NOTES AND CORRESPONDENCE

Observations of the Three Dimensional Configuration of Snow Crystals of Combination of Bullet Type**By Hiroshi Uyeda* and Katsuhiro Kikuchi**

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1. Introduction

Measurements of the axial angle between spatial branches of natural polycrystalline snow crystals, that is to say, spatial dendrites, radiating assemblage of dendrites, combination of bullets and side planes were made carefully by Lee (1972), Uyeda and Kikuchi (1976) and Kobayashi *et al.* (1976). However, the number of measurements on the snow crystals of combination of bullets was not sufficient compared with other polycrystalline snow crystals all measurements included. The reason for this is that the precipitating chance for combination of bullets is limited in a whole season, and the measurement of the axial angle between the *c*-axes of neighbouring two components of combination of bullets by the use of a universal stage under a microscope is difficult, compared with other polycrystalline snow crystals.

Kikuchi (1968) assumed that single bullet was produced by the disintegration of the combination of bullets during their descent based on the statistical treatments. The combination of bullets was suggested to grow from a frozen cloud droplet by Weickmann (1972) and Parungo and Weickmann (1973). Kikuchi and Ishimoto (1974) made their experiments in such a way as to grow several shapes of polycrystalline snow crystals from frozen water droplets using a convection type of cloud chamber. As a result, the crystal shapes of radiating assemblage of dendrites, radiating assemblage of plates and hollow prisms were found to be producible from frozen droplets. However, they did not succeed to grow the combination of bullets from a frozen droplet. Therefore, information of the configuration of

the combination of bullets are needed for an understanding of the mechanism of the origin of natural polycrystalline snow crystals.

The peak of 70° in a frequency distribution curve of the axial angle between the *c*-axes of neighbouring two bullets constituting a combination of bullets was indicated by Lee (1972), Uyeda and Kikuchi (1976) and Kobayashi *et al.* (1976). However, other peaks were ambiguous in the frequency distribution. Therefore, careful observations are necessary to clarify the axial angle between the *c*-axes of neighbouring two components constituting a combination of bullets. Furthermore at the same time it is necessary to determine the three dimensional configuration, namely, the directions of the principal axes of each component of a combination of bullets. Recently, the authors found that distinct replicas of snow crystals are available for these analyses of a combination of bullets. This paper describes the results of measurements on the properties of the snow crystals of a combination of bullets.

2. Method of examination

The samples used here were replicas of snow crystals of combination of bullets collected by one of the authors (K. Kikuchi) during over wintering from 1968 to 1969 at Syowa Station, Antarctica. The replicas have been preserved well enough to make examinations in detail. In this examination, the replicas of the broken, coagulated and evaporated crystals were excluded. Three dimensional configuration of a combination of bullets was sketched first under a stereographic microscope and photographs of it were taken next. On a distinct replica, a straight line of two components facing each other and commonness of the *a*-axes of neighbouring two components was able to be identified by means of a stereographic microscope.

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The axial angle between the c -axes of neighbouring two components was easily measured when two components were directly on the plane of a glass slide as shown in Fig. 1(a), (b) and

(c). In a case as shown in Fig. 1(d), however, the commonness of the a -axes of two components is seen, but it is difficult to determine the angle between the c -axes of them. When a combination

Fig. 1 Examples of replicas examined of a combination of bullets; (a), (b) and (c): c -axes of bullets are on the plane of the glass slide. (d): one c -axis points upward to the plane of the glass slide.

Fig. 2 Examples of replicas of a combination of bullets made up from the shape of tetrahedron. One bullet perpendicular to the plane is dropped in (d).

Fig. 4 Schematic explanations of three dimensional configuration of a combination of bullets. (a): An example of a combination of bullets, (b): A fundamental tetrahedron, (c): An expected directions of the principal axes of each bullet. Here $\angle aob' = \angle boe = \dots \approx 70^\circ$, $\angle b'oh = \angle boh' = \dots \approx 55^\circ$ and $\angle bob' = \angle hoh' = \dots \approx 40^\circ$.

identified the commonness of an a -axis of each component. Among them two bullets in which the axial angle between the c -axes is 70° and 40° had an a -axis in common. On the other hand, the two bullets in which the axial angle between the c -axes is 55° and 90° had no a -axis in common. The combination of bullets in which the axial angle between the c -axes is 90° has a b -axis in common. The ratios of the axial angles of 40° , 55° , 70° , 90° and the others between neighbouring two bullets were 4, 10, 74, 10 and 2%, respectively. This percentage was obtained from the sketches of replicas by the observations that the fundamental feature of a combination of bullets was the "tetrapod". The frequency distributions measured from the replicas in this examination agreed with that observed directly by means of a universal stage up to the present. The maximum frequency of the axial angle between neighbouring two bullets was 70° as expected.

4. Concluding remarks

Careful examinations of total number of 265 samples of replicas of snow crystals of combination of bullets type showed that the axial angle between the c -axes of neighbouring two bullets was 70° predominantly and this angle coincided with the results of the direct observations by means of a universal stage by Lee (1972), Uyeda and Kikuchi (1976) and Kobayashi *et al.* (1976) to the present. Also the minor predominances of the axial angles of 55° and 40° coincided with the observational results afore-mentioned. Though the existence of the axial angle of 90° was ambiguous by the direct observations up to the present, it was ascertained in this examination.

Although the measurements of the axial angle between neighbouring two bullets have been made to the present, the three dimensional configuration of them has not been made clear. From the present examinations, a possible three dimensional configuration of a combination of bullets was proposed as shown in Fig. 4 by the observations that the fundamental configuration to be a tetrahedron such as a "tetrapod". Fig. 4(a) shows an example of a combination of bullets made up of 5 bullets: (A), (B), (C) and (D) show the directions $o-a$, $o-b$, $o-c$ and $o-d$ from the center (o) of a fundamental tetrahedron as illustrated in Fig. 4(b) and (F) in Fig. 4(a) shows a bullet of opposite direction to bullet (B) in Fig. 4(a). Fig. 4(c) shows a three dimensional configuration of a combination of bullets made up from the maximum number of bullets as expected; $o-e$, $o-f$, $o-g$ and $o-h$ are opposite directions to $o-a$, $o-b$, $o-c$ and $o-d$ and $o-f'$, $o-g'$

Fig. 5 A schematic figure of a combination of bullets composed of the axial angles of 40° , 55° and 70° (110°).

and $o-h'$ result in the rotation of 60° of $o-c$, $o-d$ and $o-b$ around the line $\overline{ae}$. On the other hand, $o-b'$, $o-c'$ and $o-d'$ result in the rotation of 60° of $o-g$, $o-h$ and $o-f$ around the line $\overline{ae}$ likewise. From this model it is known that the axial angle of 55° between the neighbouring two bullets can not take an a -axis in common as illustrated in Fig. 5. Further, from this model it is possible to interpret the axial angle between neighbouring two bullets of a combination of bullets of 70° , 55° and 40° . However, the axial angle of 90° is not explained in this model for the present.

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砲弾集合型雪結晶の立体構造の観測

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