PART II.

THE SCIENCE OF POLISHING.[1]

By F. Osmond and A. Cartaud.

Polishing is one of the earliest arts of humanity. Its introduction serves to differentiate the two phases of the Stone Age, the palæolithic and the neolithic. As polishing could scarcely have rendered the early stone implements more useful, we are forced to conclude that its object was to render them more beautiful. From the time of Homer to the present day, poets and prose writers have alike extolled the brilliancy of arms, which rivals that of jewels; and modern methods of polishing adapted to modern machinery are but the improved methods handed down to us by these mediæval craftsmen, the armourers, goldsmiths, and jewellers, still imbued with some of that mystic empiricism which attaches to all those arts not based upon scientific considerations.

The literature of polishing is meagre, and the scientific aspects of the subject have been neglected. To this statement exceptions must be made in favour of Herschel and Foucault, whose labours included the perfection of methods for the polishing of the mirrors and lenses incidental to the application of the astronomical science to which they devoted themselves. More recently, Lord Rayleigh[1] in 1901 wrote a paper on the molecular physics involved in polishing.

It was reserved for metallurgy, which necessitates the production of highly polished surfaces capable of undergoing high microscopic enlargements, to focus attention on the art of polishing. Sorby, in his earlier researches, was at pains personally to polish his sections, and his results were undoubtedly largely due to the manual dexterity and conscientious technology which he brought to bear in the preparation of his specimens.

In the course of many years' practice, the authors have amassed a number of observations which convince them that the art of polishing involves many difficult problems belonging to chemistry, crystallography, mechanics, and molecular physics, and in view of the recent investigations of Beilby,[2] the following considerations deduced from scattered observations and discussed as they arise in the process of polishing, but dealt with in that aspect alone, may be regarded as of interest.

GRINDING.

A section is made by means of a saw, a file, the grindstone, or by any other suitable implement according to the nature of the material. It is then passed backwards and forwards over emery-paper of gradually increasing fineness, and lastly, if the ordinary commercial papers do not suffice, other papers purposely prepared from carefully washed and classified

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[1] Translated from the *Revue Générale des Sciences pures et appliquées*, vol. xvi. (January 30, 1905).

[1] *Proceedings of the Royal Institution*, xvi. p. 563.

[2] *Proc. Roy. Soc.*, vol. lxxii. pp. 218–234.

powders may be used. Care is taken to make sure that the scratches made during any one operation are eliminated by the next.

Every tooth of the file and every grain of emery leaves a scratch upon the surface. The mean effect is the sum of a great number of individual scratches, and since all these scratches are practically identical, it is only necessary to examine one. This involves that branch of mineralogy known as "sclerometry," or the measurement of hardness. The word "hardness" is used here in a narrow and conventional sense, because this property is, as a matter of fact, the resistance to permanent deformation, no matter how it may be produced.[1] Every scratch causes the abrasion of a certain quantity of matter. This is the result sought for, but it is not the only effect produced. Under the pressure of the scratching point the material is modified to a certain depth, and this modification is the most obscure and also the most interesting aspect of the question.

PENETRATION.

When, under normal conditions, a needle A (fig. 45) is applied to the horizontal surface BC of a body BCB′C′ of equal or inferior hardness, there is a tendency for the needle to penetrate the body.

This method of deformation has been studied theoretically by Hertz, and experimentally by Auerbach, and suggested to Brinell[2] a practical method of testing, the needle being replaced by a hardened steel ball.

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[1] Report to Section A, *International Testing Association*, Dec. 1892.
[2] *International Testing Association*, 1900, No. ii. pp. 83–94.

Suppose, for simplicity, that the body BCB′C′ is amorphous and brittle. Take, for example, glass, the limit of elasticity of which coincides with the breaking stress. It is well known that, under sufficient pressure, there is produced at first in the plane BC a circular fissure *mm*, concentric to the point. Under increasing pressures this fissure spreads throughout the mass, detaching from it a solid spheroid in the direction *mn*, which Professor Auerbach describes as a cone.

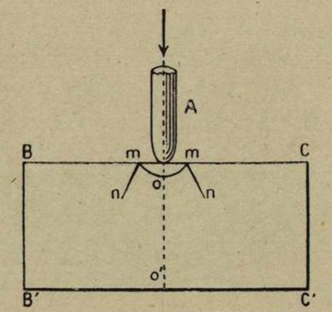

Fig. 45.—Deformation of a solid BCB′C′ by a needle A, at right angles. *mm*, the circular fissure; *mn*, cone of deformation.

Experiments made with the kind assistance of Mr Frémont have given a paraboloid rather than a cone.

This kind of fracture may be explained, as the authors have suggested in a hypothesis which certainly possesses the advantage that it confirms the observed facts. If, as seems reasonable, the transmission of the stresses is undulatory, the interference zones of the waves will be the loci of maximum deformation, and finally of fracture. In the case under consideration the needle point produces spherical waves and the face B′C′ of the solid BCB′C′ plane wave which are reflected against BC. These interference zones form two conjugate systems of paraboloids, of which fig. 46 shows a section through the common axis, the portion above BC alone being the actual axis.

The paraboloid obtained experimentally would be one of the possible paraboloids, such as *mn*. Auerbach's conical form is explained also by the same hypothesis, if to the waves which interfere different velocities are attributed. Whatever may be the case, if in the cracked solid a section *mn* is made through a plane parallel to BC, the circular crack, if not immediately visible on the polished surface, is easily brought out by etching with hydrofluoric acid.

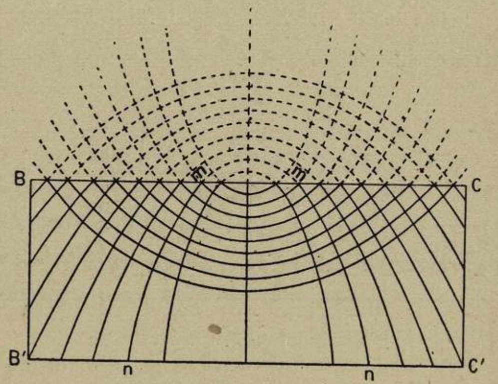

Fig. 46.—Conjugated paraboloids produced by the deformation shown in fig. 45.

The paraboloid of the system *mn* is that which first shows itself, but if sufficient force is applied a splinter such as *mon* may be detached, which would represent a paraboloid of the conjugate system (fig. 45).

These surfaces of fracture are not the only ones possible. The needle A applied along the plane BC (fig. 45), exerts a stress along all the azimuths, and vibrations parallel to the azimuths may result. These vibrations, by interfering with the spherical waves concentric to the point of the style, give rise to an infinite number of conjugate systems of paraboloids with horizontal axes. Indeed, the number of systems that can be recorded is limited, and if each of these be represented by the paraboloid of the corresponding type, we obtain, in the plane BC, fig. 47; which is the figure given by deformable metal on die-stamping. Mr Hartmann described as logarithmic spirals the curves which the authors regarded as parabolas. Although these descriptions appear totally different, the facts are equally in accord with both hypotheses, because the curves are not inscribed round the needle point in that area where their outlines would be truly characteristic.

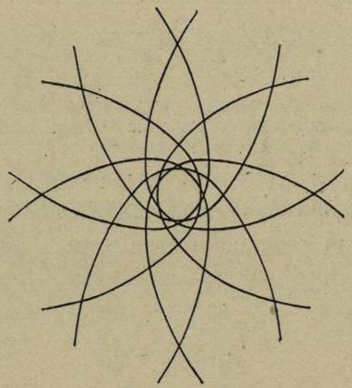

Fig. 47.—Figure formed on punching deformable metals.

Amongst the paraboloids of fig. 46, the axis of which is that of the needle point, fracture on penetration only shows once, when there is no internal pressure, and the experiments are conducted under perfectly symmetrical conditions. Generally speaking, a fracture such as that indicated by the broken line *mnopq* of fig. 48, and belonging to several paraboloids of the same system, would result.

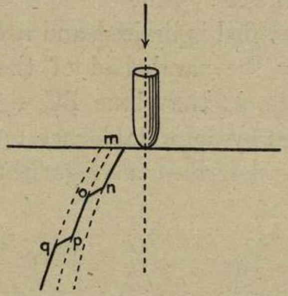

Fig. 48.—Line of rupture generated by several paraboloids of the same system, generated in a solid by the action of a point.

These considerations may throw some light on what are known as conchoidal fractures. Such a fracture is obtained by replacing the needle of fig. 45 by the edge of an axe. The surface of the fracture plane, as a whole, shows two systems of orthogonal lines (fig. 49), the profiles of which have been studied by Professor Martens. Some, which are semi-elliptical or semicircular, have the impact point as their centre; in section they show as a series of undulations becoming less and less marked as they extend further from the centre (fig. 50). Others, perpendicular to the former, have an angular outline, unequally canted and inclined towards the surface of the fracture, and frequently bifurcated (fig. 51). The semi-elliptical, or semi-circular, waves may be regarded as belonging to the consecutive phase of two conjugate systems of paraboloids with horizontal axes, and curved junctures. As regards the radiating lines with angular outlines, it is difficult to connect them with the fractured surface already described. They would seem to be secondary surfaces generated by the principal fracture following the direction of the conchoids.

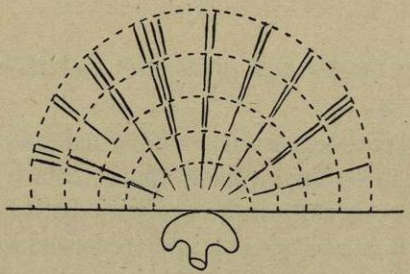

Fig. 49.—Lines of rupture obtained by the action of an axe.

Fig. 50.—Outline of the concentric lines of rupture shown in fig. 49.

Fig. 51.—Outline of radiating lines of rupture shown in fig. 49.

SCRATCHES.

1. **Brittle Amorphous Bodies.**—When, instead of simply applying the needle A to the surface BC (fig. 45), it is drawn along so as to produce a scratch, the scratch may be regarded as an integral of a series of infinitely connected penetrations, and the resulting deformation as the sheath of these penetrational deformations. The sheath of the paraboloids, such as *mn*, is a cylinder of parabolic section, and amongst possible cylinders is plane *oo* passing from the outside

through the scratch and normal to the scratched surface. This is the plane which it is sought to produce when glass is cut with a diamond. If, however, one is not a practised glazier one of the parabolic cylinders *mn* is usually produced. This is shown in fig. 52 (250 diams.); the dark band distinctly outlined on one side and shaded on the other forms an oblique fissure *mn* which reflects light beyond the objective. This is also the case in fig. 53

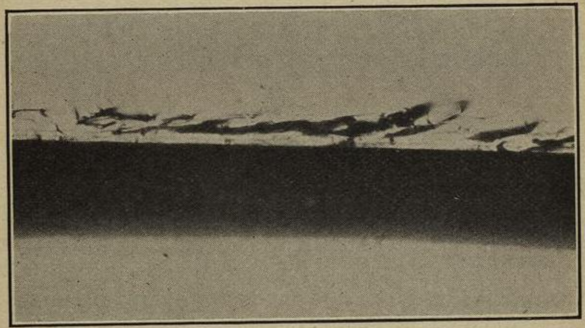

Fig. 52.—Scratch made in glass. ×250.

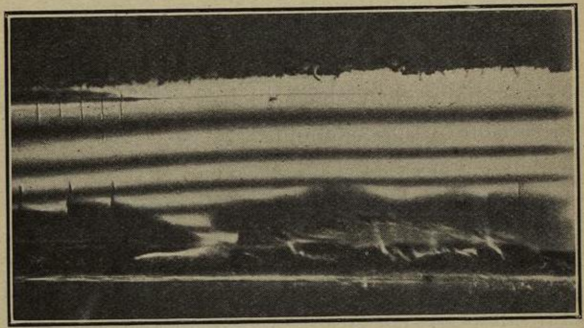

Fig. 53.—Glass cut by diamond scratch and cracked. ×125.

(plate glass scratched with a diamond, 125 diams.): here, however, a layer of air imprisoned in the crack gives rise to coloured bands parallel to the scratch, which are revealed in the photograph as light and dark bands alternately.

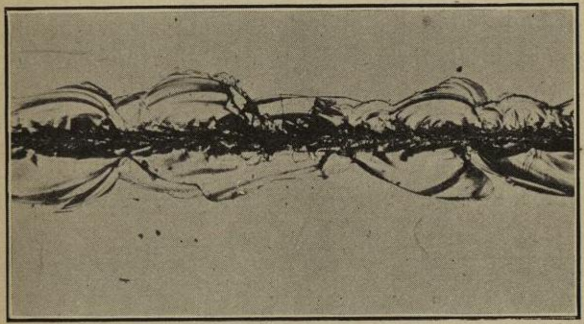

Fig. 54.—Series of abrasive scratches in glass. ×35.

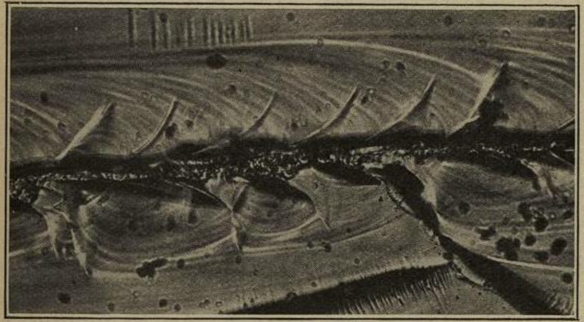

Fig. 55.—Detail of abrasive scratches shown in fig. 54. ×150.

Every application of a tangential force tends to produce a vibratory movement. In the case of glass, for example, the point, if it penetrates, detaches a splinter, disengages itself, detaches another, and so on (fig. 54, 35 diams.). Fig. 55 is the detail of the foregoing magnified 150 diameters. Against the axis, to right and left, will be noticed conchoidal splinters, separated by oblique pressure, which, later on, assume the sheathlike forms; the system of conchoids with smooth outlines becomes parallel to the scratches, and the lines in jagged outlines, curved and oblique in the direction of the axis, are transformed into fine channels at right angles to that axis. At the same time there is produced a periodical series of strings of transverse cracks of the type of the paraboloid in fig. 45. These paraboloids, however, are incomplete, and only develop in the opposite direction to the scratch. They may be accentuated by etching the surface with hydrofluoric acid. Fig. 56 (135 diams.) thus shows, after etching, a scratch on glass produced by a sewing needle. This scratch is formed by two narrow finely canalised layers, which correspond to the lines *mn* of fig. 45, and which, at intervals which would be regular on a scratch more artistically

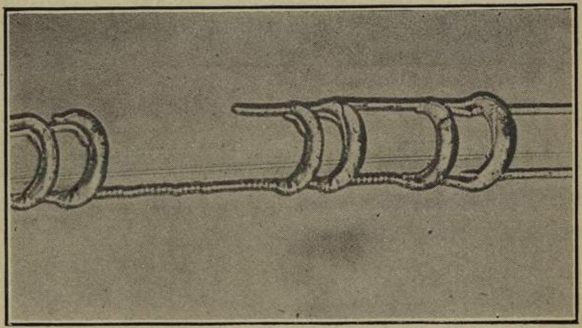

Fig. 56.—Needle scratch on glass, etched with hydrofluoric acid. × 135.

made, form thicker semicircles, the starting-points of incomplete paraboloids. In a glass, the polish of which is apparently perfect but actually imperfect, etching with hydrofluoric acid gives the appearance shown in fig. 57 (35 diams.); each scratch, imperfectly removed, is represented by a series of equidistant hatchings which, previous to etching, are almost invisible.

By fixing horizontally over a glass plate covered with a thin layer of red lead, an arrangement from which a stream of water flowed, Decharme obtained analogous figures. The height of the pipe above the plate must, of course, permit the stream of water to fall in drops. It can be shown more simply still by merely rubbing the moistened finger against the surface, the red lead recording in a permanent manner the vibrations. The phenomena can also be produced with a thin covering of pure water, but, naturally, they do not last.

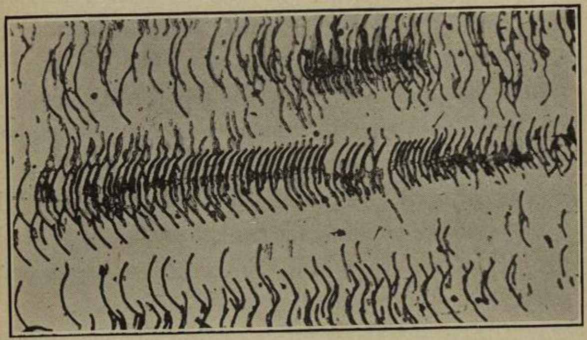

Fig. 57.—Needle scratch on insufficiently polished glass, etched with hydrofluoric acid. × 35.

When the scratch produced on glass by a diamond is limited to the torn parts shown in fig. 54, the glass is not cut through, and, inversely, the glass could be cut through without visible scratch through the plane *oo* or through the cylinder *mn* of fig. 45. Generally speaking, the scratch is both intermittent, with conchoidal rents at the surface, and continuous rents vertically through the glass.

According to Venham, the intermittent character of the scratch can be revealed in the glass by polarised light, even when the passage of the point has only produced an apparently elastic deformation. We have, however, only been able to show this by this process in the presence of a visible scratch, and by submitting the piece of glass to an even pressure between two opposed surfaces.

The appearance, or at least the completeness of the vibratory treatment, depends on the inclination of the needle. If it makes a sufficiently acute angle with the direction of motion, the needle penetrates and is easily withdrawn; the scratch tends to be continuous or appears as such. In proportion as the needle is applied more perpendicularly, penetration is facilitated, the point meets with increasing resistance, detaches a splinter, and so on. The moment the needle commences to grip is distinctly noticeable.

The phenomena connected with the scratching and cutting of glass are not new to science. Since the first half of last century it has occupied the attention of great physicists like Brewster, Attwood, and Wollaston. The trifling contributions we ourselves have made concerning it are not as original as we had at first believed. The rough draft of this section was already written when we learned of a very interesting paper by M. W. Prinz, the title of which—

"Can the results of geological experiments be applied to natural phenomena?"—does not appear particularly related to our subject. We recommend the memoir, however, to all who are interested in mechanical deformation, because of its wide scope, and because it contains many of the results we had obtained independently, before we knew of the previous work.

2. **Plastic Amorphous Bodies.**—Fig. 58 shows the scratch made by a sewing needle on a film of moist gelatine deposited on glass (115 diams.). On the axis of the scratch there will be observed a series of small equidistant channels nearly parallel to the axis.

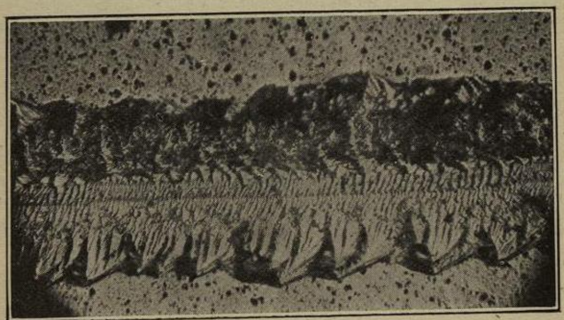

Fig. 58.—Needle scratch on moist gelatine film on glass. × 115.

Rubber, by reason of its great elastic deformability, presents somewhat peculiar properties. We have obtained films upon glass by the evaporation of a commercial solution used in the repair of pneumatic tires. In fig. 59 (250 diams.), owing either to the angle of the needle or the thickness of the film, the latter has not been cut; the material has been scored out into arrows, the points of which run in the direction of the scratch. In fig. 60 (20 diams.) the film is cut through intermittently; the rubber-like film collects in heaps at the arrow points, the needle skips over the swelling to make another cut, and so on. The incisions may be accompanied by an equally intermittent detachment of the film.

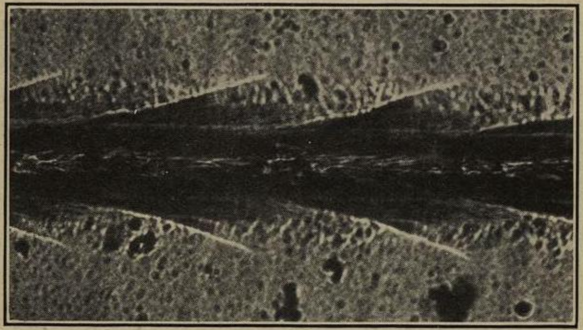

Fig. 59.—Scratch made by needle held obliquely on film of indiarubber deposited from solution on glass. ×250. Film remaining uncut.

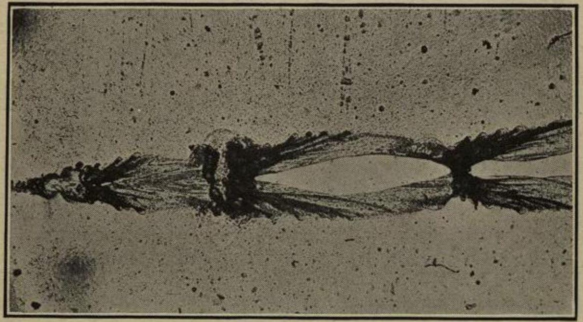

Fig. 60.—Needle scratch (needle not held as obliquely as in fig. 59) on indiarubber film (film cut). ×20.

3. **Brittle Crystalline Bodies.**—The deformations we have just been describing, and which we have met with in amorphous bodies, depend only on general mechanical laws, and for that reason may be called common deformations. They tend to be similarly reproduced in crystalline bodies, because mechanical laws are independent of the structure of bodies. As, however, crystallised bodies have a specific structure, they may also undergo correspondingly specific deformation, that is to say, as functions of their structure. In each particular case the deformations appearing are, naturally, those which are the most easily produced.

Crystalline deformations may be grouped under four principal heads, viz.:—

1. Cleavages.
2. "Networks," in the ordinary sense of the word.
3. Deformations parallel to certain crystallographic planes, considered as simple transitions both by Mugge, who calls them "transition networks," and by Ewing and Rosenhain, who described them as "slip-bands," that is to say, "surfaces of slip." On the other hand, Beilby thinks, not we believe without good grounds, that the sliding is accompanied by at least a partial destruction of the crystallographical network, and by a true allotropic transformation into an amorphous variety.
4. Beilby recognises, in addition, two forms of transition, which he designates by the symbols "M" in the transition from the crystallised state to the amorphous, and "M′" in the reverse transition. Whatever

> they may be, the crystalline deformations have a tendency to assume the same periodic appearance as the common deformations.

Fig. 61 (125 diams.) represents a vibratory scratch by a sewing needle on antimony cut along any one crystallographic face. The crystalline structure has not intervened: the scratch is a "common" one. But, as the brittleness of antimony is less than that of glass, there is no separation of conchoidal splinters.

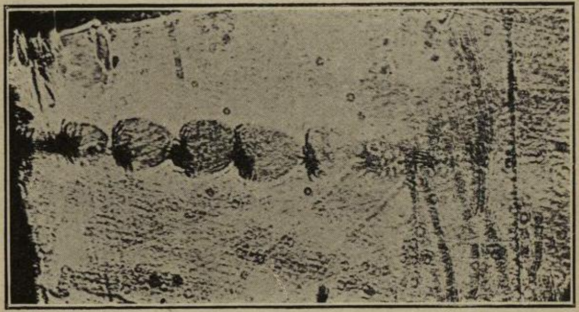

Fig. 61.—Needle scratch on facet of Antimony Crystal. × 125.

By penetration, successive cavities are formed, with a piling-up of the material behind the needle. A scratch made with the needle in a more inclined position is apparently continuous but finely striated along the axis, like that of gelatine. Mugge has also described, with regard to antimony, deformational networks which could be represented by oblique lines placed on either side of the scratch (fig. 62, 400 diams.).

Deformations in calcite are first and foremost specific. They have been studied by Cesaro and by Paul Jannettaz, who have been able to explain, by a microscopical investigation of these deformations, the variations in hardness so long observed in different directions on the same surface, and according to the direction of the scratch in the same line. We shall here content ourselves by giving a single example (fig. 63, 75 diams.) taken from the work of Jannettaz. This is a scratch made by a sewing needle on a polished cleavage plane

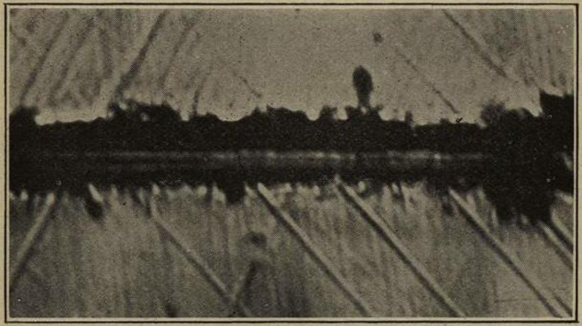

Fig. 62.—Needle scratch on Antimony. × 400.

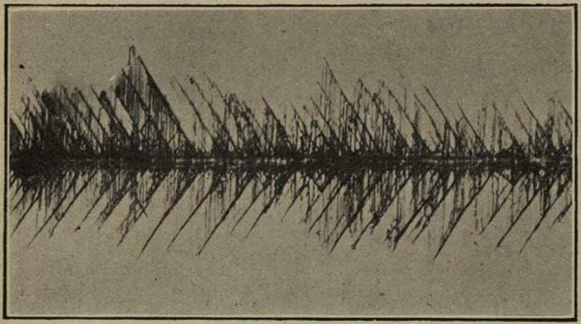

Fig. 63.—Needle scratch on polished cleavage surface of Calcite. × 75.

parallel to the smaller diagonal of a rhombus starting from the angle *e* to angle *a*. The scratch causes a series of triangular figures to appear, of which two sides are parallel to the cleavages, and the third, parallel to the greater diagonal, corresponding, according to Cesaro, to the outcrops of small reticulated lamellæ related to *b*.[1] Upon the scratch itself small channels may be noticed similar to those of gelatine, and of which it would be impossible to discern the exact nature, seeing that a specific deformation is here possible in a position normal to that of a "common" deformation.

4. **Plastic Crystalline Bodies.**—As has already been pointed out by Martens, the influence of the angle of the scratching needle and of the weight supported by it is very marked in these instances. If the needle makes a small angle with the direction of the scratch, or if it be only loaded by a small weight, a continuous furrow is traced: at least, so far as appearance goes, there is penetration only. The material which occupied the place of the furrow is piled up right and left and becomes covered with oblique folds, the nature of which is probably of the "common" type. As an example, the scratch made upon a crystal of iron by a sewing needle on any crystalline face (fig. 64, 1200 diams.) may be cited.

If the needle be sufficiently upright and loaded, it only frees itself by carrying away filaments: the scratch becomes distinctly intermittent, and the case is one of planing, a subject studied, but certainly not exhausted, by Tresca, and, more recently, by Thime, Haussner, and Codron. The shavings, even when continuous at first sight, are always made up of

broken pieces of various lengths, and the material remaining is broken up in the neighbourhood of the furrow.

We also find the periodic "common" deformations obtained on scratched glass, and shown in figs. 56 and 57, after etching a bronze containing 9 per cent. of tin after incomplete polishing, which has been insufficient to remove all the material acted upon by the ridges of a file or by rough emery paper (fig. 65, 125 diams.) with an alcoholic solution of picric acid and quinone. The regular striæ are located upon the axial portions of the crystallites, that is to say, on the harder portions first solidified, richer perhaps in copper. The photograph does not possess quite the desired clearness owing to the complication introduced by the structure of the alloy itself, and the necessity of showing simultaneously the structure and the deformations made by the scratches. There can be no doubt, however, that these deformations

Fig. 64.—Needle scratch on facet of a Crystallite of Iron. ×1200.

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[1] Neumann's *Crystallographic Symbols.*