Title	Electron Beam Welding of High Strength Aluminum Alloy (Report I)
Author(s)	Arata, Yoshiaki; Ohsumi, Makoto; Hayakawa, Yasuhiko
Citation	Transactions of JWRI. 1976, 5(1), p. 19-25
Version Type	VoR
URL	https://doi.org/10.18910/12845
rights	
Note	

Electron Beam Welding of High Strength Aluminum Alloy (Report Ⅰ)†

Yoshiaki ARATA *, Makoto OHSUMI ** and Yasuhiko HAYAKAWA **

Abstract

It has been a general consideration that super super dulalmin, the representative of which is 7075, can not be successfully welded with conventional fusion welding method. So we have been investigating the application of EB welding process to this sort of materials.

In this paper we report the penetration characteristics and the mechanical properties of 7075.

Considerable differences in welding penetration phenomenon were found between alloys depending on the sort and amount of alloying element when the penetrations do not reach to the bottom of the plate thickness (partial penetration). In particular, the penetration of 7075 which contains Zn and Mg of higher vaporization pressure as principal alloying elements is much deeper than 2xxx aluminum alloys whose main alloying element is Cu.

From the view point of mechanical properties, the properly EB welded 7075 exhibits tensile strength comparable to the yield strength of base metal, but the fracture mode seems to be rather brittle with small elongation. The fracture toughness of the weld, however, is superior to that of base metal.

1. Introduction

It has been a general consideration that super super dulalmin, the representative of which is 7075, can not be successfully welded with conventional fusion welding method. This is due to the fact that it has a severe inclination of weld cracking and extreme degradation in weld strength and quality including anti-corrosion characteristics.

We have been investigating the application of EB welding process to this sort of materials. EB welding was considered worth trying application to these materials because it is a new welding method in which heat influence can be limitted more locally than in traditional welding methods. We are reporting the penetration characteristics and the mechanical properties of 7075.

Considerable differences in welding penetration phenomenon were found between alloys depending on the sort and amount of alloying element, when the penetration do not reach to the bottom of the plate thickness (partial penetration). In particular, the penetration of 7075 which contains Zn and Mg of higher vapourization pressure as principal alloying elements is much deeper than 2xxx aluminum alloys whose main alloying element is Cu. This is probably due to the elevated pressure in beam hole caused by the vaporization of Zn and Mg during welding, and in this case, weld defects such as spikes and cold shuts were apt to be formed at the root of the weld bead.

On the other hand, from the view point of mechanical properties, the properly EB welded 7075 exhibits tensile strength comparable to the yield strength of base metal, but the fracture mode seems to be rather brittle with small elongation. The fracture toughness of the weld, however, is superior to that of the base metal, so it seems that from the standpoint of fracture toughness, this 7075 weld joint is useful if proper welding procedure is applied and sound weld is obtaind.

2. Penetration Characteristics of Aluminum Alloys

2.1 Materials and Procedure of Experiment

The chemical compositions of aluminum alloys used in this experiment are listed in Table 1. Test pieces

Table 1 Chemical composition of materials used (%)

Material	Cu	Si	Fe	Mn	Mg	Zn	Ti	Sn	V	Cd	Zr	Cr
2014	3.9-5.0	0.5-1.2	<1.0	0.4-1.2	0.2-1.2	<0.25	<0.15	—	—	—	—	—
2021	5.8-6.8	<0.2	<0.3	0.2-0.4	<0.02	<0.1	0.02-0.1	0.03 – 0.08	0.05 – 0.25	0.02 – 0.2	0.1-0.25	—
2024	3.8-4.9	<0.5	<0.5	0.3-0.9	1.2-1.8	<0.25	—	—	—	—	—	<0.1
2219	5.8-6.8	<0.2	<0.3	0.2-0.4	<0.02	<0.1	0.2-0.1	—	0.05 0.15	—	0.1-0.25	—
5083	<0.1	<0.4	<0.4	0.3-1.0	3.8-4.8	<0.1	<0.2	—	—	—	—	<0.5
7075	1.2-2.0	<0.4	<0.5	<0.3	2.1-2.9	5.1-6.1	<0.2	—	—	—	—	0.18-0.35

† Received on Dec. 3, 1975

* Professor

** Nagoya Aircraft Works, Mitsubishi Heavy Ind. Ltd.

shown in Fig. 1 were successively set in line and were bead-on-plate welded in one chamber. Welding condition of Table 2 was applied in this experiment.

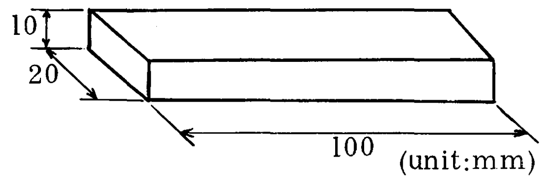


Fig. 1 Size of test piece

Table 2 Welding condition

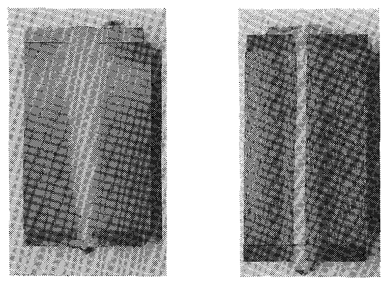
Parameter	
Accelerating voltage	150 KV
Beam current	7 mA
Welding speed	1.5 m/min
Work distance	150 mm
Focus	a_b ; 0.92 at 7 mA current
Atmosphere	1×10^{-4} Torr

2.2 Results and Discussion of Experiment

Penetration geometries of aluminum alloys listed in Table 1 are shown in Photo. 1, from which it is evident that there are considerable differences among materials. As for bead appearance, 7075 and 5083 are irregular and rugged as if eruption has occured, 2024 and 2014 are fairly smooth and wide, and most beautiful, uniform and widest are 2021 and 2219. As for the depth of penetration, 7075 and 5083 are especially narrow and deep, approximately twice those of other materials such as 2014, 2024, 2021, 2219, and penetration becomes shallower and rounder in the order of 2024, 2014, 2021, 2219. Penetration depth and bead appearance are conversely related. Longitudinal cross-section of weld beads were taken to observe the ripple of penetration, which has made clear that the same influence of chemical composition as on spikes also exists. Alloys 7075 and 5083 were accompanied with root porosities (R-porosity) and cold shuts at almost all of the spike areas.

In the case of fully penetrated welding, 7075 still exhibits, not conspicuously, above phenomena, obtaining narrower penetration than 2219 etc. (Photo 2).

Closely related to the remarkably deep penetration of 7075 and 5083 are probably the evaporation of Zn and Mg during welding which are the principal alloying elements of these materials.



(a) 2219 (b) 7075

Photo. 2 Lateral cross-section of welded bead (full penetrated, $57mm^t$)

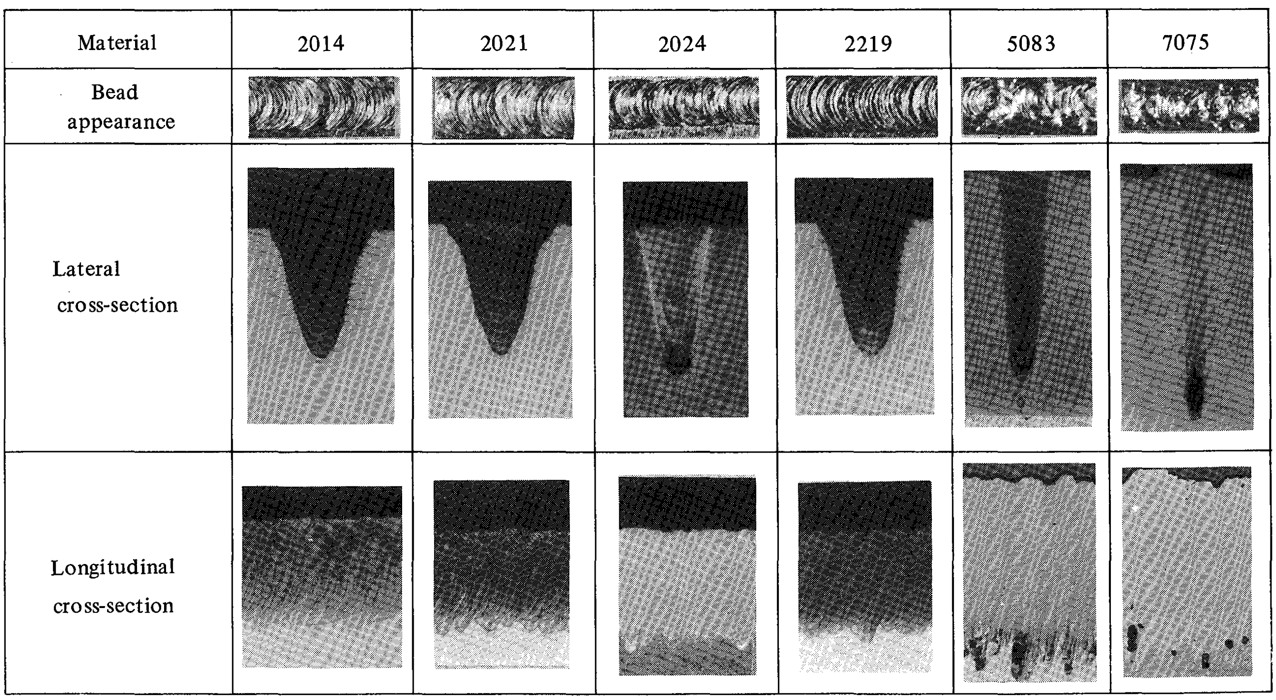


Photo. 1 Penetration geometries of aluminum alloys

A vapor pressure vs. temperature curves for individual alloying elements are shown in Fig. 2. In Fig. 2,

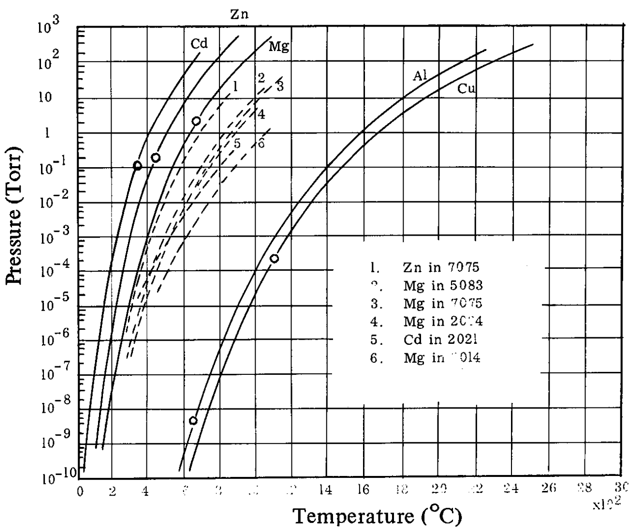


Fig. 2 Vapor pressure vs. temperature diagram

solid lines are for pure metals, while dotted lines are for alloy corrected by Raoult's law according to the following equation;

$$P_{AS} = \gamma_A N_A P_A \qquad (1)$$

where

P_{AS} = the vapor pressure of alloying element
γ_A = activity coefficient assuming 1 (γ_A=1)
N_A = mole fraction of alloying element
P_A = vapor pressure of alloying element as pure metal

$$N_A = \frac{Wt\%_A / M_A}{Wt\%_A / M_A + Wt\%_B / M_B}$$

A: alloying element
B: base element
M_A: the atomic weight of alloying element
M_B: the atomic weight of base element

In Fig. 2, it is found that the vapor pressures of Zn and Mg are approximately 10^2 and 10 Torr respectively at 1000°C, which are extraordinalily higher than 4×10^{-5} Torr of Cu, the principal alloying element of 2xxx grade aluminum alloys.

The effect of this vaporization phenomenon is proved by spectrum analysis on the longitudinal cross-section of weld fusion zones of 7075. The results are summerized in Table 3, in which vaporization rate is greater for Zn than for Mg, and increases as welding speed is reduced, Zinc content becoming below the specification requirement at a welding speed of 1250mm/min.

Table 3 Chemical composition of weld fusion zone (%)

Welding speed (mm/min)		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Specification		<0.50	<0.70	1.2-2.0	<0.30	2.1-2.9	0.18-0.40	5.1-6.1	<0.20	Bal
Base metal		0.10	0.21	1.50	0.03	2.50	0.20	5.38	0.01	
Weld fusion zone	125	0.10	0.21	1.48	0.03	2.14	0.20	3.70	0.01	
	500	0.10	0.21	1.48	0.03	2.35	0.20	4.50	0.01	
	1250	0.10	0.21	1.48	0.03	2.45	0.20	4.28	0.01	
	1750	0.10	0.21	1.48	0.03	2.50	0.20	5.10	0.01	

Observation of weld bead formation during welding and the resulted bead appearance also implies that alloying elements vaporize at considerable rate in 7075. Distinct differences in the colors of clectron beam (spectra) also exist.

3. Mechanical Properties of EB Welded 7075-T6

3.1 Preliminary test for set up of welding condition.

Plates of 7075-T6 57mm thick, were EB full penetration welded at 1 pass, by the welding condition shown in Table 4-1, at several welding speed. Internal and external quality were tested and shown briefly in Table 5. The tensile test specimens across the weld seam

Table 4-1 Welding conditions for 57 mm thick 7075-T6 plates

Accelerating Voltage	Welding Speed	Beam Current*
55 kv	127 mm/min (5 ipm)	240 mA
"	254 " (10 ")	290 mA
"	635 " (25 ")	360 mA
"	1,016 " (40 ")	470 mA
"	1,524 mm" (60 ")	600 mA
"	2,032 " (80 ")	600 mA**
"	2,540 " (100 ")	600 mA**

Welder : 60 kv, 500 mA
Work distance : 127 mm (5")
Focus : 25 mm (1") above the specimen surface at small current
a_b : 1.2 at small current; 1.0 at 250 mA current
Atmosphere : 1×10^{-4} torr

* Beam current was set at 20% over the current value with which the 57 mm thick plate can be penetrated thru by one pass.
** No higher current due to the welder capacity limitation.

Table 5 Weld quality at various welding speed

Welding Speed (ipm)	127mm/min(5)	254mm/min(10)	635mm/min(25)	1,016 mm/min(40)	1,524mm/min(60)	2,032mm/min(80)	2,540mm/min(100)
Appearance & consistency of weld bead	◐	◐	○	○	○	○	◐
Crack in deposit metal	○	○	○	○	◐	◐	◐
Crack in HAZ	○	○	○	◐	◐	●	●
Cold shut	●	◐	◐	◐	◐	◐	◐

○ good ● bad

(Fig. 3) were machined from this weld plates and subjected to test. The test results were as shown in Fig. 4. According to these experimental results, welding speed of 25 ipm seems to give the best quality and strength in the range of welding condition tested. As the speed becomes higher, there appeared the intergranular cracking of heat affected zone along the flow of the plate and the deposit metal cracking (Photo. 3). At the slower speed region, the formation of weld bead was not uniform any more (in this welding position) and the resultant cold shut prevails very much. Cold shut trouble also increased as the welding speed became higher.

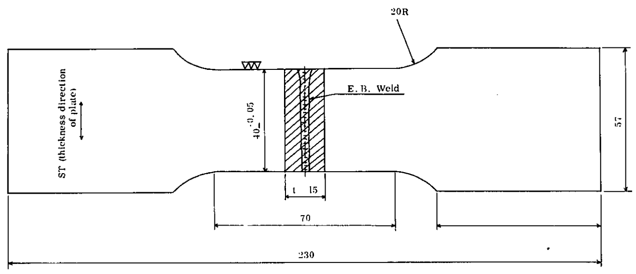


Fig. 3-1 Tensile test specimen

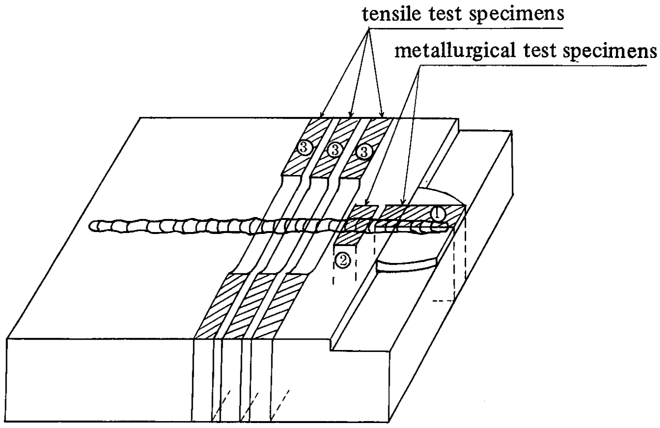
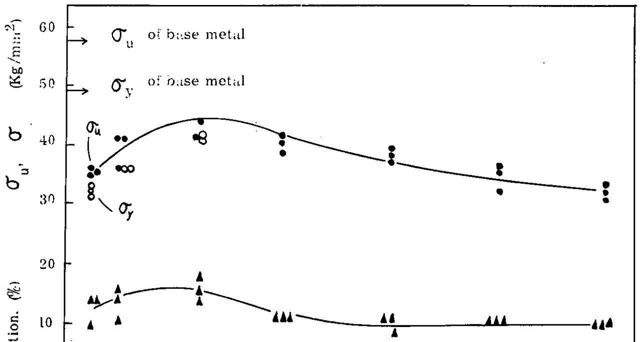
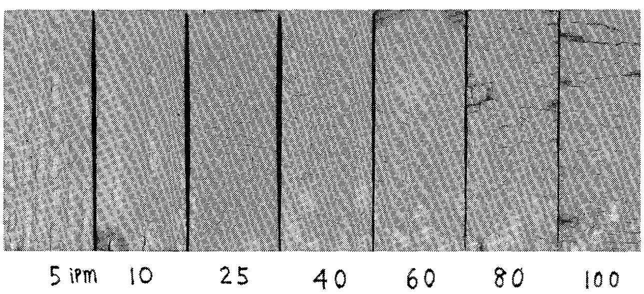
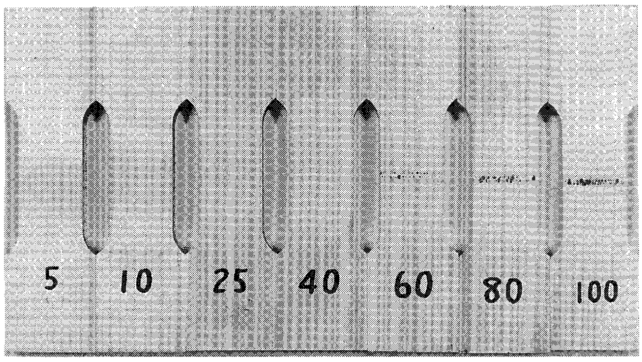


Fig. 3-2 Cutting plan for 57mm thick plate

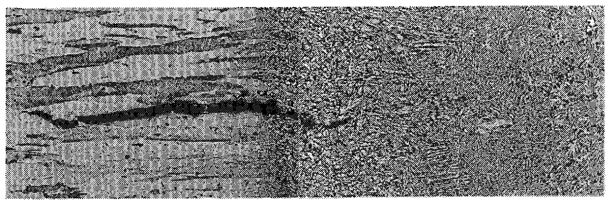




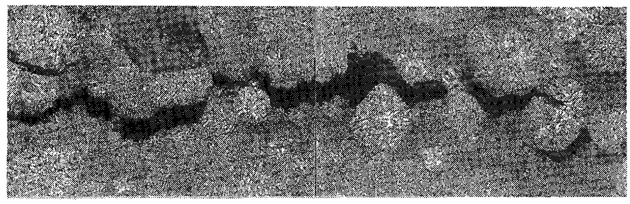
Fracture appearance
Note: White area is cold shut
Fig. 4 Tensile test results of various welding speed on 57mm thick plate



Penetrant inspection on intergranular fusion



Micro photo of above intergranular fusion x 100



Crack in deposit metal x 100

Photo. 3 Defect in weld

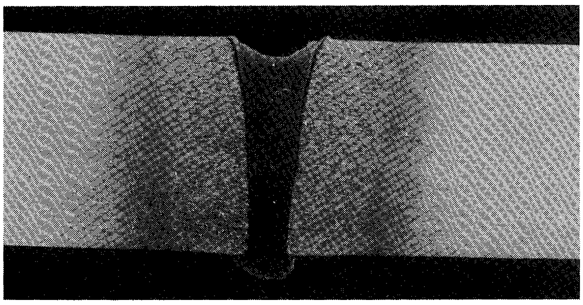
3.2 Static tensile test

Another tensile test was accomplished on 6.0 mm thick 7075-T651 plates. The welding speed of 25 ipm was chosen by the experimental results above-mentioned, and the whole welding condition was as shown in Table 4-2.

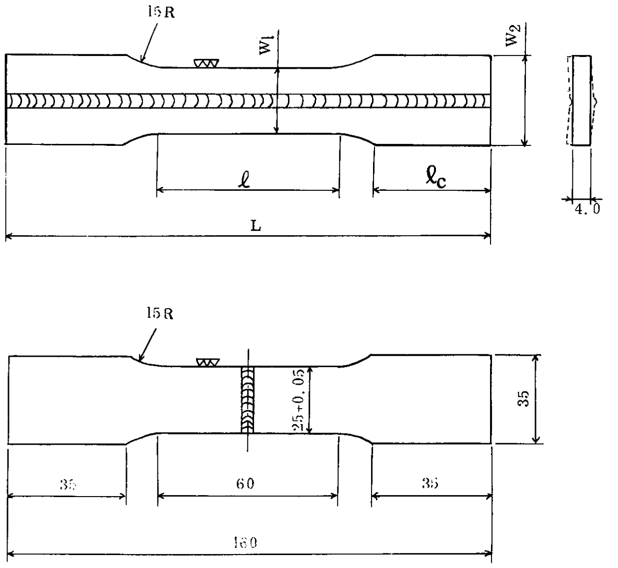
The strength under tension both along and across the weld seam direction was taken this time. For tensile test along the direction of weld seam, 4 different kind of specimen with the width of 2 mm (almost all deposit metal specimen), 15 mm (deposit metal and heat

Table 4-2 Welding condition for 6 mm thick and 30 mm thick plate

Plate thickness	6.0 mm	30 mm
Accelerating voltage	40 kV	50 kV
Welding speed	635 mm/min(25 ipm)	635 mm/min(25 ipm)
Beam current	55 mA	225 mA
Focus	1.3	1.2 at small current 1.0 at 250 ~50 mA range



cross section of 6mm thick plate



Dimension (mm)

T.P. No.	W_1	ℓ	W_2	ℓ_c	L
1	2 ±0.05	60	5	60	210
2	15 ±0.05	60	25	60	210
3	40 ±0.1	80	55	80	270
4	80 ±0.2	160	100	80	350

Fig. 5 Tensile test specimen of 6mm thick 7075−T651

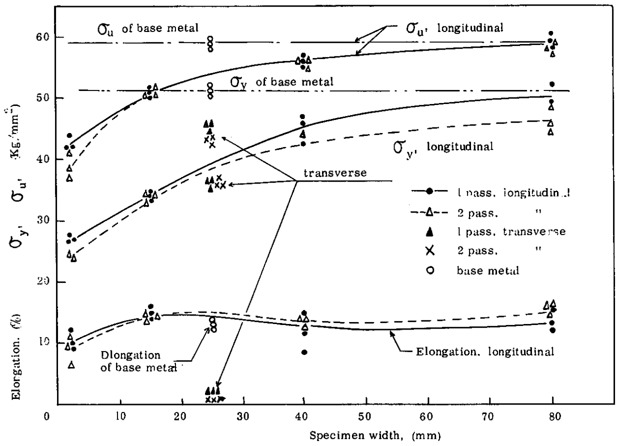


Fig. 6 Tensile test results

affected zone contained), 40 mm and 80 mm was pulled. The cutting plan details and the configuration of the specimen are shown in Fig. 5.

These test results (Fig. 6) across the seam show that the ultimate joint strength as high as 45 kg/mm^2 can be get? But the elongation was very small (2% at gage length 25 mm) and the fracture mode does not appear to be ductile enough (the same as Fig. 4., 25 ipm specimen, the fracture plane was flat and perpendicular to the tensile direction and the plate surface). However, the elongation is restricted to the narrow soft zone of weld deposit and HAZ. So this lack of elongation does not mean that the weld joint is very brittle and useless, we will discuss this matter from the fracture toughness standpoint afterwards.

The test results along the weld seam reaches very near to the base metal strength at the specimen width as short as 40 mm (only 5 kg/mm^2 less than base metal) due to the narrow weld characteristic of EB welding.

In this test, no defect including cold shut was found in the specimen and fracture face. But the strength of joint was about the data of 25 ipm specimen in Fig. 4. The effect of cold shut defect on the joint static tensile strength seems to be negligible if the extent is less than those found in the 25 ipm specimen here.

3.3 Fracture toughness test

Plates of 7075-T6, 30 mm thick, were butt welded according to the welding condition shown in Table 4-2.

Non destructive and metallurgical inspections of welded zone did not indicate weld defects at all. CKS type fracture toughness test specimens (Fig. 7) of 25 mm thickness were machined from welded plates above mentioned. Tests were made both in the as-welded and postweld T6 treated conditions. Notch was located at the center of weld fusion zone or weld bond. Test pieces were precracked on a bend testing machine rated 1690 cps, and then tensile tested using a universal testing machine in LT direction.

Test results are listed in Table 6. Fracture mode is shown in Photo. 4.

Table 6 Fracture toughness test result

Specimen No.	Condition	Location of notch	Location of crack point	Fractured at	Kc $Kg\sqrt{mm}/mm^2$
WD-1	as welded	bead center	bead center	center center/bond	139
-2	"	"	"	" "	127
-3	"	"	"	bead center	127
-4	"	"	bond	bond	110
-5	"	"	bead center	bead center	135
WB-1	"	bond	HAZ	base metal	108
-2	"	"	"	"	122
-3	"	"	"	"	126
-4	"	"	"	"	123
HD-1	T6 after weld	bead center	bead center	bond	130
-2	"	"	"	bead center	102
HB-1	"	bond	bond	HAZ	112
-2	"	"	"	"	103
-3	"	"	"	"	105
Base metal-1	T6	center			84
-2	"	"			84
-3	"	"			83

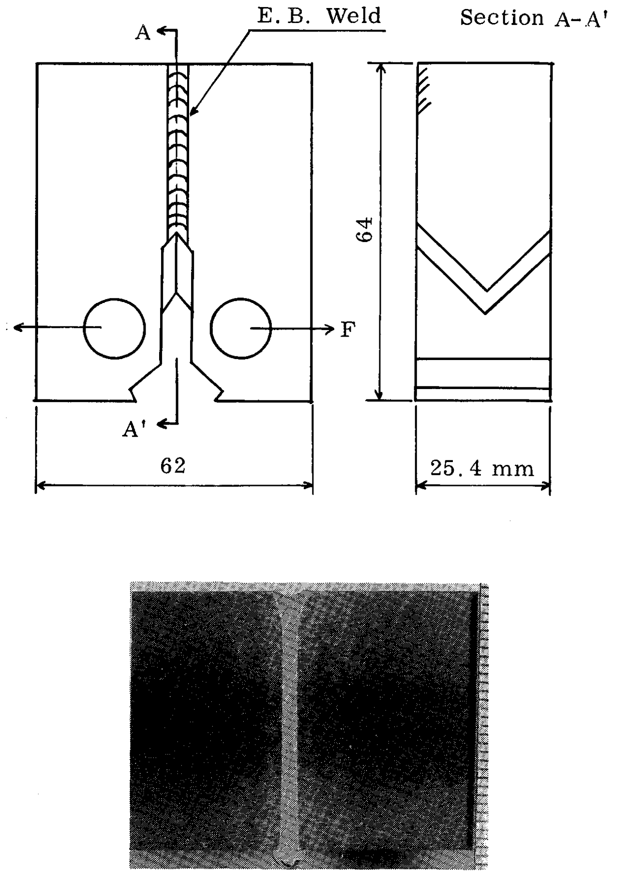


Fig. 7 Fracture toughness test specimen

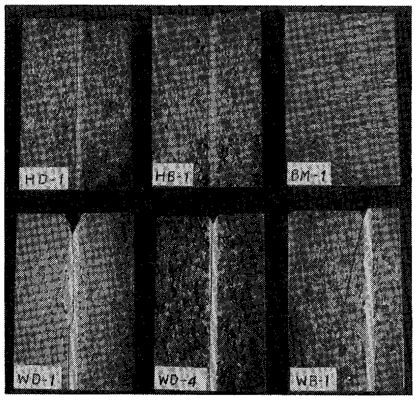


Photo. 4 Fracture mode (fracture toughness test)

Test results are as follows;

1) The fracture toughness of welded zone exceeds that of base metal ($84kg\sqrt{mm}/mm^2$), independently of the conditions after welding and the location of notch. The strength in the as-welded condition, in particular, reaches 124 kg $\sqrt{mm}/mm^2$, which is 1.5 times as high as that of base metal. Individual toughness values are considerably uniform.
2) The fracture toughness value of postweld heat treated specimen also exceed 100 kg $\sqrt{mm}/mm^2$. In this case hardness distribution is uniform and there exist no soft zone of weld.
3) Some of the fracture surfaces shift from weld fusion zone to weld bond. Imcomplete fusion is suspected at the shift point, but no decrease in fracture toughness is accompanied.

4) The fracture of test pieces notched at weld bond wholly propagates from heat affected zone to base metal.
Test pieces recovered in hardness through postweld T6 treatment has shown the same inclination, proving the superior toughness of weld fusion zone.
5) All of the fractured surfaces exhibit normal plain-strain condition.

4. Summery

1) Partial penetration phenomenon of EB welded aluminum alloys is considerably affected by vaporizing alloying elements. In the welding of 7075 and 5083 which contain high-vaporization-pressure elements of Zn and/or Mg, the bead surface is irregular and rugged, and narrow penetration about twice as deep as 2xxx aluminum alloys is obtained with high inclination of occurring the root defects such as cold shuts or spikes.
2) Tensile strength of EB welded 7075 T6 reaches as high as yield strength (0.2% offset) of base metal if proper welding condition is employed, but the fracture appears to be brittle with very small elongation and bend test develops the same result. Fracture toughness of welded zone, however, exceeds that of base metal, proving superior weld toughness.

Reference

1) M. Ohsumi, et al,: MITSUBISHI JUKO GIHO, (1970-5)
2) A. H. Meleka: Electron Beam Welding: Published by Mcgraw-Hill (1971)
3) Y. Arata et al.: Study on Characteristics of Weld Defect and its Prevention in Electron Beam Welding, (Report I, II, III), Trans. of JWRI Vol 2, No.1 (1973); Vol 3, No.1, No.2 (1974)