The Effect of Rolling on Single Crystals of Aluminium.

By

Shinsuke Tanaka

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ABSTRACT

The effects of rolling on the single crystals of aluminium were investigated by the X-ray photographic method. The single crystals used in the present experiment were obtained from aluminium plates of about 1 mm. in thickness by the stress method. The deformation of the crystals could be observed even after 2-3 % rolling, and the small crystals produced by the destruction began to rotate after 6 % rolling, and finally they became fibrous structures of different types according to the initial orientations of the crystals and the direction of the rolling. But the axes of the fibers always coincided with the direction of rolling, and they could be classified into three forms, of which the first was characterised by the [110] direction parallel to the axes of fibers and the (001) planes nearly parallel to the rolled surface, and the second, by the [112] direction parallel to the axes of fibers and the (110) planes nearly parallel to the rolled surface, and the third, by the [111] direction parallel to the axes of fibers and the (110) planes nearly parallel to the rolled surface.

There may probably exist another arrangement characterised by the axes of the fibers being the same as in the third type but (112) planes being parallel to the rolled surface instead of (110) planes, although proof of this is uncertain.

However there seems to be no simple relation existing among the initial orientation of the crystal, the direction of rolling and the final state of the fibrous structure.

It is well known from the X-ray examination that the micro-crystals in a metal subjected to the various cold works take a definite arrangement. The regularity is peculiar to the kind of the metal as well as to the method of working. The writer took X-ray photographs of rolled thin platinum foils showing the extreme regularity, and reported on them in the previous paper[1]. However, the X-ray photographs obtained from aluminium and silver foils show a somewhat complex and irregular struc-

1 These Memoirs, **8**, 319 (1925); **9**, 197 (1925).

ture. The orientations of the micro-crystals in rolled aluminium sheets have been investigated by several authors, who have obtained quite different conclusions. Mark and Weissenberg[1] concluded that there were two non-related groups of lattice positions, of which the first was characterised by the [112] direction parallel to the direction of rolling and the (110) planes parallel to the rolled surface, and the second, by the [100] direction parallel to the direction of rolling and the (100) planes parallel to the rolled surface. Uspenski and Konobejewski[2] found only the first group of the lattice positions and not the second one. Weber[3] reported another conclusion, that the [111] direction lay parallel to the direction of rolling and the (112) planes parallel to the rolled surface. Further work on the same subject by Owen and Preston[4] led them to the same conclusion as Weber's.

The author found that the large single crystals of aluminium were differently affected by rolling in various directions. This phenomenon was investigated by the photographic method with X-rays radiated from a molybdenum anticathode. The single crystals were obtained from aluminium plates of about 1 mm. in thickness by the stress method. Many transmission and reflection X-ray photographs were taken by the aid of the same apparatus as in the former experiments. The transmission photographs of single crystals show the fine Laue spots, but these spots become larger and somewhat diffuse by about 2-3 % rolling, which seems to denote some distortion of the crystal lattice. If the samples are rolled more than 6%, these spots lengthen to become strips directed toward the central spot; the positions of the strips are not yet altered from those of the spots, but they seem to indicate the occurrence of some rotation of the small crystals. Next, by about 10% rolling these strips become many radiating bands starting from the central spot, though they have no symmetry, indicating the fibrous structure of the sample. After that they arrive at a remarkable period which persists rather longer. In this period they become only several diffuse radiating bands distributed rather symmetrically and showing clearly the fibrous structure peculiar to the direction of rolling. This characteristic is clearly observable until the thickness of the samples is reduced to about 0·01 mm.. All the transmission photographs, however, taken of the thinner specimens show only some diffuse concentric rings. This is shown in the photographs

1 Zs. f. Physik, **14**, 328 (1923); **16**, 314 (1923).
2 Zs. f. Physik, **16**, 215 (1923).
3 Zs. f. Physik, **28**, 69 (1924).
4 Proc. Phys. Soc., Lond, **38**, 132 (1926).

reproduced in Figs. 1, 2, 3, 4, and Fig. 5 in Plate I. The peculiarity of the effect of rolling can be more clearly observed in the reflection photographs.

This phenomenon was investigated in many samples of 0·1 mm. in thickness which show the peculiarity distinctly in both transmission and reflection photographs, and seem to be very interesting. There must exist some different kinds of arrangements of the micro-crystals in the specimens, corresponding to the differences in the photographs. It was ascertained with many samples that the chief cause was difference in the direction of rolling and not the manner of rolling notwithstanding the existence of no simple relation between the direction of rolling represented by the crystallographic data and the arrangement of the micro-crystals.

Table I.

Symbols of the types	Total number of radiating bands corresponding to (111) planes	The angles ψ between the line of symmetry and radiating bands. (on one side of the line of symmetry)	The spectral lines in the reflection photographs
A	6	30°, 90°, 150°	(001) (001)+(311)
B	6	18°, 90°, 162°	(110) (110)+(311)
C	6	0°, 70°, 110°	(110) (100)+(110)+(311)

The author took many reflection and transmission photographs and observed that the former were composed of two or more spectral lines corresponding to the K_α & K_β lines of molybdenum reflected from (100), (110), (311) planes and the latter had generally six radiating bands corresponding to the (111) planes and show the three types of fibrous structure characterised by the distribution of those bands. Some of those photographs are reproduced in the annexed figures in Plate II.

Of the reflection photographs, Fig. 9, Fig. 11 and Fig. 13 have only two spectral lines, corresponding to (100) and (110) planes respectively; Fig. 10 and Fig. 12 have additional lines corresponding to (311) planes, and Fig. 14 all of the six spectral lines. All the reflection photographs belonged to one or other of these types and did not show the rest. The samples giving the photographs of Fig. 9 and Fig. 10 by reflection gave those of Fig. 6 by transmission, and the samples giving the reflection photographs of Fig. 11 and Fig. 12 gave the transmission photographs of Fig. 7, and the same for Fig. 13, Fig. 14 and Fig. 8.

The angles ψ between each radiating band corresponding to (111) planes and the line of symmetry parallel to the axis of fibrous structure and also nearly parallel to the direction of rolling, were all measured with transmission photographs. The mean values of those angles ψ observed with respect to the radiating bands situated on one side of the line of symmetry are given in the third column of Table I.

Now, if we take [100], [111], [110], [311], [112], [210] directions as the axes of fibrous structures supposed to be parallel to the surface of the specimen, simple calculations give us the angles φ corresponding to the radiating bands produced by (111) planes with respect to the known wave lengths of the characteristic radiations of molybdenum. They are given in the second column of Table II. The above-mentioned axes lie in some of the crystal planes (100), (110), (111), (311), (112), (210), which are given, in Table II, in the first line of each part corresponding to each direction of planes taken as the fibre axis. Consequently those planes can sometimes become parallel to the surface of the specimen. For example, when the [100] direction is taken as the fibre axis, only 011, 010, 012 planes can become parallel to the surface of the specimen. The angles Φ in Table II are those of rotation of the crystals around the fibre axis from the position at which one of the planes given in the first line of each part of Table II is parallel to the surface of the specimen, to the position in which the crystals reflect the *K*-radiation of molybdenum by their (111) planes. For example, the crystal whose $\bar{1}10$ plane is parallel to the surface of the specimen must be rotated $15^\circ\ 40'$ around the [110] direction in order to reflect the *K*-radiation of molybdenum by its 111 plane.

As the writer employed the diverging beam of X-rays, the appearance of the fine spectral lines in our reflection photographs showed that the reflecting planes of each micro-crystal must lie in one plane nearly parallel to the surface of the specimen. However, if a certain plane lie strictly in one plane, the radiating bands can not be obtained in transmission photographs. Therefore the majority of the micro-crystals have certain planes parallel to the surface of the specimen while some parts deviate slightly. It must be noted that two sets of crystals can exist in the material after rolling, the one set being the optical image of the other in the plane of rolling and giving the radiating bands at the positions $180^\circ - \psi$ in Table II, and the writer deduced the following conclusions.

1) The micro-crystals in the samples which give photographs belonging to the type A must be arranged in such an orientation that

Table II.

Indices of the reflecting planes	Calculated Values of ψ	Φ				
I [100] direction is taken as the fibre axis						
		011	010	012		
111	54°	78°	33°	59°		
$\bar{1}11$	54°	78°	33°	59°		
$1\bar{1}1$	54°	12°	33°	6°30′		
$11\bar{1}$	54°	12°	33°	6°30′		
II [111] direction is taken as the fibre axis						
		$\bar{1}10$	$11\bar{2}$			
111	—	—	—			
$\bar{1}11$	70°45′	50°20′	20°30′			
$1\bar{1}1$	70°45′	50°20′	20°30′			
$11\bar{1}$	70°45′	9°20′	78° 0′			
III [110] direction is taken as the fibre axis						
		$\bar{1}10$	$1\bar{1}1$	001	$1\bar{1}2$	$1\bar{1}3$
111	34°30′	15°40′	70°20′	19°40′	39° 0′	49°10′
$\bar{1}11$	90°	45°40′	10°30′	26°10′	9° 0′	1°
$1\bar{1}1$	90°	45°40′	81°	26°10′	61°10′	51°30′
$11\bar{1}$	34°30′	15°40′	70°20′	19°40′	39° 0′	49°10′
IV [311] direction is taken as the fibre axis						
		$0\bar{1}1$	$\bar{1}12$			
111	28°20′	18°30′	54°20′			
$\bar{1}11$	79°50′	9°	63°50′			
$1\bar{1}1$	58° 0′	62°10′	10°40′			
$11\bar{1}$	58° 0′	62°10′	22°50′			
V [112] direction is taken as the fibre axis						
		$\bar{1}10$	$11\bar{1}$	$0\bar{2}1$	$\bar{3}11$	
111	17°10′	27°30′	52°40′	22°10′	3°20′	
$\bar{1}11$	61°30′	58°10′	12°10′	6°50′	74°40′	
$1\bar{1}1$	61°30′	58°10′	12°10′	51°40′	26°20′	
$11\bar{1}$	90°	9° 0′	81° 0′	41°50′	22°30′	
VI [210] direction is taken as the fibre axis						
		001	$\bar{1}20$	$\bar{1}21$		
111	38°15′	51°30′	9°50′	33°50′		
$\bar{1}11$	74°50′	27°20′	43°50′	67°50′		
$1\bar{1}1$	74°50′	27°20′	43°50′	19°40′		
$11\bar{1}$	38°15′	51°30′	9°50′	14°20′		

their fibre axes coincide with the [110] direction and most of their (001) planes are nearly parallel to the rolled surface. The maximum deviation from this orientation which is produced by the rotation of the crystals about the fibre axis seems to be about 26°. The angle between the two planes 001 and $1\bar{1}3$ is 25° 20′, and this is the reason why the spectral lines corresponding to (311) planes are added in some reflection photographs.

2) The samples which give the photographs of type B have such an orientation of micro-crystals that the fibre axis coincides with the [112] direction and the $\bar{1}10$ plane coincides with the rolled surface. The maximum deviation from this orientation is about 28°. The angle between the $\bar{1}10$ & $\bar{3}11$ planes is 31° 20′, and this is the reason why the spectral lines corresponding to (311) planes are added in some reflection photographs. This arrangement is the same as that observed by Mark and Weissenberg, Uspenski and Konobejiewski.

3) For the samples which give the photographs of type C, the [111] direction is naturally taken as the fibre axis and the $\bar{1}10$ plane the rolled surface provided that the deviation is about 10° for both parallelisms. The deviation of the former gives the radiating bands at $\phi=0°$, and that of the latter gives the radiating bands at $\phi=70°$.

It must be noted that, for the similar fibre axis, $11\bar{2}$ planes may be taken as the rolled surface admitting a deviation of about 21°. The cause of the absence of the spectral lines corresponding to the (112) planes in the reflection photographs is uncertain because the atomic density of these planes is very small compared with that of the other reflecting planes. The smallest angles between the (112) planes and the (100), (110), (311) planes are 34° 50′, 30° 10′, 8° 30′ respectively, and the comparative smallness of these angles may be the reason why rather diffuse spectral lines corresponding to the (100), (110), (311) planes appear together on some reflection photographs. This arrangement was observed by Weber and Owen though it is uncertain in the present experiment.

Next the writer made a study of the relation between the direction of rolling and the fibrous structures above mentioned. It seemed natural to consider that the final structures were chiefly due to the direction and the plane along which the rolling was started from the following facts: 1 no photographs indicated any change in the fibrous structure during the advance of the rolling process, 2 the different samples obtained from a crystal by rolling in the different directions generally give the different types of photographs, 3 two crystals in a specimen when rolled in a direction usually give the different types of photographs.

The orientations of the crystallographic axes for every specimen were determined by the X-ray method introduced by Prof. U. Yoshida,[1] and the surface of the specimen and the direction of rolling are determined in connection with the crystallographic axes. Moreover the writer calculated following angles for each specimen:

1 The angles between the direction of rolling and the axes of fibres which may come out in the final characteristic structure.
2 The angles between the direction of rolling and the planes which can become parallel to the rolled surface in the final state.
3 The angles between the original surfaces of the crystals along which the rolling was started and the axes of the fibres which may come out in the final structure.
4 The angles between the original surface of the crystal along which the rolling was started and the planes which may become parallel to the rolled surface in the final state.

Many different crystallographic planes appeared parallel to the surfaces of the specimens and there seems to be no simple relation existing among the initial orientations of the crystals, the directions of rolling and the final constitution of the fibrous structure.

In conclusion the author wishes to express his sincere thanks to Prof. M. Ishino for the interest he has taken in the present research.

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1 Jap. J. Phys., **4**, 133 (1927).

Fig. 2

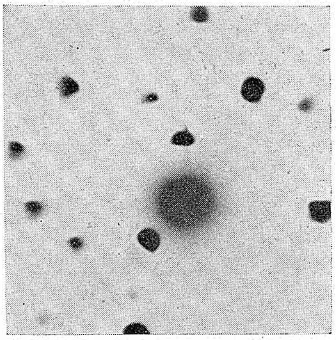

Fig. 1.

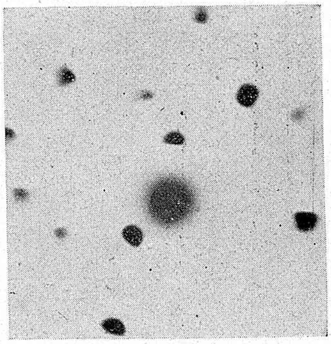

Fig. 3.

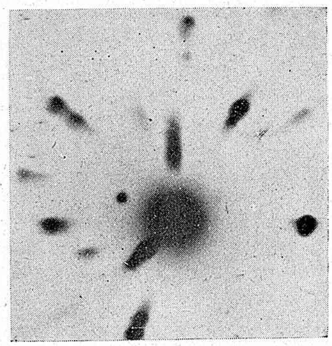

Fig. 5.

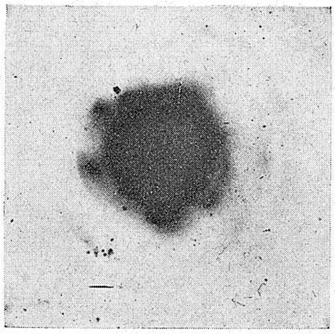

Fig. 4.

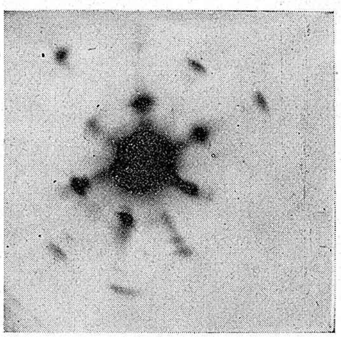

Fig. 6.

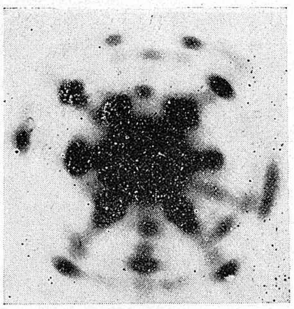

Fig 7.

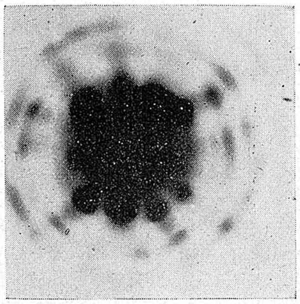

Fig. 8.

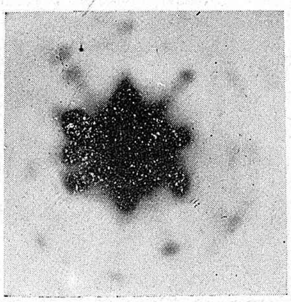

Fig. 9.

Fig. 10.

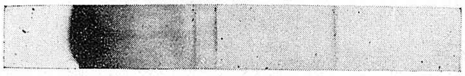

Fig. 11.

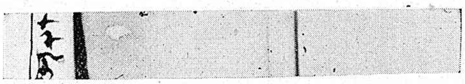

Fig. 12.

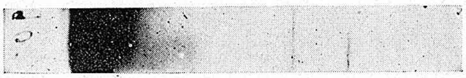

Fig. 13.

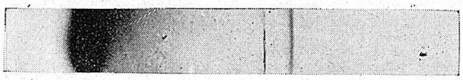

Fig. 14.