Effect of Weld Solidification Mode on Tensile Properties of Aluminum Weld Metal†

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Abstract

Bead-on-plate welding was performed on sheets of 99.96% and 1050 aluminum and 5052 and 5083 aluminum alloys with GTA. Macrostructures of the weld metal varies when the welding conditions and the materials are changed. The effect of the weld solidification mode on tensile properties of the weld metal was investigated. The results showed that the tensile strength of the weld metal of 99.96% and 1050 aluminum was approximately the same as the base metal. On the other hand, the elongation of the weld metal decreased much when the growth direction of the columnar crystals became normal to the tensile axis. The tensile strength of the weld metal of 5052 aluminum alloy increased as the amount of the equiaxed dendrites in the weld metal increased. Moreover, the weld metal of 5083 aluminum alloy which consisted of only the equiaxed dendrites had nearly the same tensile strength as the base metal.

Besides, the investigations were made on the relationship between tensile properties of the weld metal and the width of the columnar crystal and also on features of tensile cracks in the weld metal. It was observed that the width of the columnar crystal did not have significant effect on the tensile properties of the weld metal. Tensile cracks were observed to initiate mainly along grain boundaries of the columnar crystals when the growth direction of the columnar crystals became normal to the tensile axis.

1. Introduction

The welding parameters that affect weld solidification mode are as follows: welding current, arc voltage, welding speed and purity of materials[1]. The relationship between these parameters and weld solidification structure has been investigated in detail by the authors[1]. That is, columnar crystals are generally developed from fusion boundary into weld metal. The microstructure in the columnar crystal change from planar to cell and cellular dendrite as growth proceeds into the weld metal. Moreover, equiaxed dendrites are developed when commercially pure aluminum is welded in a high speed and the welding is performed on aluminum alloys.

By the way, columnar crystal zone in the aluminum weld metal has fiber texture, whose fiber axis is [100][2]. Equiaxed dendrite zone, however, does not have the fiber texture and this zone is isotropic. Besides, grain size in the weld metal is larger than that in the base metal. The fiber texture and the grain size in the weld metal would affect tensile properties of the weld metal.

The present investigation was undertaken to determine the effect of weld solidification mode on tensile properties of the weld metals of pure and commercially pure aluminum and corrosion resistant aluminum alloys. The corrosion resistant aluminum alloys have been used extensively and welding has been generally performed on these alloys also. Then, the investigation was made on the relationship between tensile properties and width of the columnar crystal. Moreover, features of tensile cracks in the weld metal were examined.

2. Experimental Procedure

Materials used for this investigation were 99.96% aluminum, 1050 aluminum, and 5052 and 5083 aluminum alloys. Sheets 1 mm in thickness were used. Chemical compositions of each material are tabulated in **Table 1.**

Table 1. Chemical compositions of materials used (wt%).

Materials	Cu	Si	Fe	Mg	Mn	Zr	Cr	Ti	Al
99.96% aluminum	0.004	0.014	0.020	—	—	—	—	—	99.96
1050 aluminum	0.01	0.10	0.31	—	—	—	—	—	Bal.
5052 aluminum alloy	0.01	0.10	0.25	2.36	0.01	<0.01	0.20	0.01	Bal.
5083 aluminum alloy	0.02	0.08	0.21	4.37	0.50	<0.01	0.18	0.04	Bal.

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Bead-on-plate welding was performed with GTA (DCRP). In welding a specimen was restrained with a restraint jig not to warp by thermal strain and a thin plate of asbestos was laid under the specimen to prevent burn-through of molten metal.

Specimen size was 80 mm in width and 200 mm in length. The bead-on-plate welding was performed along the center of the specimen for a length of about 170 mm. The welding speeds were 104, 250, 500, 750 and 1000 mm/min. Welding current was always determined to get a full penetrated weld bead for each welding speed. Width of the weld metal was about 9 mm. Hence, macroscopically the weld metal would grow two-dimensionally. Then, the relationship between weld solidification mode and tensile properties was investigated by using Instron type tensile machine. Strain rate used was 5 mm/min and the maximum load of the testing machine was 5 tons. Shape and size of a tensile specimen were as shown in **Fig. 1.** As seen in Fig. 1 the tensile test was performed on all weld metal and load axis was parallel to welding direction. Before the tensile test all of the specimens were annealed at 350°C for one hour to releave the strain due to the machining of the specimen.

In examining the relationship between tensile properties and width of columnar crystal 1050 aluminum sheets were used. Grain sizes of the base metals were changed by annealing the specimens which had been tensile-strained by elongation of 5, 7.5, 10, 15 and 20% at 600°C for 20 hours. The bead-on-plate welding was performed on these base metals at a speed of 750 mm/min. Since the columnar crystal grows epitaxially on the half-melted crystal of the base metal[3], the width of the columnar crystal is the same as the base metal at the fusion boundary.

In examining features of tensile cracks welded joints whose size was as shown in **Fig. 2.** were used. The tensile test was stopped as soon as a tensile crack was observed in the weld metal.

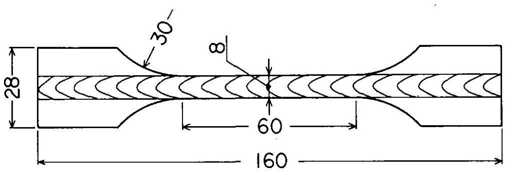


Fig. 1. Shape and size of a tensile test specimen.

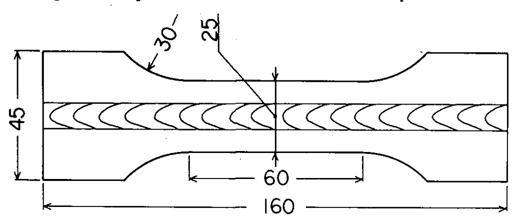


Fig. 2. Shape and size of a specimen for examining features of tensile cracks

3. Experimental Results

3.1 Effect of welding speed

An example of stress-strain curves for the base metal and weld metals welded in speeds of 250 and 1000 mm/min of 99.96% aluminum is shown in **Fig. 3.** The elongation of the weld metal which had been welded at a speed of 250 mm/min was approximately the same as the base metal. In a welding speed of 1000 mm/min, however, the elongation was much smaller than the base metal. On the other hand, tensile strength was almost the same for each specimen.

The relationship between welding speed and tensile strength for 1050 aluminum is shown in **Fig. 4.** Besides, the relationship between welding speed and elongation for 1050 aluminum is shown in **Fig. 5.** In both figures the minimum and maximum values are shown to indicate the amount of scatter in measured values. Open circles in the figures represent the mean values. The result for a welding speed of zero shows the one for the base metal. The tensile strength was almost the same as the base metal when the welding speed increased. The elongation, however, decreased

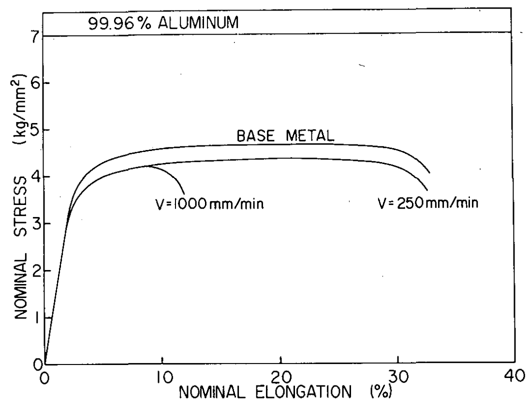


Fig. 3. An example of stress-strain curves for the base metal and weld metals of 99.96% aluminum.

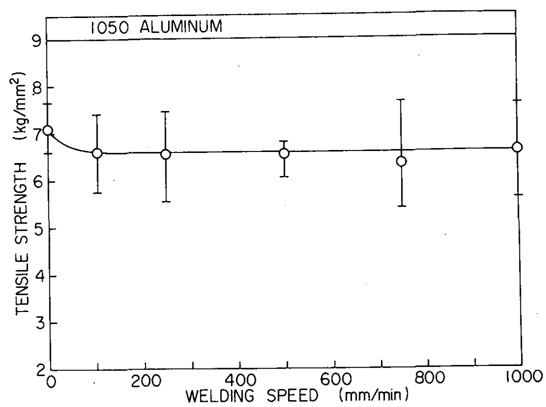


Fig. 4. Relationship between welding speed and tensile strength for 1050 aluminum.

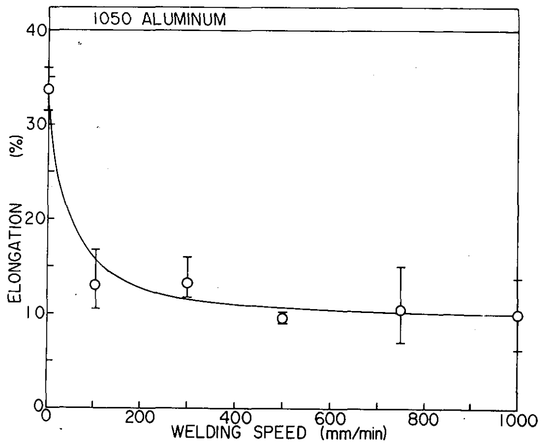


Fig. 5. Relationship between welding speed and elongation for 1050 aluminum.

much for the weld metals comparing with the base metal and decreased gradually as the welding speed increased (Fig. 5).

An example of stress-strain curves for the base metal and the weld metals of 5052 aluminum alloy welded in speeds of 250 and 750 mm/min is shown in **Fig. 6.** In these curves a characteristic change, i. e. serration was observed. The serration is due to the Portevan-LeChatelier effect. This phenomenon was also observed in 5083 aluminum alloy but not in 99.96% and 1050 aluminum. The relationship between welding speed and tensile strength and elongation is shown in **Fig. 7** and **Fig. 8,** respectively. The tensile strength of the weld metal welded in a low welding speed was much smaller than the base metal but increased gradually when the welding speed increased. The change of the elongation was similar to that for 1050 aluminum shown in Fig. 5.

The results of 5083 aluminum alloy are shown in **Table 2.** In 5083 aluminum alloy the tensile strength and the elongation of the weld metal were approximately the same as the base metal.

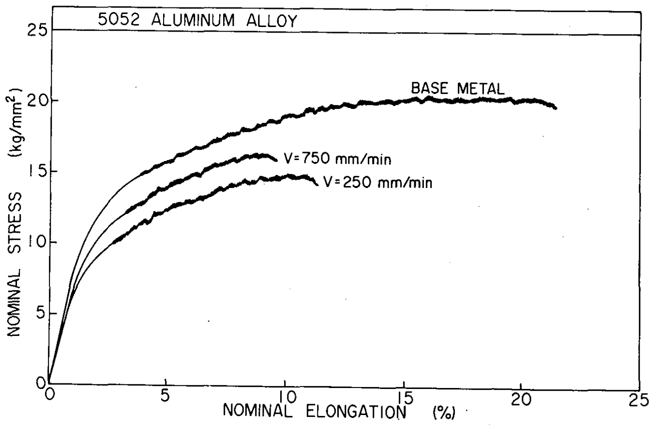


Fig. 6. An example of stress-strain curves for the base metal and weld metals of 5052 aluminum alloy.

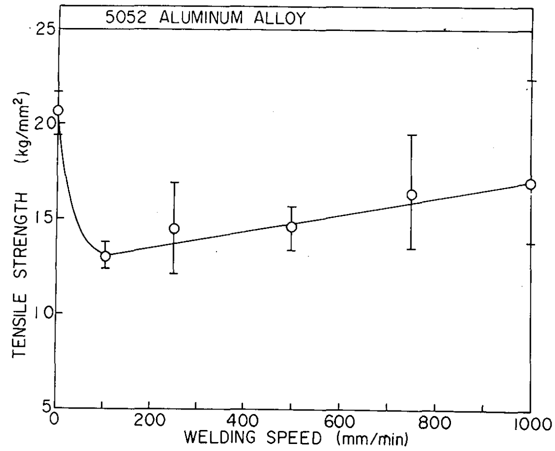


Fig. 7. Relationship between welding speed and tensile strength for 5052 aluminum alloy.

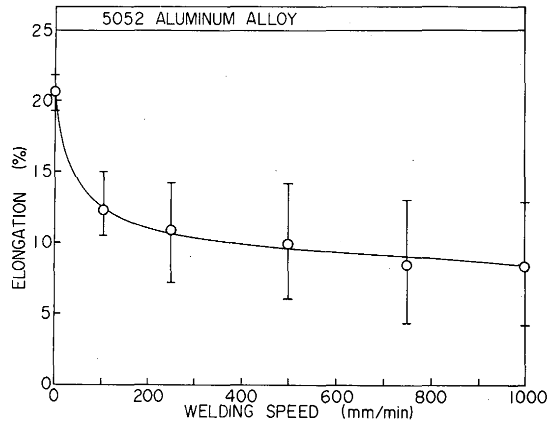


Fig. 8. Relationship between welding and elongation for 5052 aluminum alloy.

Table 2. Change of tensile properties of the weld metal of 5083 aluminum alloy.

	Tensile Strength (kg/mm²)	Elongation (%)
Base Metal	35.6	19.4
	37.5	17.6
	37.5	17.6
(mean)	36.9	18.2
V=250 mm/min	35.8	19.6
	34.7	19.0
	37.2	17.6
(mean)	35.9	18.7
V=750 mm/min	37.5	18.0
	37.2	18.4
	35.6	18.8
(mean)	36.8	18.4

3.2 Effect of width of columnar crystal

The bead-on-plate welding was performed on the specimens of 1050 aluminum which had been grain-coarsened by the strain-anneal method at a speed of 750 mm/min. Then, the effect of width of columnar crystal on the tensile properties was examined. A similar study was done on the base metal as well as the weld metal. The results obtained are shown in **Figs. 9** and **10.**

The tensile strength of both weld metal and base metal were almost the same when the width of the columnar crystal and the grain size increased. Besides, it was observed that the elongation had not changed when the width of columnar crystal increased. The elongation of the base metal was larger than the weld metal. This result was similar to that shown in Fig. 5.

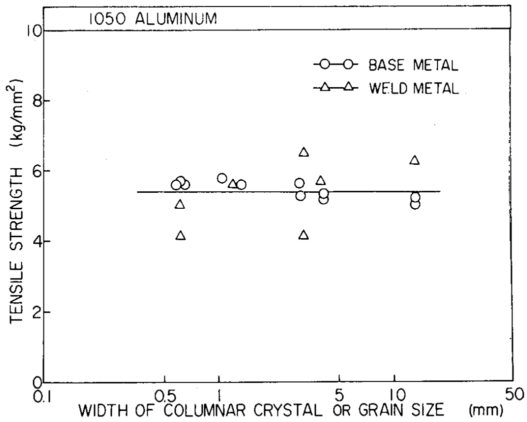


Fig. 9. Effect of width of columnar crystal on tensile strength for 1050 aluminum.

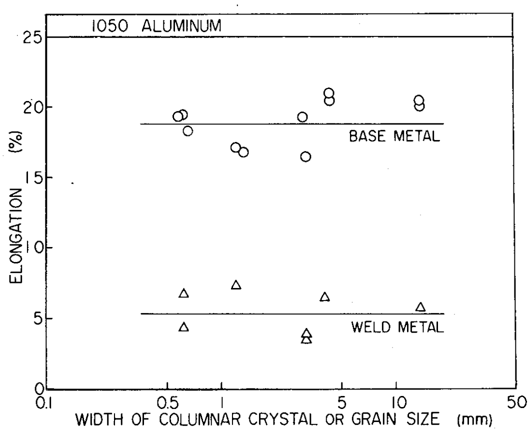


Fig. 10. Effect of width of columnar crystal on elongation for 1050 aluminum.

3.3 Feature of tensile cracks

Features of tensile cracks are shown in **Photo. 1 (a), (b)** when the welding was performed at a speed of 1000 mm/min. Photo. 1 (a) and (b) show the results for 99.96% aluminum and for 1050 aluminum, respectively. In these cases cracks were observed to initiate mainly along grain-boundaries of the columnar crystals.

Feature of a tensile crack is shown in **Photo. 2**

(a) For 99.96% aluminum

(b) For 1050 aluminum

Photo. 1. Feature of tensile cracks when the welding was performed at a speed of 1000 mm/min.

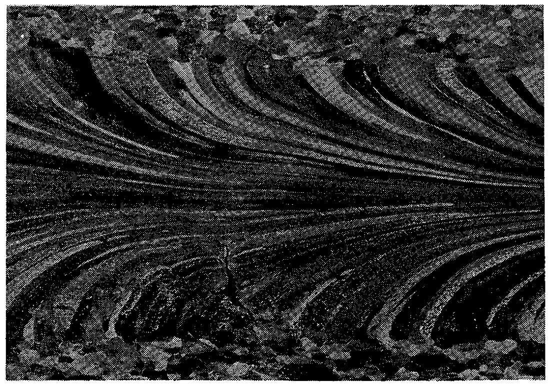


Photo. 2. Feature of tensile crack when the welding was performed at a speed of 250 mm/min.

when the welding was performed on 99.96% aluminum at a speed of 250 mm/min. The crack did not initiate along a grain boundary of a columnar crystal in this case. The crack was observed to develop approximately normal to the tensile axis.

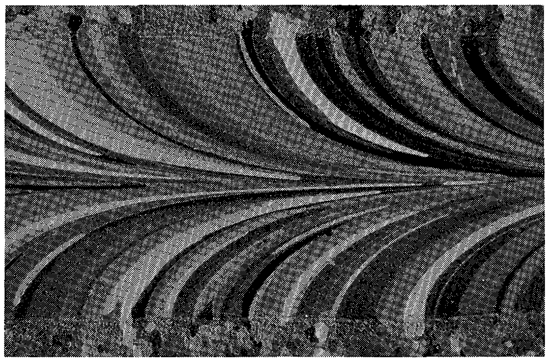
4. Discussion

As shown in Figs. 3, 4 and 5 the tensile strength of the weld metal of 99.96% and 1050 aluminum was almost the same as the base metal. The elongation, however, of the weld metal decreased much in comparison with the base metal. This phenomenon is closely related to the weld solidification mode. Macrostructures of the weld metal of 99.96% aluminum are shown in **Photo. 3 (a), (b).** Besides, macrostructures of 1050 aluminum are shown in **Photo. 4 (a), (b).**

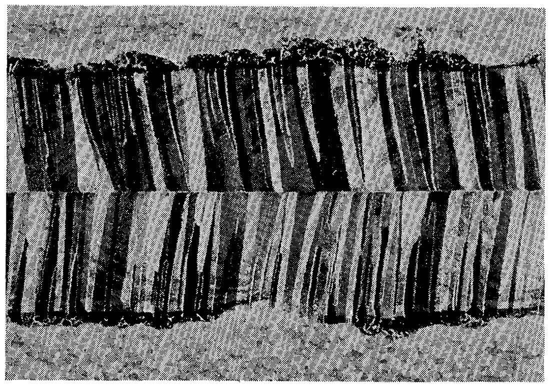
In 99.96% aluminum only the columnar crystals are developed and the crystals grow parallel to the direction of maximum temperature gradient[4]. When the weld metal is welded at a low welding speed and is tensile-strained the columnar crystals are elongated to the direction parallel to the tensile axis. As seen in Photo. 3 (a) the columnar crystals grow parallel to the welding direction, *i. e.* the tensile axis, near the center of the weld metal. This part of the weld metal is particularly elongated. This phenomenon is apparent when Photo. 3 (a) is compared with Photo. 2. Hence, the elongation of the weld metal welded at a low welding speed is large. On the other hand, the columnar crystals grow approximately normal to the welding direction, *i. e.* the tensile axis, when the welding is performed in a high speed (Photo. 3 (b)). When the weld metal is tensile-strained each columnar crystal rotates and does not elongate much to the direction of the tensile axis under the restraint of adjoining columnar crystals. Hence, the elongation of the weld metal welded at a high speed is small.

In the case of 1050 aluminum the solidification mode differs a little from that of 99.96% aluminum. In a low speed weld metal, the columnar crystals grow approximately normal to the welding direction near the fusion boundary and then the stray crystals[5] grow to the center of the weld metal (Photo. 4 (a)). When such a weld metal is tensile-strained the columnar crystals near the fusion boundary does not elongate much and then the elongation is not so large as in 99.96% aluminum. In a high speed weld metal, the columnar crystals grow approximately normal to the welding direction and the equiaxed dendrites are developed a little closer to the weld center. Hence, the elongation is small similarly to the case of 99.96% aluminum.

As seen in Fig. 6 the stress-strain curves of 5052

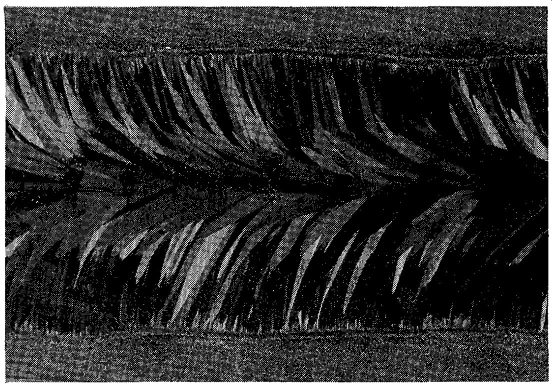


(a) V=250 mm/min

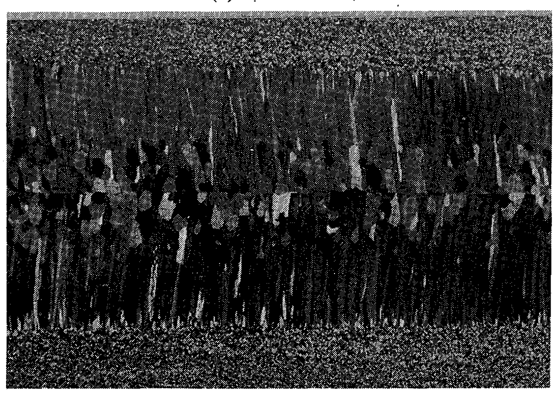


(b) V=1000 mm/min

Photo. 3. Macrostructures of the weld metal of 99.96% aluminum.



(a) V=250 mm/min



(b) V=1000 mm/min

Photo. 4. Macrostructures of the weld metal of 1050 aluminum.

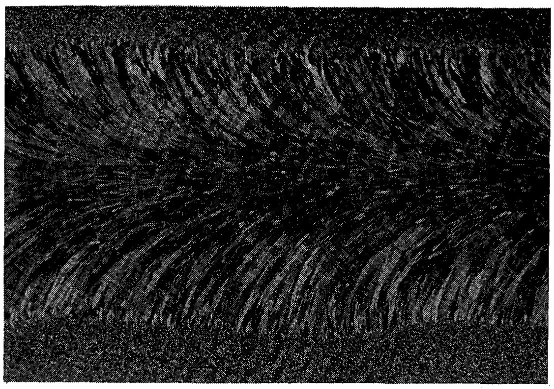
aluminum alloy are saw-toothed. This is frequently called the Portevin-Le Chatelier effect. The explanation is based on strain aging[6]: individual dislocations are not believed to move smoothly through the lattice but from time to time are thought to be held up for a while, for example, at intersections or internal stress peaks. When a dislocation is held up, solute atoms have an oppotunity to diffuse to it and lock it, so that the stress must be raised to move it again. Thus the process of strain aging is believed to occur during the straining.

Macrostructures of the weld metal of 5052 aluminum alloy are shown in **Photo. 5 (a) ~(d).** In the weld metal which was welded in a speed of 104 mm/min only the columnar crystals are observed. When the welding speed increases the equiaxed dendrites are developed near the center of the weld metal and the area where the equiaxed dendrites are developed increases. The relationship between the amount of the equiaxed dendrites in the weld metal and the tensile strength is shown in **Fig. 11.** The values of the tensile strength in Fig. 11 are referred to the result in Fig. 7. As seen in Fig. 11 the tensile strength increased as the amount of the equiaxed dendrites in the weld metal increased. This would be due to the fact that the columnar crystal zone is anisotropic but the equiaxed dendrite zone is isotropic.

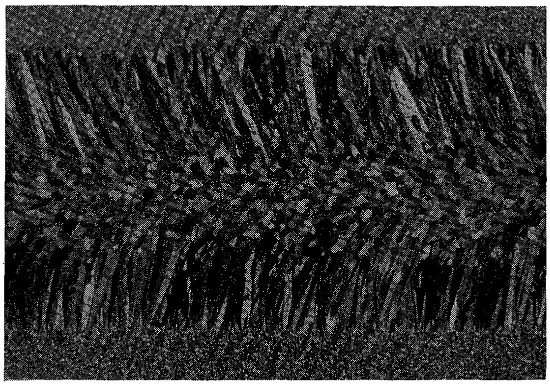
From the result shown in Fig. 11 it is considered that the weld metal consists of only the equiaxed dendrites would have approximately the same tensile strength as the base metal. When the welding was performed on 5083 aluminum alloy whose chemical compositions were tabulated in Table 1 only the equiaxed dendrites were observed nearly over the weld metal. An example of macrostructures of this material is shown in **Photo. 6.** The tensile strength of the weld metal of 5083 aluminum alloy were approximately the same as the base metal (Table 2). That is, the weld metal which consists of only the equiaxed dendrites have nearly the same tensile strength as the base metal. Besides, the elongation of the weld metal was approximately the same as the base metal.

The yield strength and the tensile strength increase as the grain size decreases[7]. This phenomenon, however, was not observed in this investigation. That is, the tensile strength did not change when the grain size or the width of the columnar crystal increased. This would be due to the grain size or the width of the columnar crystal was considerably large.

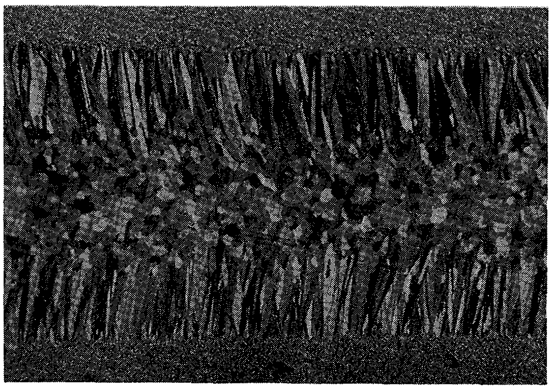
As seen in Photo. 1 tensile cracks were observed to initiate mainly along grain boundaries of the columnar crystals when the welding was performed at



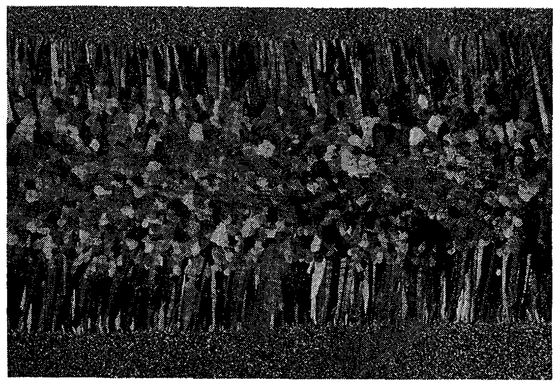
(a) V=104 mm/min



(b) V=500 mm/min



(c) V=750 mm/min



(d) V=1000 mm/min

Photo. 5. Macrostructures of the weld metal of 5052 aluminum alloy.

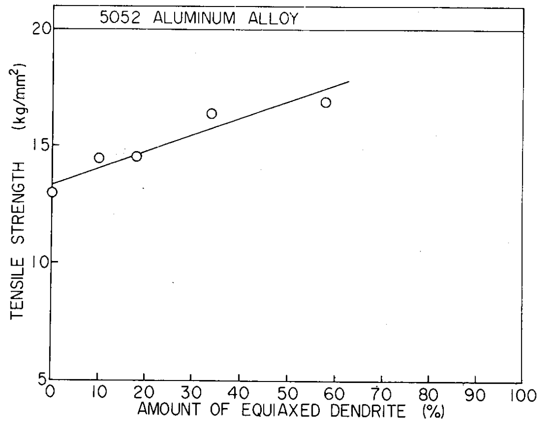


Fig. 11. Relationship between amount of equiaxed dendrites in the weld metal and tensile strength.

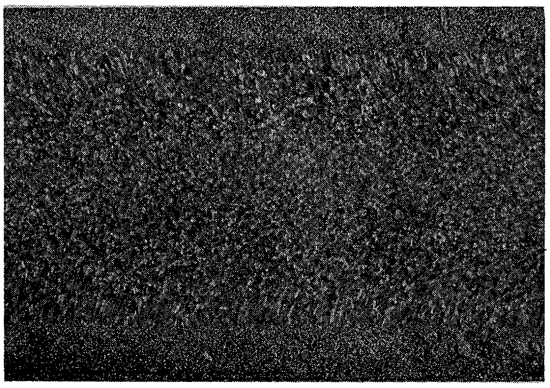


Photo. 6. An example of macrostructures of the weld metal of 5083 aluminum alloy.

a high speed. In this case the columnar crystals grow nearly normal to the tensile axis and each columnar crystal is under the restraint of adjoining columnar crystals when the weld metal is tensile-strained. Then, it is considered that cracks initiated along grain boundaries of the columnar crystals.

5. Conclusions

Some effects of weld solidification mode on the tensile properties of aluminum weld metal were investigated by performing welding on 99.96% aluminum, 1050 aluminum, and 5052 and 5083 aluminum alloys with GTA. Main conclusions obtained are as follows:

(1) When only the columnar crystals were observed in the weld metal of 99.96% and 1050 aluminum the tensile strength was approximately the same as the base metal.

(2) When the growth direction of the columnar crystals became normal to the tensile axis the elongation of the weld metal decreased much.

(3) The tensile strength of the weld metal of 5052 aluminum alloy increased as the amount of the equiaxed dendrites in the weld metal increased.

(4) The weld metal of 5083 aluminum alloy which consisted of only the equiaxed dendrites nearly over the weld metal had approximately the same tensile strength and elongation as the base metal also.

(5) The width of the columnar crystals did not have significant effect on the tensile properties of the weld metal.

(6) Tensile cracks were observed to initiate mainly along grain boundaries of the columnar crystals when the growth direction of the columnar crystals became normal to the tensile axis.

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