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Features in Weld Solidification Structure of High Purity Aluminum Sheet

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Abstract

The growth mode of the subgrains and the preferred orientation have been investigated with the weld metal of high purity aluminum sheets.

The columnar crystals grow approximately parallel to the direction of the maximum temperature gradient as inward growth proceeds. The subgrains observed in the columnar crystals have no easy growth direction and also grow parallel to the direction of the maximum temperature gradient. Moreover, a competitive growth was observed near the center in the weld metal.

1. Introduction

As already made clear the subgrains which are developed in an aluminum weld metal grow in the direction of $\langle 100 \rangle$[1,2]. This direction is called the easy growth direction[3]. However, when the difference between the direction of the maximum temperature gradient and the direction of $\langle 100 \rangle$ of a specimen is large, the subgrains are compelled to grow in the direction near the direction of the maximum temperature gradient[1,2]. This phenomenon is prominent when the purity of a material increases[2]. For example, it was observed that in 99.93%-aluminum the growth direction of the subgrains shifted from the direction of $\langle 100 \rangle$ to the direction of the maximum temperature a gradient little (about ten degrees) when the angular difference was large.

In this report investigations were made on the growth mode of the subgrains and preferred orientation in the columnar crystal zone in the weld metal of high purity aluminum sheets.

2. Material Used and Experimental Method

The material used in this investigation is a 99.96%-aluminum 1 mm thick sheet. Chemical composition of the material is tabulated in **Table 1.**

Table 1 Chemical composition of the material used (wt %)

Cu	Si	Fe	Al
0.004	0.014	0.020	99.96

Experimental methods are as follows;

(1) Study on the growth direction of subgrains

It is desirable to use specimens with coarse grains to study the growth direction of the subgrains because of the easiness of the microscopic observation and X-ray diffraction analysis. Hence, the specimens in which the grains had been coarsened to 2 to 3 cm in diameter were prepared by annealing the material (1/2 H) as received for 20 hours at the temperature of 650°C.

The bead-on-plate and spot weldings were performed with GTA. The welding conditions were as follows; welding current: 45A, arc voltage: 19V and welding speed: 250 mm/min. The widths of the weld metal in the top and back sides were almost the same and therefore the heat flow was considered to be two-dimensional.

After the welding, the solidification structures were observed with the optical microscope and the orientations of the specimens were determined by the back reflection Laue technique. The diameter of the slit used was 1 mm. Thus the investigation was made on the relation between the growth direction of the subgrains and the direction of the maximum temperature gradient at solidification interface.

(2) Study on the preferred orientation in the columnar crystal zone

In examining the preferred orientation in the columnar crystal zone a material as received was used. The welding speeds were 250 and 1250 mm/min. The shape of the molten pools was elliptical in the former and tear drop in the latter. The welding direction was parallel to the rolling direction.

Orientations of arbitrary fifteen columnar crystals were determined by the back reflection Laue method at the locations of $y=0$, 50 and 80% in the weld metal for the welds of 250 mm/min welding speed and of $y=$ 0, 50 and 90% for the welds of 1250 mm/min welding speed. Here, the parameter y is a non-dimensional representation of the location in the weld metal, and

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$y=0\%$ and $y=100\%$ represent the fusion boundary and the center of the weld metal, respectively. The diameter of the slit used was 0.1 mm. Each orientation was represented in terms of (200) pole figure. Besides, the direction of the maximum temperature gradient at each position was measured from the inclination of the puddle locus.

Moreover, an investigation was made on the relation between the preferred orientation observed in the columnar crystal zone and the number of crystals in the weld metal. The fact that the preferred orientation is observed in the weld metal shows that a competitive growth occurs near the fusion boundary and consequently the number of columnar crystals decreases as inward growth proceeds[2]. The number of columnar crystals, n, which existed in the length of about 20 mm, l, parallel to the welding direction was counted. Then the number of columnar crystals per unit length was calculated by dividing n by l.

3. Experimental Results and Discussions

3.1 *Growth Direction of Subgrains*

Fig. 1 is a diagram of stereographic projection of a single crystal which was welded with GTA spot. As seen from Fig. 1, the specimen surface is nearly parallel

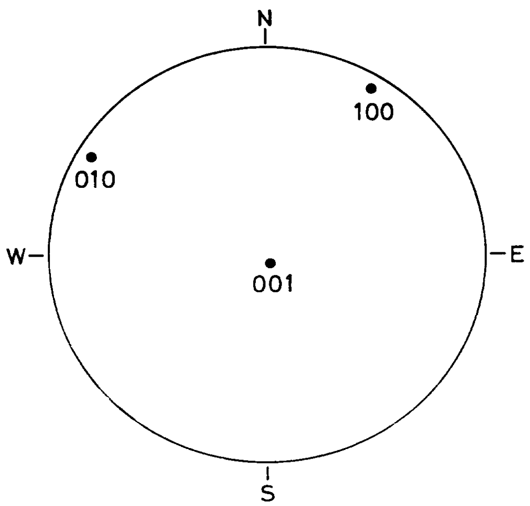


Fig. 1 Stereographic projection of a single crystal welded with GTA spot

to the plane of (001).

Accordingly, the subgrains developed in the weld metal would grow parallel to the direction of each ⟨100⟩ if the 99.96%-aluminum has an easy growth direction of ⟨100⟩.

Photo. 1 shows the microstructure of a weld nugget whose orientation is shown in Fig. 1. Each stripe in the nugget observed in Photo. 1 represents the growth direction of the subgrains, that is, the subgrains developed in the weld metal of 99.96%-aluminum grow centripetally to the center of the weld nugget. This phenomenon is quite different from the phenomena observed in 99.93% and commercially pure aluminum

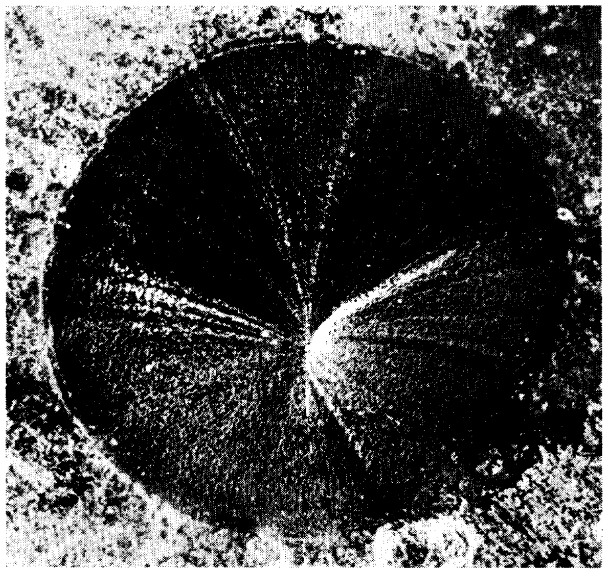


Photo. 1 Macrostructure of weld nugget of a single crystal whose orientation is shown in Fig. 1

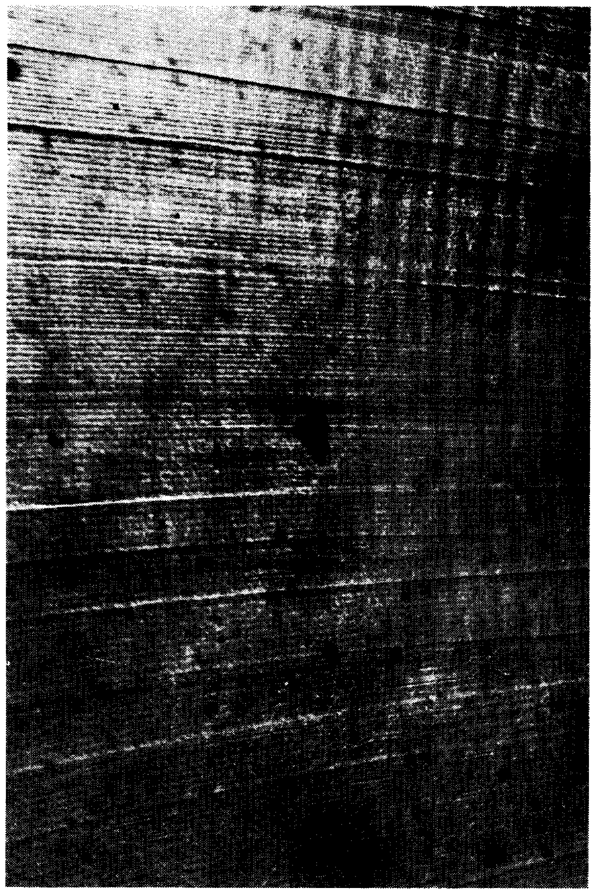


Photo. 2 An example of microstructures in weld nugget shown in Photo. 1 (×60)

sheets[1,2]. A typical example of microstructures in the weld nugget is shown in **Photo. 2.** Other stripe patterns observed vertically in Photo. 2 are puddle isotherms. Hence, the direction of the maximum temperature gradient is right and corresponds to the direction of $\overrightarrow{WE}$ in Fig. 1. Although the angle between the direction of the maximum temperature gradient and the direction of $[\bar{1}00]$ reached the value of about 30 degrees as seen in Fig. 1, the subgrains were observed to grow nearly parallel to the direction of the maximum temperature gradient.

The orientation and microstructures of a single crystal which was bead-on-plate welded at the speed of 250 mm/min are shown in **Fig. 2** and **Photo. 3**, respectively. Photo. 3(a), (b) and (c) show the microstructures near the fusion boundary, in the intermediate location between the fusion boundary and the center of the weld metal, and near the center of the weld metal, respectively. At the welding speed of 250 mm/min the direction of the maximum temperature gradient is normal to the welding direction near the fusion boundary and gradually inclines to the welding direction as inward growth proceeds and finally is parallel to the welding direction in the center of the weld metal. As seen in Photo. 3, the growth direction of the subgrains is approximately parallel to the direction of the maximum temperature gradient described in the above. Consequently, it is concluded that in 99.96%-aluminum the subgrains have no easy growth direction which is observed in 99.93%- and commercially pure aluminum[1,2], and grow approximately parallel to the direction of the maximum temperature gradient.

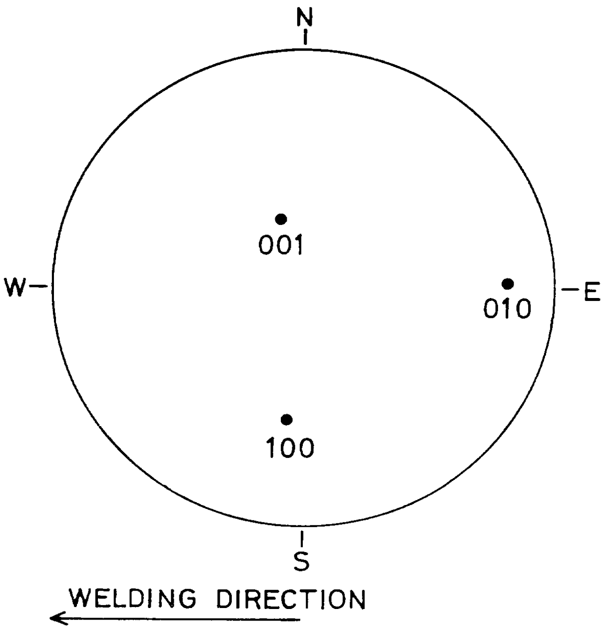


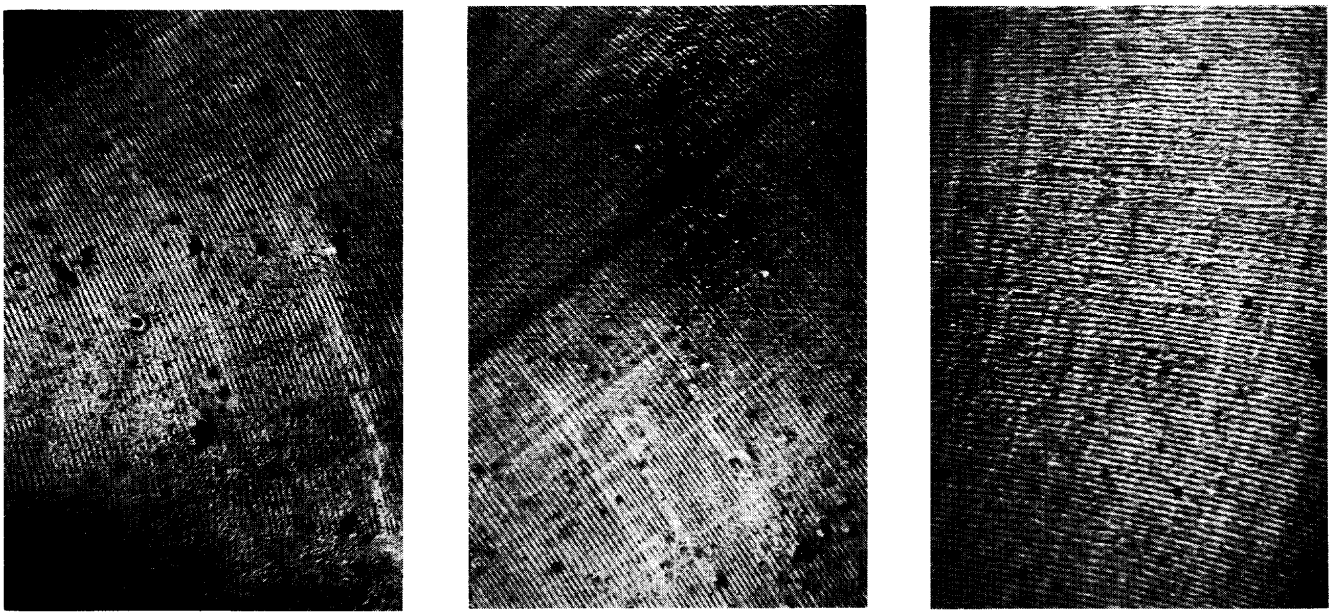
Fig. 2 Stereographic projection of a single crystal welded with GTA at the welding speed of 250 mm/min

Besides, as seen in Photo. 1 and Photo. 3 no stray crystal[2,3] was observed in 99.96%-aluminum even when the angular difference between $\langle 100 \rangle$ and the direction of the maximum temperature gradient was so large. It is concluded, therefore, that it becomes much difficult for stray crystals to be formed in the weld metal when the purity of the material increases.

3.2 *Preferred Orientation in Columnar Crystal Zone*

Photo. 4 shows the macrostructure of 99.96%-aluminum which was bead-on-plate welded at the welding speed of 250 mm/min. The columnar crystals grow approximately parallel to the direction of the maximum temperature gradient and consequently grain boundaries of the columnar crystals bend in the welding direction as inward growth proceeds.

An example of microstructures is shown in **Photo. 5.** As seen in Photo. 5 the grain boundaries of the columnar crystals are nearly parallel to the direction of the subgrains which are observed in the columnar crystals.



(a) (b) (c)

Photo. 3 Microstructures in the weld metal of a single crystal whose orientation is shown in Fig. 2 (×60)
(a) Near the fusion boundary
(b) In the intermediate location between the fusion boundary and the center of the weld metal
(c) Near the center of the weld metal

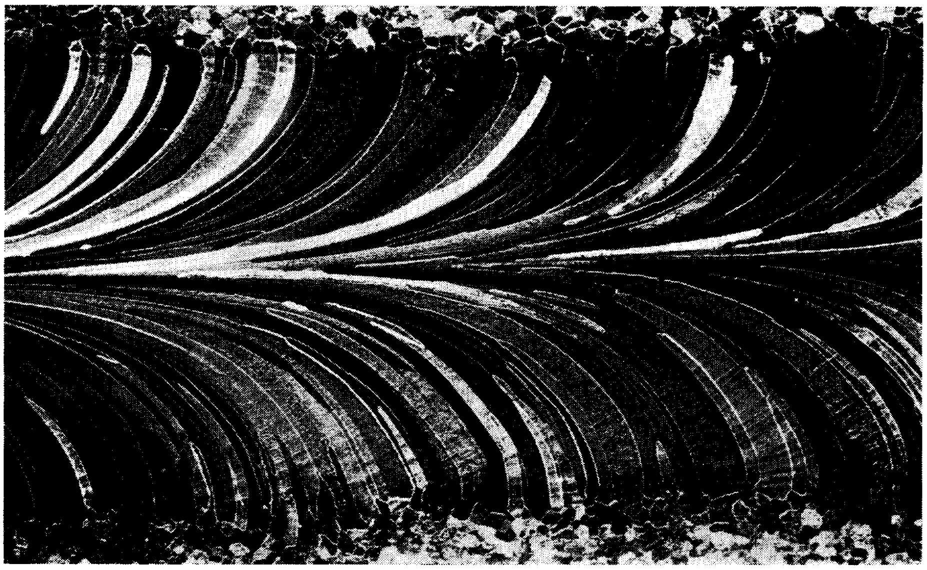


Photo. 4 Macrostructure of the weld metal at the welding speed of 250 mm/min

Photo. 5 Microstructure in the weld metal at the welding speed of 250 mm/min (×60)

In the weld metal of the commercially pure aluminum sheets which were welded at a low welding speed the grain boundaries of the columnar crystals were nearly straight[2]. In this case the subgrains grew approximately in the direction of ⟨100⟩. From these results, it is concluded that the mode of the grain boundaries of the columnar crystals is related closely to the growth direction of the subgrains in the columnar crystals.

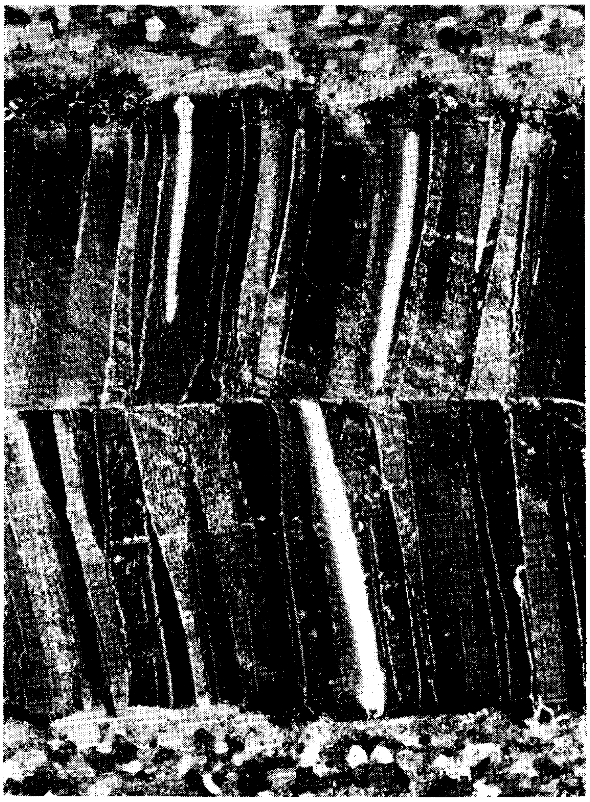


Photo. 6 Macrostructure of the weld metal at the welding speed of 1250 mm/min

Photo. 6 shows the macrostructure of the weld metal which was bead-on-plate welded at the welding speed of 1250 mm/min. At the high welding speed the molten pool is tear-drop shaped and hence the columnar crystals grow straightly to the center of the weld metal. Accordingly, the columnar crystals which grow from both fusion boundaries in Photo. 6 meet with each other in the center of the weld metal. At the location which is very close to the center of the weld metal the subgrains curve abruptly as shown in **Photo. 7** because the direction of the maximum temperature gradient becomes parallel to the welding direction in

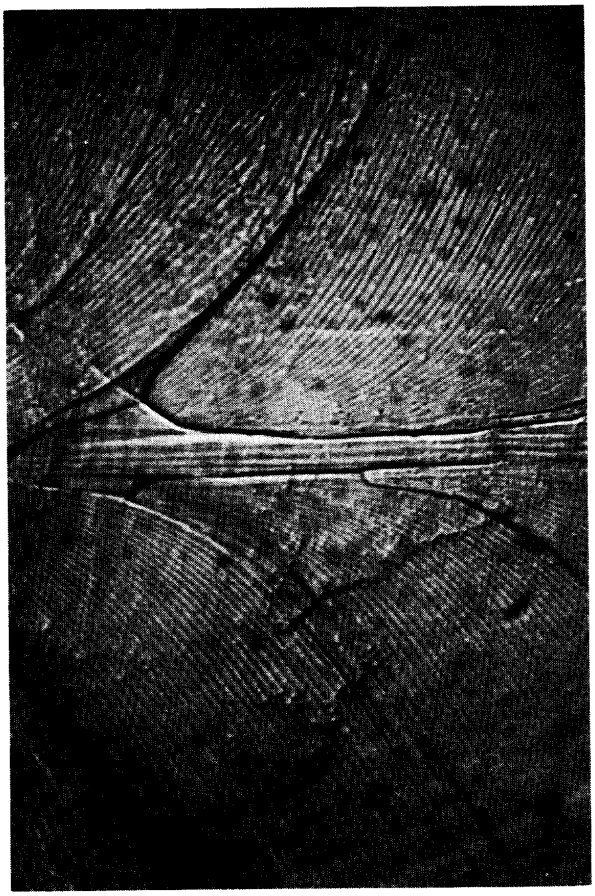


Photo. 7 Microstructure near the center of the weld metal at the welding speed of 1250 mm/min (×100)

the center of the weld metal.

Next, an investigation was made on the preferred orientation in the columnar crystal zone. **Fig. 3(a), (b)** and **(c)** are pole figures at the locations of y=0, 50 and 80% of the weld metal which was welded at the welding speed of 250 mm/min, respectively. The projection plane is parallel to the specimen surface. An arrow n_θ represents the direction of the maximum temperature gradient at each location.

In Fig. 3(a) the distribution of poles of (200) is not random. This would be due to the phenomenon that the base metal near the fusion boundary was influenced by the weld thermal cycle and the rolling texture of the base metal considerably changed. In Fig. 3(b), however, the poles of (200) distribute randomly. Accordingly, it is considered that a competitive growth does not occur as far as the location of y=50%. On the other hand, Fig. 3(c) shows that the [100] fiber texture is developed and a symbol F.A. stands for the fiber axis. As seen in Fig. 3(c) the fiber axis is approximately parallel to the direction of the maximum temperature gradient. That is, the competitive growth is completed near the location of y=80%.

Fig. 4(a), (b) and **(c)** are (200) pole figures at the locations of y=0, 50 and 90% of the weld metal which was welded at the welding speed of 1250 mm/min, respectively. That Fig. 4(a), which shows the pole figure at the fusion boundary, is different from Fig. 3(a) would be due to the difference in the weld thermal cycle. As seen in Fig. 4 the competitive growth does not occur either as far as the location of y=50%. The [100] fiber texture, however, is developed at the location of y=90%.

Fig. 5 shows the relation between the parameter y and the number of columnar crystals per unit length parallel to the welding direction. The number of columnar crystals is almost the same up to y=40% and after that it begins to decrease slightly. That is, a competitive growth occurs at the location where y is larger than about 40%. The phenomenon that a competitive growth is observed in 99.96%-aluminum is also clear from the observation of the macrostructures in Photo. 4 and Photo. 6, in which some columnar crystals developed from the fusion boundary disappear at the location near 40 to 50% or more.

As the additional consideration, the extent of the constitutional supercooling zone increases generally as the growth proceeds from the fusion boundary to the center of the weld metal[4,5]. Accordingly, it is considered that a competitive growth would not occur in the case of the cellular solidification interface with a small extent of the constitutional supercooling zone but would occur in the case of the cellular interface with a large extent of the constitutional supercooling zone.

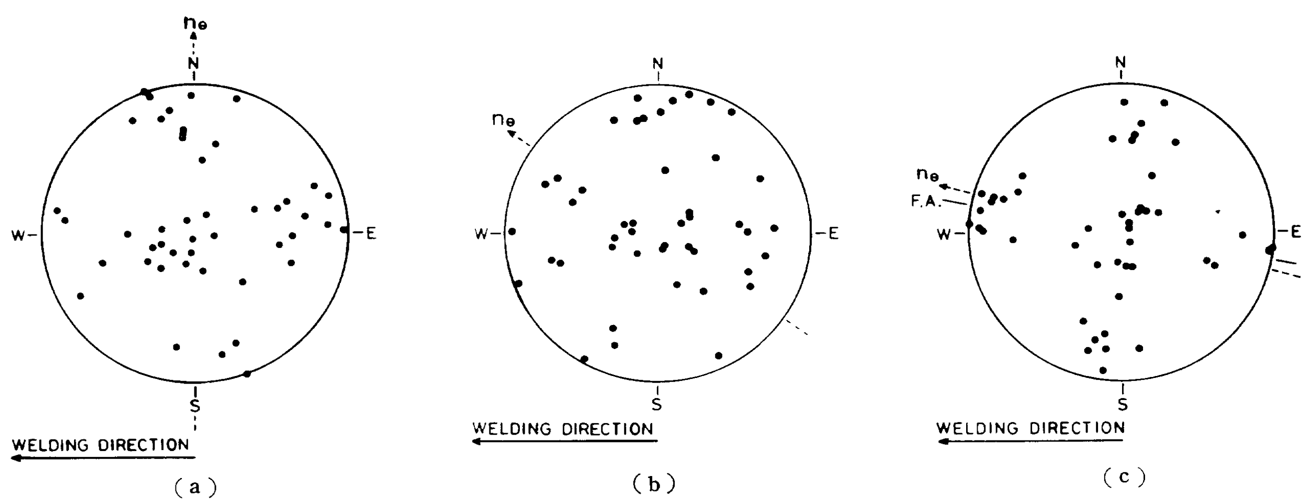


Fig. 3 (200) pole figures of the columnar crystal zone in the weld metal at the welding speed of 250 mm/min

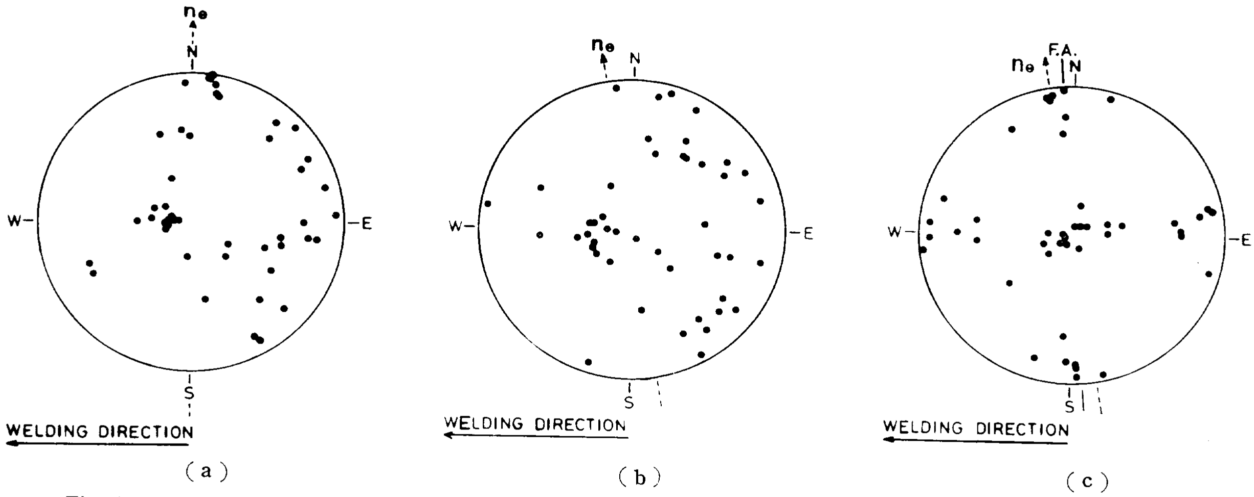


Fig. 4 (200) pole figures of the columnar crystal zone in the weld metal at the welding speed of 1250 mm/min

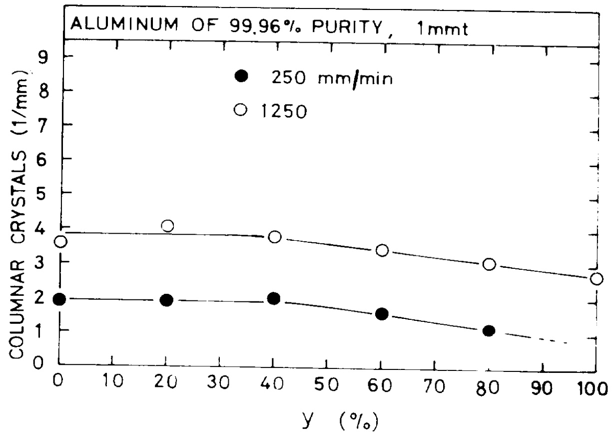


Fig. 5. Relation between the number of columnar crystals per unit length and the parameter y

4. Conclusions

Investigations were made on the growth mode of the subgrains and the preferred orientation in the columnar crystal zone in the weld metal of high purity aluminum sheets. The conclusions obtained are as follows;

(1) In the weld metal of 99.96%-aluminum sheets the subgrains had no easy growth direction and they grew approximately parallel to the direction of the maximum temperature gradient.

(2) At the low welding speed the growth direction of the columnar crystals was normal to the welding direction near the fusion boundary and gradually changed to parallel to the welding direction as inward growth proceeded.

(3) At the high welding speed the columnar crystals grew straightly and approximately normal to the welding direction.

(4) A competitive growth was observed near the center of the weld metal and the fiber texture with the fiber axis of [100] was observed in the columnar crystal zone.

References

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