# Effects of the Direction of Drawing on the Arrangement of the Micro-crystals in Aluminium Wire and on its Tensile Strength and Broken Fracture

By

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Abstract

By means of micro- and Laue-photographs the effect of the direction of drawing on the arrangement of the micro-crystals in drawn wire of aluminium was examined; and the effects on the tensile strength and on the broken fracture were also studied by an ordinary tensile testing machine and micro-photographs and radiographs.

In the exterior part of the wire drawn always in the same direction, the micro-crystals, whose crystallographic [111] axes are inclined to the direction of the drawing towards the exterior side and lie on a cone, were most predominant. In the wire drawn in reverse directions alternately, the micro-crystals were so arranged in the exterior part, that the [111] axes were inclined to the axis of the wire on both sides, interior and exterior, and the amount of their angular displacements was less than that of the one drawn always in the same direction. In both wires, the inclination of the [111] axis stated above became smaller as the core of the wire was approached, and it also became smaller with the increased reduction in diameter caused by successive drawing. The change in the arrangement of the micro-crystals was marked in the cases of 87% to 89% reductions in diameter and it diminished with further reduction, and in the wires reduced by about 94% in diameter hardly any change could be recognised in the radiographs.

The wire drawn in the same direction was more hardened and brittle than that drawn in reverse directions alternately and the tensile strength and the broken fracture differed in both cases though the difference was small in the former case.

## Introduction

Many investigators have already ascertained that the direction of the axis of the fibrous arrangement of micro-crystals in hard drawn wire is nearly parallel to the axis of the wire, and that in the facecentred lattice form its crystallographic directions are [111] and [100][1]. Some years ago, I suggested that in aluminium wire the [111] directions are not strictly parallel to the axis of the wire but lie in a cone with a small vertex angle about this axis.[2] Since then, this subject has been studied in other metals (Cu, Au, Ag, Ni) by many investigators.[3]

In the present experiment, I have examined the effect of the direction of drawing on the arrangement of the micro-crystals in aluminium wires by means of Laue-photographs, and the effects on the tensile strength and on the broken fracture of it were also studied by means of an ordinary tensile testing machine and micro-photographs and radiographs.

## Experimental Method and Results

### 1. Materials

The experiment was, in most cases, carried out with aluminium circular wires of 0.3 to 0.9 mms. in diameter, which were prepared by drawing one part of a rod of about 5 mms. in diameter, through metallic dies successively always in the same direction, and also by drawing the other part in reverse directions alternately. Previous to cutting the rod into two parts it was annealed uniformly, and the dies and the drawing speeds etc. used in preparing the two kinds of wires were exactly the same.

### 2. X-Ray Examination of the Fibrous Arrangement

At each stage of the drawing of the two kinds of aluminium wires, the Laue-photographs were taken with the whole wire or with a definite part of it, by sending a narrow and circular beam of X-rays, which started from the focus on the Mo-target of a Coolidge

1. M. Ettisch, M. Polanyi & K. Weissenberg: Zeit. f. Phys., **7**, 181 (1921), Zeit. Phys. Chem., **99**, 322 (1921).
   A. Ono: Memoirs Coll. Eng. Kyushu, **2** (1922)
   G. Sachs & E. Schiebold: Zeit. f. Metallk, **17**, 400 (1925).
2. T. Fujiwara: These Memoirs, **8**, 339 (1925).
3. E. Schmid & G. Wessermann: Zeit. f. Phys., **42**, 779 (1927).
   S. Takeyama: These Memoirs, **12**, 259 (1929).
   G. Greenwood: Zeit. f. Krist., **72**, 309 (1929).
   W. E. Remmers: Trans. A. I. M. E., p. 106 (1930).
   R. W. Drier and C. T. Eddy: Trans. A. I. M. E., p. 140 (1930).

tube, perpendicularly to the axis of the wire. The portions of the wire to be examined were prepared by removing enough of the outer layer of the wire to leave the proper thickness, by dissolving it in hydrochloric acid. The arrangement of the micro-crystals in these specimens was determined by treating their X-ray radiographs thus taken with the crystallographic globe devised by Prof. U. Yoshida, Kyoto Imperial University[1], and some effect of the direction of drawing on the fibrous arrangement of the micro-crystals in the aluminium wire could be detected. Some of the Laue-photographs thus taken are shown in Plates I and II.

## 3. Tensile Strength and Fracture of Broken Edge

The tensile strength of the aluminium wires was measured, at each stage of drawing, by the usual testing method with an ordinary tensile testing machine. The tensile strength, in Kg. per mm.,$^2$ obtained for various sizes, is tabulated in Table I, where the value of the

Table I

| Diameter of wire in mm. | | 2.17 | 1.67 | 1.28 | 1.00 | 0.79 | 0.64 | 0.60 | 0.54 | 0.43 | 0.34 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tensile strength in kg./mm.$^2$ | Same direction. | 13.8 | 17.3 | 18.3 | 22.2 | 24.4 | 28.6 | 32.8 | 32.6 | 36.7 | 39.3 |
| | Reverse direction. | 14.0 | 17.2 | 18.9 | 21.4 | 24.3 | 28.6 | 29.5 | 31.8 | 35.5 | 36.5 |

wires drawn always in the same direction and that of the wires drawn in reverse directions alternately are given in the 2nd and 3rd horizontal rows respectively.

The tensile strength of the wire drawn in the same direction was, as is seen in Table I, a little greater than that of the wire drawn in reverse directions for wires smaller than 0.6 mms. in diameter.

The fracture of the broken edge was then studied by means of micro-photographs. It was found that all of the wires drawn in reverse directions alternately were broken with the fractures shown in Fig. 8 in Plate I, and that those drawn always in the same direction were broken into two kinds of fractures as shown in Figs. 7 & 8 in Plate I, and many fractures of the kind shown in Fig. 7, Plate I, appeared

1. U. Yoshida: Japanese, J. Phys., **4**, 133 (1927); S. Takeyama: These Memoirs, **12**, 257 (1929).

in wires of 0.64–0.54 mms. in diameter. In Table II the number of broken fractures of the kind shown in Fig. 7, Plate I, at different stages of drawing, is tabulated in percentage against that of the fractures shown in Fig. 8, Plate I.

Table II

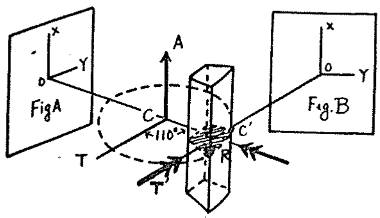
| Diameter of wire in mm. | | 1.00 | 0.79 | 0.64 | 0.60 | 0.54 | 0.43 | 0.34 |
|---|---|---|---|---|---|---|---|---|
| Number of Fractures of the kind shown in Fig. 7, Plate I, in %. | Same direction. | 0 | 0 | 85 | 80 | 70 | 65 | 40 |
| | Reverse direction. | 0 | 0 | 0 | 10 | 0 | 0 | 0 |

## Discussion of the Results

The Laue-photographs taken in the present experiment were nearly the same as those already obtained by me,[1] but those taken with wires 0.5–0.9 mms. in diameter, drawn always in the same direction through a certain numbers of dies, differed from the former ones, and the change in the X-ray radiographs taken with the wires drawn always in the same direction and in those drawn in reverse directions alternately appeared clearly, as may be seen in Figs. 1, 2, 3, 4, 5 and 6 in Plate I. Figs. 1, 3 & 5 Plate I, are the diffraction patterns obtained with wires of 0.54 mm. in diameter drawn in the same direction and Figs. 2, 4 and 6, Plate I, are those with wires of the same size drawn in reverse directions alternately. In these patterns Figs. 1 and 2, Plate I, were taken with circular wires by sending a beam of X-rays, which covered all parts of the cross section of the wire, perpendicularly to the axis of the wire; and Figs. 3, 4, 5 & 6 were taken with definite parts of the wires as shown in Fig. 1, where Fig. A corresponds to Figs. 3 and 4, Plate I and Fig. B corresponds to Figs. 5 & 6 Plate I, respectively. In Fig. 1 the plane RCT is a cross section perpendicular to the axis of the wire, the shadowed part is a portion illuminated by X-rays, RC the radial direction, CA the axis of the wire, CT the direction inclined at an angle of about 110° to the radial direction CR, C′T′ is parallel to CT and the lines provided with two arrows indicate the directions of the incident X-rays respectively.

1. T. Fujiwara: loc. cit.

Fig. 1

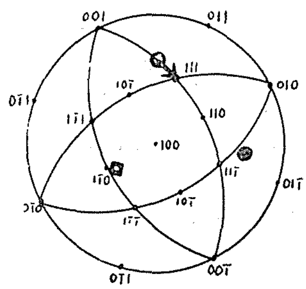



The clear difference which can be recognised between these Laue-photographs taken with two different kind of wires, is that in all the radiographs in Figs. 2, 4 & 6, Plate I taken with the wire drawn in reverse directions alternately, the bands and spots are distributed symmetrically to the lines OX and OY, but in the radiographs taken with the wires drawn in the same direction they are distributed symmetrically only to the vertical line OX, except in Fig. 5, Plate I. In Fig. 5, Plate I, the bands and spots are distributed unsymmetrically to both the lines OX and OY and the radiating band due to the atomic plane (111), which appeared in the direction OX, parallel to the axis of the wire in Fig. 6 of Plate I, which was taken with the wire drawn in the reverse way, appears in the direction making an angle of about 20° to OX. The change in the diffraction patterns stated above was marked in wires, 0.54 mm. in diameter, reduced 89% in diameter, and with further reduction in diameter by further drawing it diminished and in wires thinner than 0.30 mm. in diameter the change could hardly be recognised in the radiographs.

In the wires of the same size the change mentioned above was marked in the exterior layer and was hardly recognised in the interior layer, as is shown in Figs. 1, 2, 3 and 4 in Plate II. Figs. 1 & 2, Plate II are the diffraction patterns taken with wires 0.64 mm. in diameter. The radiographs shown in Figs. 3 and 4 in Plate II were taken with the same wire, etched to a diameter of 0.25 mm.

From Figs. 1, 3 and 5, Plate I, taken with a definite portion of the wire, it was found that in the exterior part of the wire drawn always in the same direction the micro-crystals, whose crystallographic [111] axes are inclined to the direction of the drawing towards one side as shown in Fig. 2 in stereographic projection, are most predominant. In Fig. 2, where an extreme orientation of the crystal is represented, the points marked ○, ● and □ respectively indicate the direction of the drawing, the radial direction and the direction of the beam of incident X-rays, and the arrow shows the direction of the angular displacement of the crystallographic [111] axis from the axis of the wire. In the case of the wire drawn in reverse directions alternately, the micro-crystals are so arranged in the exterior part that the [111] axes are inclined to the axis of the wire on both sides and the amount of their angular displacements is less than that of the wire drawn in the same way.

Fig. 2




It was also found that the inclination of the [111] axis became smaller as the core of the wire was approached and in the core of both wires, 0.64 mm. in diameter, prepared by two different kinds of drawings, a double structure was found though the number of micro-crystals arranged with the [100] direction parallel to the fibre axis was small. One of the typical Laue-photographs is shown in Fig. 5, Plate II, which was taken with the same wire as that which gave rise to Fig. 1, Plate II, after it had been etched to a diameter of 0.13 mm. The inclination of the [111] axis became smaller with the increased reduction in diameter caused by successive drawings; and in hard-drawn wire, 0.11 mm. in diameter, the structure was one in which the [111]-direction was nearly parallel to the fibre axis or the direction of drawing. Fig. 6 in Plate II, is a Laue-photograph taken with wire of 0.11 mm. in diameter, drawn always in the same direction.

Now in a circular drawn wire, as has already been suggested, the preferred orientation of the micro-crystals seems to change gradually from the surface of the wire to its core; therefore the [111] axis mentioned above is arranged in a conical manner and the vertex angle of the cone is larger in the exterior layer than in the interior, as is represented diagrammatically in Figs. 3 and 4. Figs. 3 and 4 represent the arrangements of the trigonal axis in the outer layer of the wire drawn in the same direction and in reverse directions respectively, and in these diagrams the lines provided with two arrows indicate the direction of drawing and the lines provided with one arrow the [111] axis. But strictly speaking the [111] axis slightly deviated from the generating line of the cone mentioned above as is shown in Fig. 3, where the dotted lines indicate the deviated position of the [111] axis.

When such a wire, in which the micro-crystals are arranged as shown in Figs. 3 and 4, is illuminated by X-rays, then the spots and bands appearing on the photograph in a certain direction will be mostly caused by the atomic planes of the crystals situated at a

Fig 3.

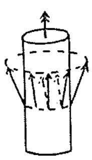
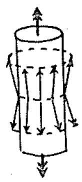


Fig. 4



definite position in reference to the direction of the incident X-rays; and thus the diffraction patterns due to the atomic (111) planes will become as shown in Figs. 5, 6 & 7. These are the typical figures calculated from the above considerations, Figs. 5 & 6 being the case of the wire drawn always in the same direction, and Fig. 7 that of the wire drawn in reverse directions alternately. In these diagrams the shadowed parts indicate the part of the cross section of the wire which is illuminated by the X-rays, and the curved lines *a*, *b*, *c* and *d* indicate the positions of the diffraction spots caused by the atomic (111) planes of the crystals situated at the positions, A, B, C and D respectively. The lines provided with two arrows and one arrow indicate respectively the direction of the illuminating X-rays and the direction of drawing. The correctness of the considerations above stated will be seen from the agreement of the diagrams thus calculated with the Laue-photographs actually taken. Fig. 7, Plate II, corresponds to the calculated diagram shown in Fig. 5; Fig. 1, Plate I and Fig. 1 Plate II to Fig. 6 and Fig. 2, Plate I, and Figs. 2 & 8, Plate II, to Fig. 7. A fine structure of the lines *a*, *b*, *c* and *d* in the calculated diagrams is seen clearly in these Laue-photographs.

It is well known that when a crystal aggregate in a wire is subjected to a drawing process each grain which has a certain preferred orientation is deformed by two different kinds of forces, extension in the direction nearly parallel to the direction of drawing and compression parallel to the radial direction of the wire. This deformation is usually considered to take place by slipping on certain appropriate atomic planes, causing the micro-crystals to take a definite orientation with respect to the direction of force. Though the exact mechanism of the deformation of the crystals in the wire produced by drawing is not yet clear, but the foregoing orientation of the micro-crystals in a drawn wire of aluminium seems to be explainable, at least to some extent, by a combination of the results already obtained by others in the cases of extension[1] and compression.[2]

1. G. I. Taylor and G. F. Flam: Proc. Roy. Soc., **102**, 643 (1923).
   K. Fujii: These Memoirs, **13**, 101 (1930).
2. S. Tsuboi: These Memoirs, **11**, 375 (1928).
   Y. Fukami: These Memoirs, **12**, 261 (1929).

It has already been stated that some differences in the tensile strength and the broken fracture could be detected with two kinds of the wires prepared by drawing in different manners. Some differences between the two kinds of the wires can also be observed in the breaking marks caused on the surface of the wires by bending, as is shown by the micro-photographs reproduced in Figs. 9 and 10 of Plate II. Fig. 9 corresponds to the wire drawn in the same direction, and Fig. 10 to the wire drawn in reverse directions alternately. The

Fig. 5

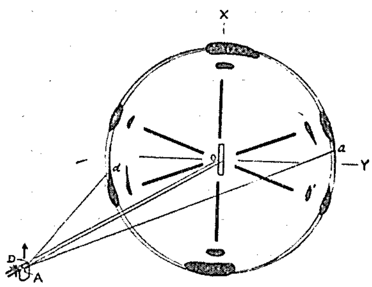


Fig. 6

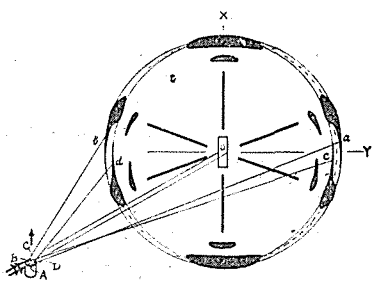
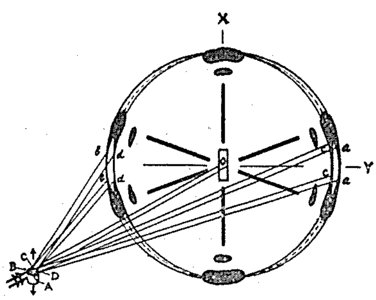


Fig. 7



diameter of the wire is 0.54 mm. in both cases. It seems to be possible to say clearly now, from the present investigation, that the differences in the properties of the two kinds of the wires as above stated are due, though not wholly, to the difference in the arrangement of the micro-crystals in the two kinds of the wires, as was stated before.

In conclusion, I wish to express my sincere thanks to Prof. U. Yoshida, of the Kyoto Imperial University for the interest he has taken in this research.

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## Plate I

(The arrow indicates the direction of drawing)

Fig. 1

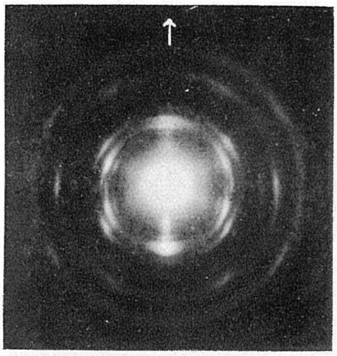


Fig. 3

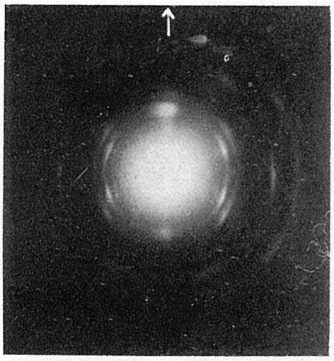


Fig. 5

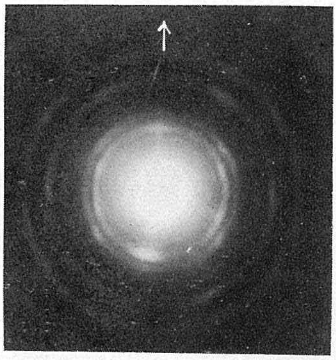


Fig. 2

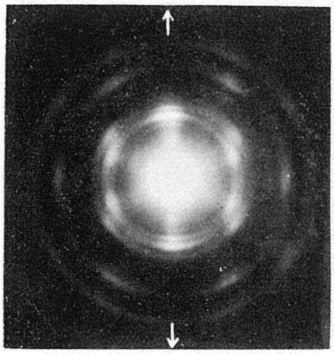


Fig. 4

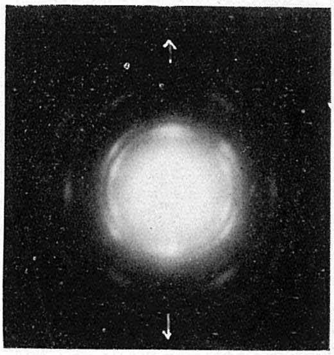


Fig. 6

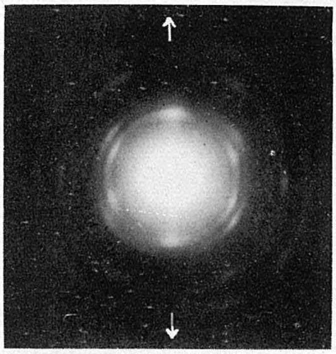


Fig. 7

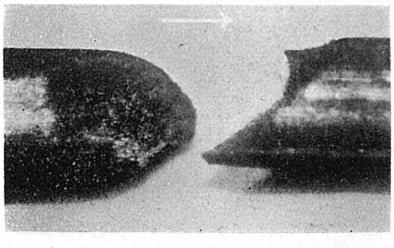
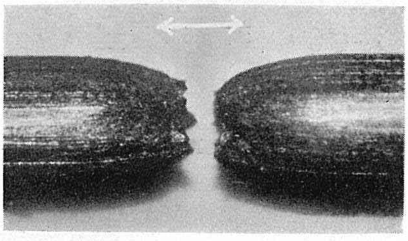


Fig. 8



## Plate II

(The arrow indicates the direction of drawing)

Fig. 1

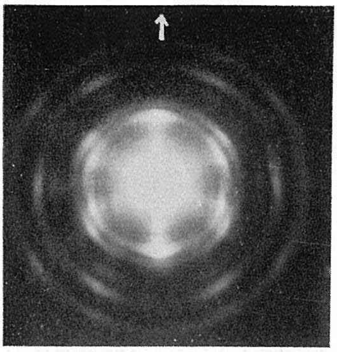


Fig. 3

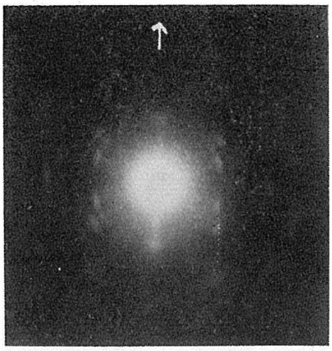


Fig. 5

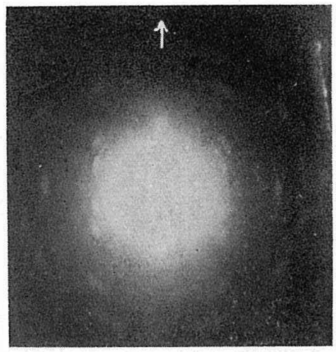


Fig. 2

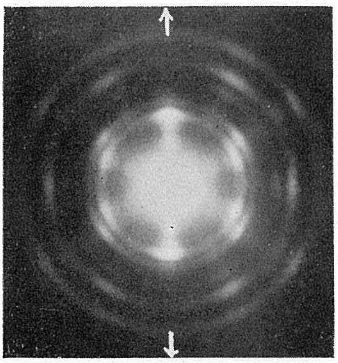


Fig. 4

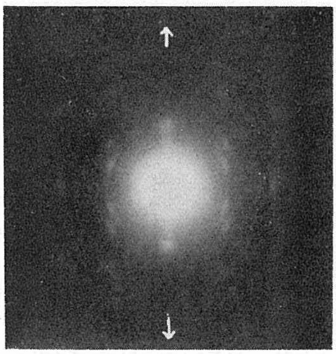


Fig. 6

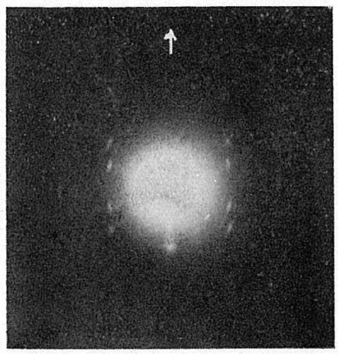


Fig. 7

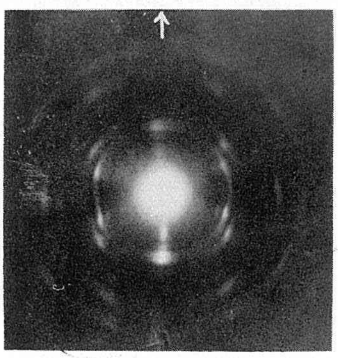


Fig. 8

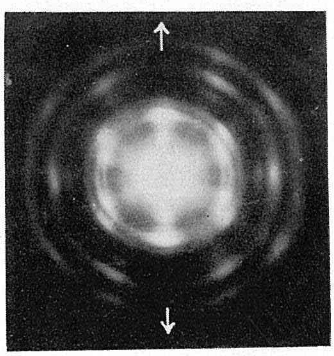


Fig. 9

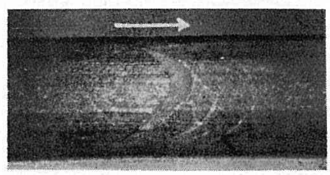


Fig. 10