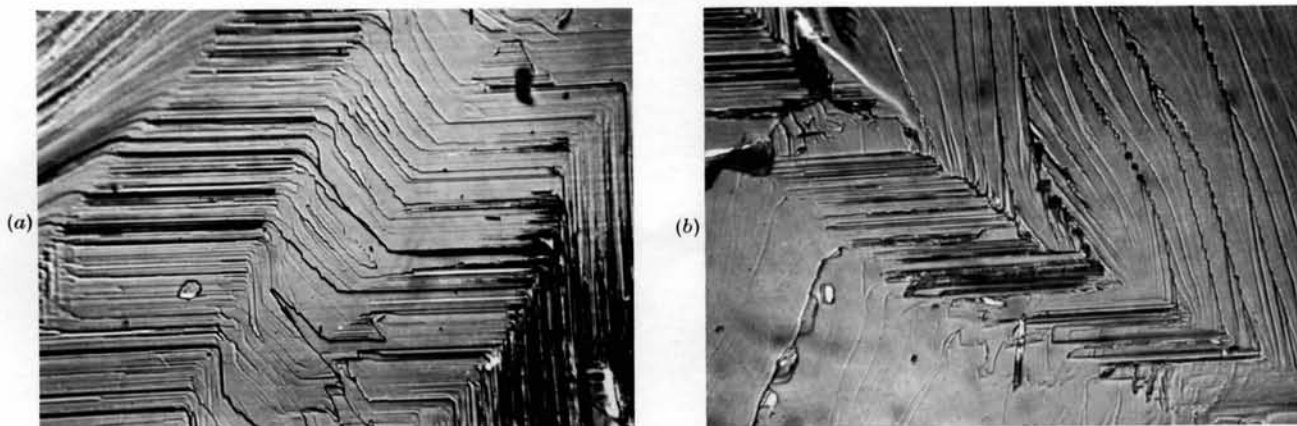


Fig. 8. Fractographs of sodium chloride showing marked crystallographic, lamellar, and mosaic markings, with a virtual absence of hackle structure. (a) 212  $\times$ ; (b) 237  $\times$ .

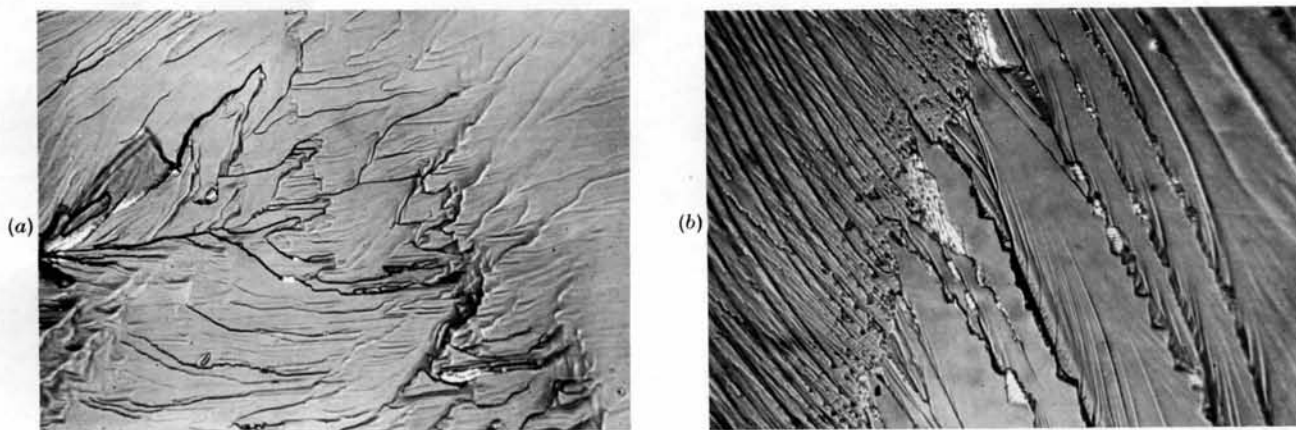


Fig. 9. Fractographs of sodium chloride depicting markings relating to crystal growth and imperfection. (a) 212  $\times$ ; (b) 237  $\times$ .

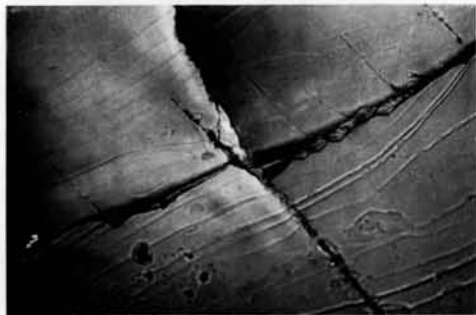


Fig. 10. Junction of four lineages appearing on a cleavage facet of sodium chloride. 325  $\times$ .

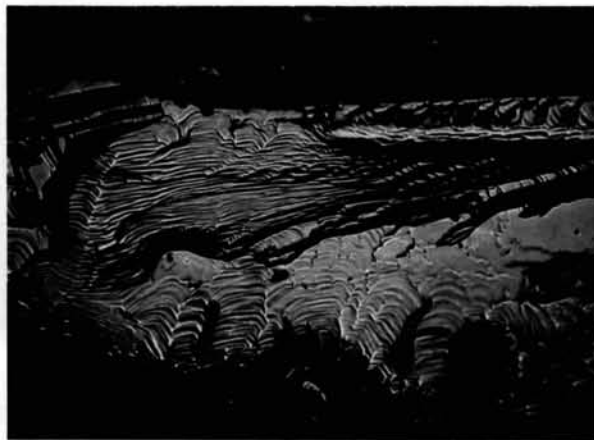


Fig. 11. Crystal of resublimed iodine showing lamellar formations. 175  $\times$ .

then by incipient cleavage on both primary and secondary plane families, next by completed separation on the plane or planes contributing the facet. Apparently the striae form at the instant of the formation of the new surface, for they uniformly overlie all other structures.

In Fig. 2 (b) the twin bands are markedly irregular in width. Of principal interest, however, is the pronounced 'tree-ring' structure providing repeated undulations of the surface.

While each fractograph must be separately considered with regard to the extent to which stress resolutions and 'hackle'\* effects intrude upon the pattern, the important aspect of the fractographic pattern seems to be in most cases, at least for metals, that it is essentially *a pattern of growth imperfection and crystal architecture*—not a pattern superimposed by the fracturing stress. It is a common reaction of the new observer to explain the fractographic pattern on the basis of stress pattern, probably because the macro-form of cleavage is often dictated by stress relationships; but its micro-forms seem more often to relate directly to the crystal architecture, sometimes with a complete exclusion of hackle effects. If this point is not made clear by Fig. 2, then further patterns should be studied in the other publications. The relation of the fractographic pattern to mosaic imperfection (Zapffe, 1946*b*) and to the original crystal growth (Zapffe, Landgraf & Worden 1948*b*) has been amply demonstrated; and it will be the principal contribution of this paper to make similar disclosures for non-metallic crystals.

Apparently it is true that crystals of low symmetry, and amorphous materials such as glass, readily express the transient stress pattern, even on a micro-scale, as a hackle traverse of cleavage. Crystals of higher symmetry, however, which include most metals, have such strong directionality in both a crystallographic and an imperfection sense that cleavage forcibly follows the greater weaknesses.

In the particular case of Fig. 2 (b), for example, the authors believe that the undulating markings represent growth distortions caused by the alloy component, rather than a shock-wave or a related effect of the rupturing stress. The presence of the second component, antimony, has presumably caused a distortion during the growth of the crystal which was sufficient to introduce a marked imperfection pattern, but was insufficient to cause a subdivision into smaller and separately oriented grains.

#### Non-metallic structures in cast molybdenum

In the casting of molybdenum by the electric-arc process (Parke & Ham, 1947), carbon is utilized for removing the excess oxygen which would otherwise make the metal non-forgeable. The fractograph in Fig. 3

reveals both the oxide and the carbide phases in a piece of molybdenum which fractured through the grain boundary where these non-metallics accumulate. This is a particularly interesting example of non-metallics expressing themselves on the fractographic pattern, for the position of the carbide 'feathers' at the top of the figure and the growthlike characteristics of the oxide granules provide a strongly visual suggestion that the oxide here is an invading phase progressing into a carbide area and destroying the latter phase by a reaction producing escapable carbon-oxide gas (Zapffe, Landgraf & Worden, 1948*c*).

#### Fractographs of some common chemical crystals

With this brief mention of several cleavage phenomena of semi-metallic or non-metallic nature in metallurgical studies, we shall now examine fractures of some non-metallic substances. Further details of fractographic structures in metals can be found in the listed references.

Immediately, one is confronted with the problem of transparency or translucency, which characterizes many non-metallic or 'chemical' crystals and makes the observation of cleavage surfaces much more difficult than for opaque substances such as metals. A number of modifications in procedure is possible, of course, supplanting the use of oblique illumination. These include (a) polarized light, (b) dark-field illumination, (c) 'sensitive tint', and possibly (d) interferometric methods, such as that of Tolansky (1946). Color fractography also holds great promise. Certain of these methods will be described in later communications. Here, however, we shall restrict the study to the simple conventional technique, using oblique light for bringing out surfacial detail.

#### Copper sulphate

In Fig. 4, a fractograph of a C.P. copper sulphate crystal (see Table I) shows the effectiveness of oblique illumination in bringing out surfacial detail even on this type of material. Perhaps because of the low order of symmetry of copper sulphate (triclinic), crystallographic registrations are characteristically lacking, at least in casually grown crystals. The cleavage pattern predominates in the hackle type of marking, as shown.

#### Nickel sulphate

In some contrast to copper sulphate, crystallographic markings are readily observed on cleavages of nickel sulphate. This conforms to what seems to be a general rule which shall now be so stated: *Crystals of higher orders of symmetry increasingly express their principal plane families and their growth imperfections in cleavage phenomena, whereas amorphous solids and crystals of lower symmetry submit to the hackle pattern induced by stress.*

Fig. 5 shows two typical fractographs of this tetragonal material, nickel sulphate, with flat cleavage terrain and numerous rectilinear markings. Nickel

\* 'Hackle' refers to patterns which relate to characteristics of the fracturing stress and disclose nothing of the architecture of the matrix. The term should not be confused with the mineralogists' use of 'hackly' structure.

sulphate and copper sulphate are thus as readily distinguished fractographically as they are by other means, such as by color. On the other hand, secondary cleavages and hackle-type markings can also be found in nickel sulphate which follow an irregular course and display a pattern somewhat like that of copper sulphate.

In Fig. 5 (a), one should note the several clear instances of stepwise rectilinear markings that comprise a composite which at lesser magnification might be mistaken for a marking on another plane family. This carries some significance for remarks soon to follow on the micellar theory for the solid state.

For a similar reason, the fanlike markings in Fig. 5 (a) may have considerable significance, for they suggest a lineage-type substructure. Their strong interrelationship with the pitlike markings conforms with the concept that these latter represent impurities (solid, liquid, or gas) rejected locally in the course of the growth of the lineage. The fractograph therefore reveals a history of the crystal growth (Zapffe, Landgraf & Worden, 1948b). The meandering markings are not hackle, but are traces of imperfection structure in the crystal. This opinion is confirmed by the progressions of pits which can be found in the same array in the absence of a cleavage trace passing through them.

In Fig. 5 (b) a great amount of pockmarking or pitting is in evidence; but the pitting has no particular pattern, at least viewed in this dimension, and only a few of the meandering 'lineage' markings appear. Cleavage here is restricted to one or a very few lamellar levels; whereas in Fig. 5 (a) the cleavage has followed parallel planes on a number of lamellar levels, the 'lineage markings' being profiles of these lamellae.

Attention will also be called to an interesting observation that can be made with these crystals, but which is difficult to photograph. A freshly cleaved surface, at a magnification of several hundred diameters, will often reveal some peculiar optical activities which seem to concern a precipitation of the water of hydration along cleavage surfaces a micron or so beneath the exposed facet, and apparently along the surfaces of underlying lamellae. The observation is consistent with the concept, soon to be discussed, that these crystals essentially comprise blocklike and lamellar assemblages.

#### *Potassium dichromate*

In Fig. 6 two fractographs of potassium dichromate show a combination of markings, each of which might be discussed at some length.

First, there are the irregular traces, which may or may not be expressions of local rupturing stresses. A considerable difficulty would be involved in explaining all markings of both fractographs on the basis of hackle structure; and the authors believe instead that many of the markings relate to an imperfection structure which provides a pattern of weakness subsequently followed by, or strongly influencing, the cleavage. However, the structure, at least in Fig. 6 (a), is remarkably complex.

Secondly, there are regular markings, sharply defined in Fig. 6 (b) as planar boundaries which either stop or deflect the wandering traces, and in Fig. 6 (a) as triangular markings suggesting the crystal symmetry of this material (monoclinic or triclinic).

In Fig. 7 a fractograph of this same material definitely introduces the question whether a fundamental crystal substructure exists having the nature of a 'block', or 'lamella', or 'mosaic' unit. One will observe that the principal marking here is not so much a hackle as it is a profile of lamellae whose uniformity of thickness becomes apparent as the cleavage progresses toward the top of the field and off to the left on to the adjoining face which recedes from focus. This indication of a composite structure is almost universally observed on cleavage facets. Virtually all materials seem to deform and cleave in a manner which involves a substructural unit of such periodicity that it strongly suggests the concept of 'periodic structure' proposed by Zwicky (1929), and earlier defined by Darwin (1914a, b) on the basis of X-ray evidence as a 'mosaic structure'. There are other interesting markings in Fig. 7, parallel to the principal cleavage edge and to each side of it; and a band coming from the left and intersecting the cleavage edge near its center contains detail which is reversed in direction and is somewhat suggestive of the twinning activity in bismuth.

#### *Sodium chloride*

Much more striking as demonstrations of a fundamental substructural unit existing within the crystal are the fractographic patterns found in sodium chloride crystals. In Fig. 8 the principal markings appearing in both fractographs are rectilinear, in keeping with the cubic symmetry of sodium chloride; and where irregular markings appear, they often plainly display a stepwise composite of small-scale cubic directions. The lamellae indicate everywhere a generally constant thickness; and that dimension seems also to be that of the minimum observable block size. Hackle structure is virtually absent. This is consistent with the remark earlier made regarding pattern type and crystal symmetry; and it indicates that with the non-metallic crystals as with metallic crystals there are two principal pattern types: (I) patterns expressing intrinsic crystal weaknesses and imperfections, and (II) patterns expressing local resolutions of stress. Copper sulphate, shown in the previous Fig. 4, illustrates Type II; sodium chloride, Type I. Potassium dichromate (Figs. 6, 7) seems to combine both types.

As for the visibly mosaic constitution of rocksalt, this is no new issue. Gross (1924) used other optical means to reveal lattice disturbances along the slip planes in sodium chloride, as did Obreimow & Shubnikov (1927). Gyulai & Hartly (1928) demonstrated that salt crystals under pressure respond to deformation in sudden increments, and that the electrical conductivity similarly changes discontinuously, consistent with a concept of a physically subdivided crystal.

Stepanov (1940, 1947) used crossed nicols also to show the role of mosaic imperfections in the deformation of rocksalt. Joffé (1928) granulated sodium chloride with electrical fields less than 1 % of the theoretical bonding energy; and in 1934 he increased the tensile strength of rocksalt twentyfold by testing crystals during immersion in hot water (Joffé, 1934), apparently thereby altering the condition of a micro-crack structure, the reality of which can be readily granted on viewing the fractographs in Fig. 8.

Pohl (1937) and Hilsch & Pohl (1938) treated sodium chloride in sodium vapor and showed with the ultra-microscope that the sodium aggregates throughout a mosaic structure—an eminently logical observation in view of the structures revealed in Fig. 8.

As for the matter of '*F*-centers' and coloration of irradiated sodium chloride crystals, Smekal (1928 *a, b, c*) made a strong argument for this phenomenon in favor of a subdivided crystal structure. Seitz (1946) does not seem to require a mosaic structure to account for the phenomenon; but such a structure is certainly consistent with the observations, and readily explains them. Fractographs like those in Fig. 8 disclose a substructure which would necessarily result in '*F*-center' phenomena. Further arguments neglecting the fact of this structure would therefore seem to be in error.

These remarks on Fig. 8 are lengthened because it is the authors' belief that one of the outstanding contributions of the fractographic technique is its direct display of intracrystalline imperfection when and where it exists. A distinction between 'real' and 'ideal' crystals is generally admitted to-day by all students of the solid state; but the nature of the distinction is not yet agreed upon. Here we are probably observing imperfection phenomena directly.

Recently this laboratory released a new theory for the constitution of matter in general, and the solid state in particular (Zapffe, 1949 *a, b*) based largely on these observations. While the details of the theory must be sought in the original paper, it will suffice here to describe it essentially as an *isocolloidal* concept in which the liquid state comprises a mass of free-moving *micelles* which orient and 'gel' at the solidification temperature. The individual micelle essentially preserves its identity in the solid state to provide the unit structure variously named the 'block', 'mosaic unit', and so forth by previous writers; and the intermicellar boundaries provide the zones heretofore variously referred to as 'imperfections', 'microcracks', 'rifts', and so forth. This isocolloidal concept is not unlike the one originally proposed by von Weimarn (1907), later by Alexander (1922 *a, b, c, d*), and recently by Klyatchko (1936). It provides a universal presence of imperfection which theories such as Smekal's lack; and it offers a possibility of thermodynamic verification, which has been the specific failure of other theories of 'periodic' structure.

However, these matters will not be pursued further here. They are introduced to emphasize that—in the authors' opinion after some years of research with

fractography—a principal importance of the technique lies in the direct observations it provides of intracrystalline imperfection through the imposition of the imperfection weaknesses upon the cleavage traverse. A careful study of cleavage facets may therefore reveal the true nature of the much-argued 'mosaic' nature of crystals, as indeed the writers believe it has.

Returning now to fractographs of sodium chloride crystals, one can picture with some advantage the crystals in Fig. 8 as massive composites of micellar units arranged in a lamellar array relating to the original crystal growth. Similar strong lamellar features are frequently observed in all crystal studies; and they logically follow from a conventional layerlike growth process much as described by Stranski (1930), Straumanis (1931 *a, b*, 1932) and others, except that the depositing unit or *Baustein* is the micelle.

Clearly, the patterns in Fig. 8, which are readily and characteristically found in sodium chloride crystals, represent cleavage which has progressed at an angle to the primary cleavage plane, rather than following a single one. The result is the stepwise projection of lamellar profiles, each lamella representing a potential individual (001) cleavage surface. This is an important point, because it reaffirms the conclusion drawn for metals (Zapffe, 1946 *b*) that both plastic and clastic movements, also solid-state chemical phenomena in general, have their nucleation predetermined in position by these pre-existent inhomogeneities. Thus, slip is known never to occur at spacings less than those here designated as micellar diameters; and the same is probably similarly true for cleavage and for precipitations in the solid state.

In Fig. 9 two further patterns are shown for sodium chloride. The fractograph in Fig. 9 (*a*) is virtually free of sharp lamellar profiles. It represents instead an (001) separation along one or a very few lamellae. The figure is therefore essentially a section cutting into the plane of the fractograph in Fig. 8 (*a*) and revealing the surfacial texture, rather than the profile, of a lamella. The branching pattern and certain of the slight modulations therefore may refer to lineage-type and other inhomogeneities which taken together measure the departure of the system from perfected equilibrium.

In Fig. 9 (*b*) a less common pattern is found which shows a change of cleavage type at a boundary not clearly understood. Experience with similar effects in molybdenum (Zapffe, Landgraf & Worden, 1948 *c*), tungsten (Zapffe & Landgraf, 1948 *b*) and antimony (Zapffe & Landgraf, 1948 *a*), however, might suggest that the pattern to the left represents an interlineage separation. Egli reports that this crystal, grown from a seed, proceeded to develop with a high order of perfection for about  $\frac{1}{16}$  in. and then degenerated into lineage growth. In Fig. 10, more certain evidence appears for such a substructure. Since this specimen was a single crystal, the heavy markings dividing the field into four sections are very likely the boundaries of lineages.



*Iodine*

In Fig. 11 the surface of a crystal of resublimed iodine is shown. The marked lamellar structures strongly resemble those just presented, and many of other crystals, metallic and non-metallic alike. This conforms with the micellar concept of crystal growth, which applies equally to crystal growth from the gas phase (Zapffe, 1949a).

**Conclusion**

From the foregoing study, the following conclusions may be tentatively drawn:

(1) Fractography as a microscope technique is directly applicable to non-metallic chemical crystals as well as to metals.

(2) Oblique illumination usually provides sufficient clarification of surficial features even for transparent crystals, although techniques with polarized light, dark-field illumination, sensitive-tint, and color photography may be developed with further advantage.

(3) As with metals, non-metallic crystals provide a great latitude of patterns, with individual pattern types containing distinctive features by which the material and certain factors in its history can be identified.

(4) As with metals, two principal classes of fracture pattern seem to obtain: (I) patterns intrinsic to the crystal, and (II) patterns intrinsic to the system of stresses producing cleavage.

(5) 'Hackle' structure is the Type II pattern, and it predominates in crystals of low symmetry and in amorphous bodies, probably because the lack of marked directionality in such matrices allows the stress pattern to express itself without significant deviations.

(6) Type I patterns, as opposed to Type II 'hackle', predominate in crystals of high symmetry and well-developed directionality, often to suppress completely the hackle evidences of stress resolutions.

(7) Type I patterns constitute the most important contribution of fractography, for they disclose (a) the general architecture by which the particular crystal can usually be readily distinguished, and (b) the imperfection structure, which is a problem of increasing importance in studies of the solid state.

(8) Type I patterns for chemical crystals contain much direct evidence for 'mosaic' and 'lamellar' constitution, in keeping with the micellar theory recently announced by this laboratory.

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