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Study on Characteristics of Weld Defect and its Prevention in Electron Beam Welding (Report III)†
—Characteristics of Cold Shut—

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Abstract

The investigations of the characteristics of cold shut occurred in the electron beam weld metal have been done using aluminum and iron-based alloys.

Consequently, three types of cold shuts occurred as follows. They are; a-type occurred in the spikes, b-type occurred in connection with the porosity, c-type occurred in the vicinity of root except a-type and b-type.

A lot of occurring numbers of cold shuts belonging to c-type in the weld metal of aluminum alloy was observed compared with the case in the iron-based alloy.

It was recognized that cold shut tends to exist in the vicinity of strong spike and this condition corresponded well with the occurring zone of R-porosity.

It was known that the high pressure vapor element included in the base metal segregated in the cold shut zone unlike ripple line and its metallurgical combination was defective.

1. Introduction

It is well known that there are various kinds of typical weld defects in the electron beam weld metal. The occurring characteristics and metallurgical features of weld porosities among these defects have been already reported[1), 2)].

On the other hand, the cold shut is a special microscopical weld defect like a crack at first sight only seen in the electron beam weld. It is very difficult to be detected by the non destructive inspection according to the visual and radiographic inspection, further by the macroscopic observation about weld section unlike the porosity case.

It is considered that the shape of cold shut presents so sharp appearance like a crack different from the porosity that the defect drops the notch toughness and fatigue strength of the weld metal and remarkably affects the mechanical properties of weld joint. Study about these questions is not practically carried in the present situation.

Therefore, in this study, characteristics of the cold shut occurred in the electron beam weld metal was investigated utilizing few kinds of materials used such as aluminum alloy and so forth. That is; with the investigations about the condition of the occurring distribution of cold shut, the solidification structure and elements analysis in the vicinity of cold shuts, relation between cold shuts and spikes, porosities, bending and fatigue test of the weld including cold shuts were performed. And also by the measuring of the temperature at the weld, some consideration about the occurring causes of cold shuts was done. The results of these experiments are reported hereinafter.

2. Experimental Procedure

2.1 Material used

Materials used in these experiments are as follows: These materials used are three kinds of Aluminum Alloys such as 1200 pure aluminum, 5083 alloy which contained 4.6% magnesium and 7NO1 alloy which contained 4.6% zinc, 1.2% magnesium respectively, and two kinds of iron-based alloys such as SM41 carbon steel for weld structure and SUS304 austenitic stainless steel. All of aluminum alloys were annealed after rolling. The shape of the weld specimen is of 200—300 mm in length, 100 mm in width and 30 mm in thickness. Chemical composition of these materials used is shown in **Table 1.**

Table 1. Chemicbl compositions of materials used.

Wt (%) – | – p.p.m.

Element / Material	C	Si	Mn	P	S	Fe	Ni	Cr	Cu	Al	Mg	Zn	others	H	O	N
1200	—	0.13	0.01	—	—	0.54	—	—	0.03	Bal.	—	0.01	—	0.4	24	1.6
5083	—	0.14	0.64	—	—	0.21	—	0.15	0.04	Bal.	4.60	0.01	Ti 0.02	0.4	6	16
7NO1	—	0.11	0.39	—	—	0.23	—	0.23	0.07	Bal.	1.20	4.64	Ti 0.08 Zr 0.13	0.5	15	8
SM41	0.18	0.04	0.79	0.009	0.015	Bal.	—	—	—	—	—	—	—	0.0	316	35
SUS304	0.08	0.79	0.99	0.025	0.010	Bal.	8.76	18.29	—	—	—	—	—	4.4	29	230

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2.2 Welding Method and Conditions

Two kinds of whole vacuum type of EB-welder, 150KV—40 mA (6 KW) High Voltage Type (Hamilton Type) and 60 KV—500 mA (30 KW) Low Voltage Type (Sciaky Type), were employed and with welding bead as the material used, a bead-on-plate test by the partial penetration welding was performed. As a procedure, the upslope and downslope welding was performed as in the last time experiments adopting slope welding method.

To establish this experimental welding conditions, penetration depth of aluminum alloy aimed at almost 20 mm in both cases of using high and low voltage type welders and in case of iron-based alloy, about 30 mm penetration depth was aimed at. Welding conditions adapted was shown in **Table 2.**

Table 2. Welding conditions used in this experiment.

Welding condition / Materials	Beam voltage V_b (kv)	Beam current I_b (mA)	Welding speed v_b (c.p.m)	Visual focal point D_F^* (mm)	Slope angle θ_s (°)	Pressure P_{ch} (Torr)
1200	150	30	60	280	±30	4×10^{-4}
	50	150	160	200	±30	〃
5083	150	30	60	280	±30	〃
	50	100	160	200	±30	〃
7N01	150	30	60	280	±30	〃
SM41	150	30	30	280	±30	〃
SUS304	150	30	30	280	±30	〃

2.3 Observation of Cold Shut and Measuring Method

Microstructure at the longitudinal sections of the various materials of beads welded by the partial penetration welding method in welding condition which had mentioned above was observed. Etching reagents mentioned below were employed by the cold shut observation in the optical microscopic structure.

SM41, SUS304—10% $C_2H_2O_4$ electrolytic etching
1200, 5083, 7NO1—20% $HClO_4$ electrolytic polishing
5% HF etching

Concerning about the measurement of the cold shuts occurred, numbers of cold shuts which was observed within a range divided at 0.05 intervals of a_b^* value respectively (28 mm in high voltage type, 20 mm in low voltage type) in the longitudinal section specimen were measured by using optical microscope. Besides, about a typical cold shut, elements analysis was performed by a electron probe microanalyzer (EPMA).

2.4 Bending and Fatigue Test

A simple bending and fatigue test were performed to investigate the influence by the cold shuts affecting mechanical characteristics. And the metallurgical characteristics of the weld including cold shuts were investigated. Brief drawing of bending test is shown in **Fig. 1.** Bending test specimen was adopted from longitudinal section specimen as shown in Fig. 1 to form a right angle with its direction to the longitudinal direction of the specimen when the cold shuts locate at the adjacent zone of its center.

Size of the bending test specimen is 5 mm in thickness ×5 mm in width ×50 mm in length. Observable face of the cold shut in this specimen as a bending face was to form an angle of 5°. Instron universal testing machine was used in this bending test.

The change of the cold shuts clearance was observed from the microstructural point after bending test. Further, fracture surface pattern of the cold shut in the broken specimen by the bending test was observed through a scanning electron microscope and investigated its partial elements analysis by EPMA.

Fatigue test was performed by means of Schenk type fatigue testing machine (Max. 30 Kg-m, 1800 r.p.m). Specimen's shape used and adopting method is shown in **Fig. 2.**

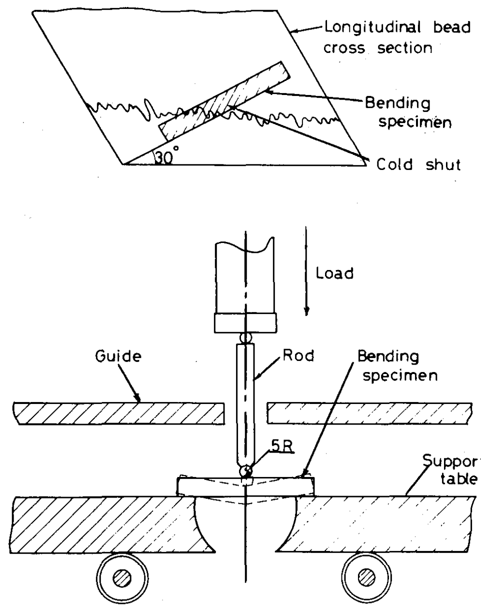


Fig. 1. Experimental procedure for bending test.

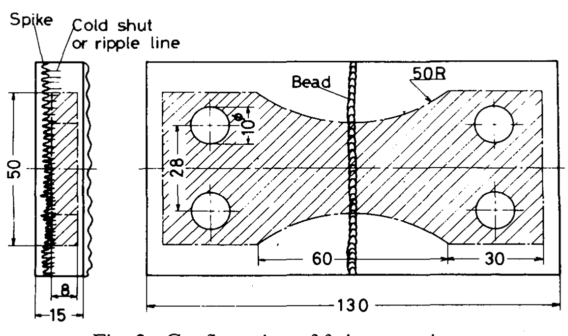


Fig. 2. Configuration of fatigue specimen.

3. Experimental Results

3.1 Occurring Form of Cold Shut

After the micro-structural observation of the cold shut occurred in the welding metal about each material used, its type can be classified into three types as follows:

1) Occurred in spike (a-type)
2) Occurred in relation to the porosity (b-type)
3) Occurred in the adjacent root zone except 1) and 2) (c-type)

Typical forms of cold shuts were shown in **Photo. 1.**

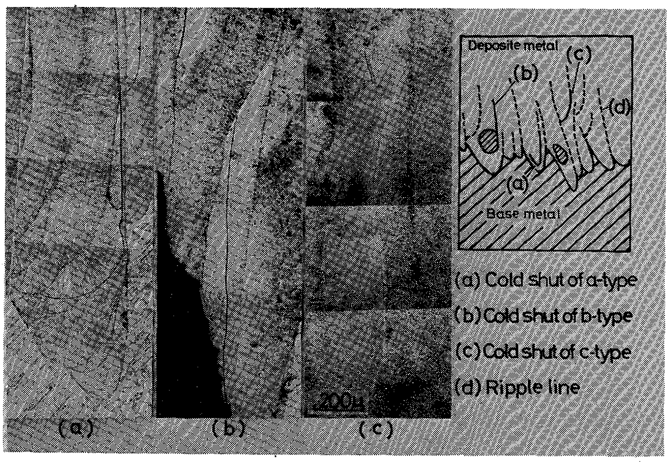


Photo. 1. Microstructures of various type of cold shut (SUS304).

Cold shut in a-type was sometimes called 'Necklace' cracking[3)] and lots of them were seen at the spike portion where no porosities appeared and they were realized when comparatively weak spikes existed.

Cold shut in b-type especially has a strong relativity with the R-porosity. In many cases, few cold shuts were occurred from one porosity.

Lots of cold shuts in c-type were observed to the utmost among these three types especially in aluminum alloy. Cold shut in aluminum alloy is short as its feature in length compared with it in the iron-based alloy. It was observed that the cold shut occurred in using low voltage type welder was comparatively longer in length than in high voltage welder.

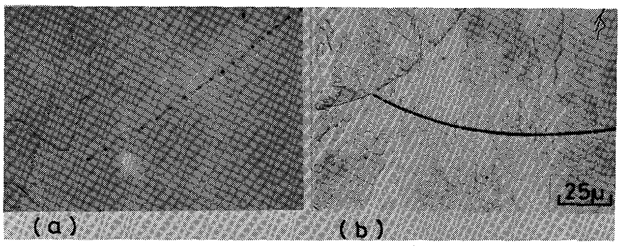
In structural observation by an optical microscope, cold shuts were clearly observed with about 400 magnifications using etching reagent mentioned in the item of experimental method and distinguished easily from ripple line.

This example is shown in **Photo. 2.**

3.2 Occurring Distribution of Cold Shut

The results of measurements about the distribution of occurred cold shuts are as follows.

A case of upslope and downslope welding in the high voltage type electron beam weld metal is shown in **Fig. 3** and **Fig. 4,** upslope welding in the low voltage type electron beam weld metal in **Fig. 5,** as a distribution curve for each case.



Phot. 2. Microstructures of cold shut and ripple line.
(a) 1200 (b) SUS304

Distribution curve of the spike are shown in Fig. 3, 4 and 5 at the same time in order to compare with these cold shuts. Results of these investigations are mentioned separately in every material as follows.

(1) Aluminum Alloy

As shown in Figs. 3 and 4, many cold shuts were observed within the range of a_b^* which expresses 0.55—0.85 in both of the upslope and downslope welding of 1200 pure aluminum high voltage weld. Especially, this tendency was remarkably found in the adjacent zone of maximum penetration welding position ($a_b^* \fallingdotseq 0.65$). On the other hand, cold shuts occurred within the range of a_b^* which expresses 0.70—1.20 in the low voltage type and numbers of occurring in maximum value is about 1/2 of numbers in case of high voltage type.

In 5083 alloy, cold shuts were occurred over the wide range with the maximum occurring value which shows higher or equal value compared with the case of 1200 pure aluminum and its occurring positions were strikingly found in the maximum penetration position.

Occurring numbers of the cold shuts showed almost constant maximum value in the a_b^* value expressing over 0.65 in case of the upslope welding of 5083 alloy in the high voltage type. In case of the downslope welding its numbers showed maximum value in the a_b^* value expressing 0.65 and its tendency also showed the same as in 1200 aluminum.

Besides, the same tendency as mentioned above was recognized in the cold shuts occurring in 1200 aluminum and 5083 alloy in case of the low voltage type and the numbers showed almost constant value when a_b^* value expressed over 0.85 in the 5083 alloy's case.

Lots of cold shuts occurred over the wide range of a_b^* both of the upslope and downslope welding by the high voltage type in 7NO1 alloy and many of them

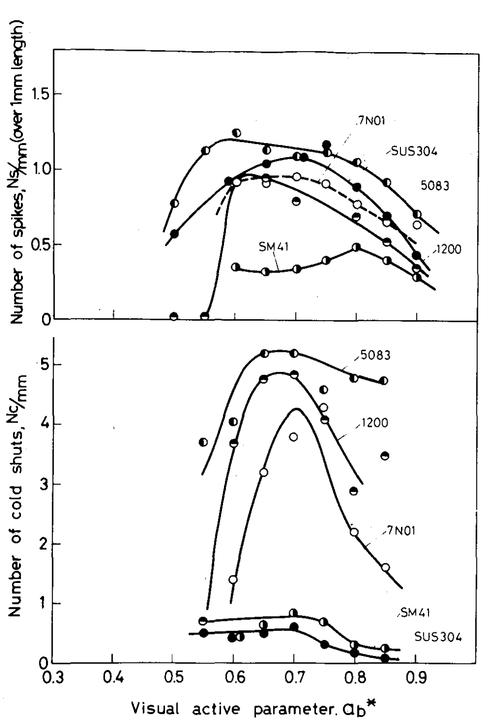


Fig. 3. Relationship between visual active parameter (a_b^*) and cold shut, spike number in the beam welds. (upslope welding in high voltage type.)

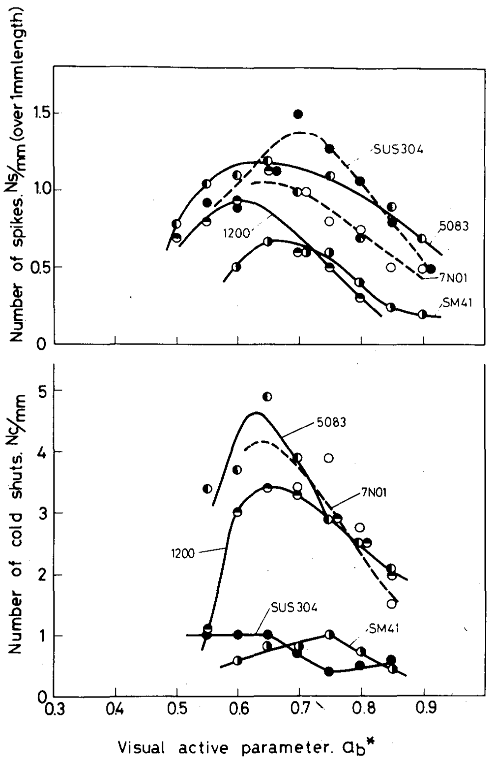


Fig. 4. Relationship between visual active parameter (a_b^*) and cold shut, spike number in the beam welds. (downslope welding in high voltage type.)

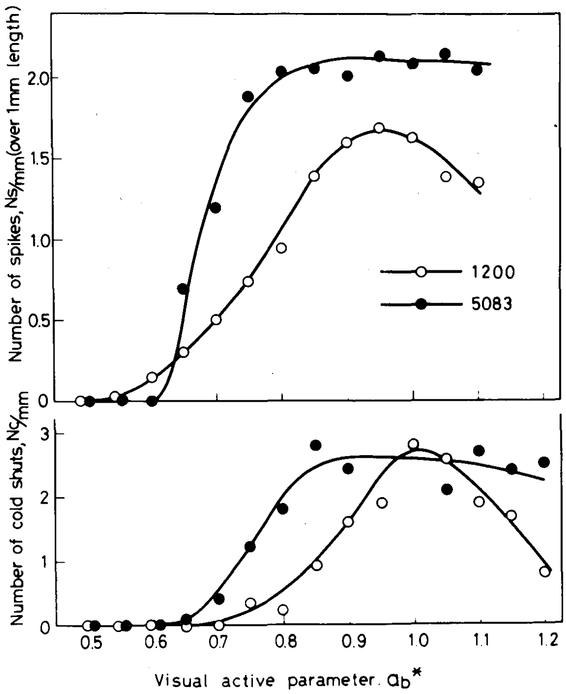


Fig. 5. Relationship between visual active parameter (a_b^*) and cold shut, spike number in the beam welds. (upslope welding in low voltage type.)

were remarkably observed in the adjacent zone where the maximum penetration depth was obtained. This tendency was found in case of 1200 aluminum as well.

It is considered that the occurring numbers of cold shuts were generally fewer to some extent in the downslope welding than in upslope welding in any alloys of 1200, 5083 and 7N01 by the high voltage type.

(2) Iron-based Alloy

Cold shuts occurred over the wide range of a_b^* value in SM41, SUS 304 weld by the high voltage type. However, its occurring numbers were very few compared with aluminum alloy in its maximum value which were 1/4—1/5 of numbers in aluminum alloy.

The remarkable difference of the cold shuts between the cases in the upslope and downslope welding was not observed. And the relativity between the cold shuts occurring tendency and penetration depth was not specially recognized.

3.3 The relation between Cold Shut and Spike, Porosity

A distribution curve of the occurred cold shuts in comparison with the curve of the occurred spikes as shown in Fig. 3, 4 and 5, any relations in the distribution tendency between both of them were not recognized in case of iron-based alloy such as SM41 and SUS 304. However, they corresponded mutually well in aluminum alloy and showed a tendency that the more spiking numbers increases the more cold shuts occurred.

Longitudinal section of macrostructure and radiograph of the weld by the low voltage welder in 1200

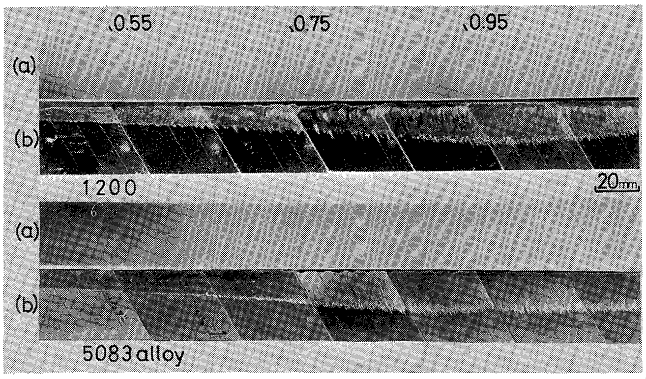


Photo. 3. Radiographs and macrostructures in the longitudinal section of aluminum alloy beam welds.
(a) Radiograph (b) Macrostructure

and 5083 alloys are shown in **Photo. 3.**

Some weak spike existed under 0.62 of a_b^* value at which the cold shut began to be occurred in 5083 alloy and the spikes became strong as numbers of the cold shuts gradually increased. And a lot of needle spikes was observed at the a_b^* value which is over 0.85 where the occurring numbers of cold shuts became nearly constant.

Above mentioned situation showed the same tendency about 1200. The spike became gradually weak at a_b^* value exceeds 1.05 carrying the decreasing numbers of the cold shuts occurrence.

As the relation between cold shuts and the porosity was clearly shown in the radiograph, the occurred R-porosity was recognized at the position where the cold shuts began to occur at a_b^* value is equal to 0.62 in 5083 alloy. The shape of the R-porosity showed rather roundness until the occurred cold shuts has obtained the maximum numbers. However, the R-porosity showed mostly a needle like shape at a_b^* value exceeds 0.85.

Thus, it was recognized that the occurrence of cold shuts has a close relation with the occurring condition of porosity and spike than the depth of penetration.

The starting point of the cold shut occurring in the small side value of a_b^* showed a tendency with the smaller a_b^* value than in the starting point of the R-porosity occurring in 1200 slightly unlike to the condition of 5083.

3.4 Results of Elements Analysis of Cold Shut

Elements analysis of cold shut existed at the weld and ripple line portion was performed by EPMA. As a results, segregation of magnesium in 5083 alloy, zinc in 7NO1, manganese in SM41 and SUS 304 in the cold shut portion was recognized. The elements except aluminum was not obseved about the cold shut portion in 1200 pure aluminum.

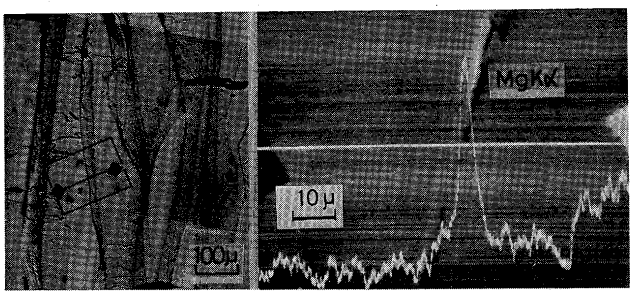


Photo. 4. Line scanning analysis across cold shut in 5083 alloy beam welds.

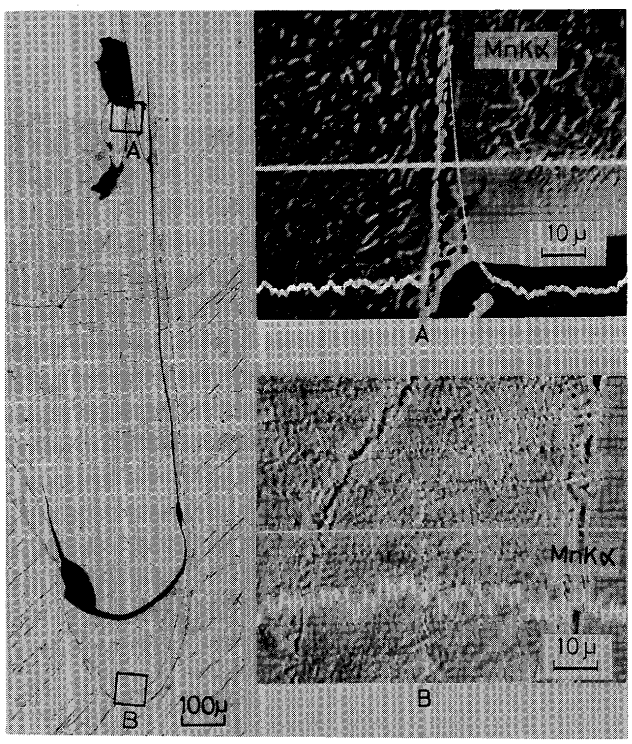


Photo. 5. Line scanning analysis across cold shut (A) and ripple line (B) in SUS304 beam welds.

Elements analysis was performed about ripple line. However, any remarkable segregation was not observed in any of the materials used. One of these results of typical analysis is shown as an example in **Photo. 4** and **5.**

3.5 Results of Bending and Fatigue Test and Fracture Observation

The change was observed in performing bending test of the weld including cold shut. It was recognized that cracks occurred along the cold shuts in the whole material used. Microstructure before and after bending test of 1200 and SUS 304 is shown in **Photo. 6.** Observation of cold shut before bending test without etching was impossible, so it was certified the crack had not existed originally.

Scanning electron microphotograph of cold shut

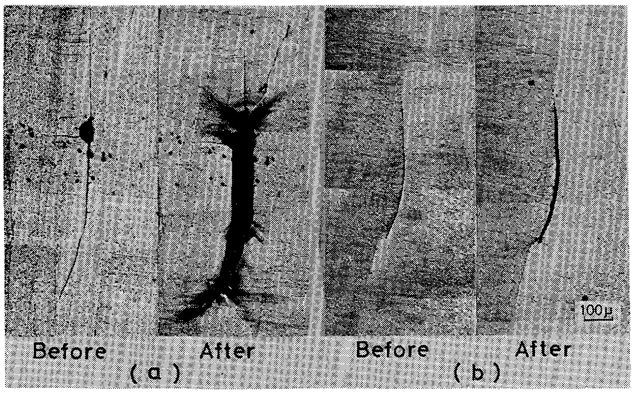


Photo. 6. Microphototographs of the cold shut before and after bending test.
(a) 1200 (b) SUS 304

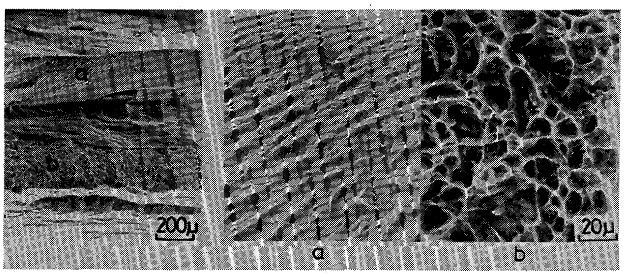


Photo. 7. SEM of fracture surface after bending test (1200).
(a) Cold shut (b) Deposite metal

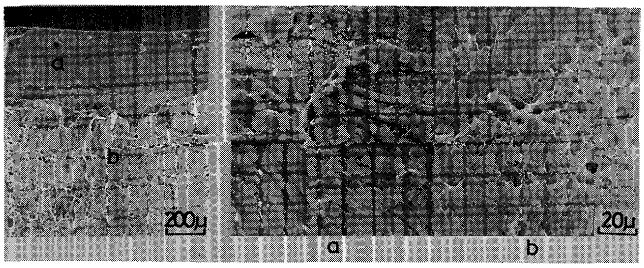


Photo. 8. SEM of fracture surface after bending test (5083 alloy).
(a) Cold shut (b) Deposite metal

fracture surface in 1200 and 5083 alloys is shown in **Photo. 7** and **8.** Dimple pattern like layer was observed partially in 1200 and cellular pattern resembling with a pattern inside the R-prosity was observed partially in 5083 alloy by Photo. (a). It was known that the pattern of the cold shut fracture surface was utterly different from the dimple pattern observed in a sound welding fracture surface as shown in Photo. (b) had a defective metallurgical combination.

After direct spot analysis about these fractures surface by · EPMA the elements except aluminum didn't practically exist in 1200. Segregation of magnesium and manganese were observed respectively as the case of cold shut section in 5083 alloy and SUS 304.

The results of a fatigue test concerning the weld including cold shuts, sound weld, base metal by using

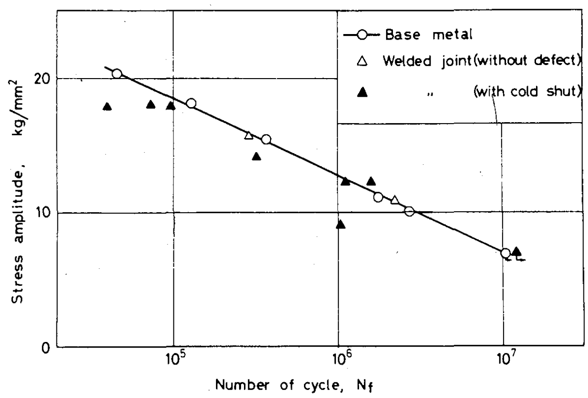


Fig. 6. Results of fatigue test of 5083 alloy welded joint.

5083 alloy is shown in **Fig. 6.** The weld including cold shuts showed a tendency to drop the fatigue strength with loosening without any constant relations like a base metal or a sound weld which has the straight lined condition.

In observation of the fatigue fracture surface by a scanning electron microscope, it was recognized that the same patterns as found in the fracture after bending test were observed at every turn and the cold shut influenced the crack occurrence or propagation and worked to drop the mechanical property of the weld metal.

It was observed that the high vapor pressure elements included in the base metal segregated unlike to the ripple line, and its metallurgical combination was defective.

4. Consideration

Characteristics of cold shut occurred in electron beam weld metal was investigated. Further, in order to considerate the cause of the cold shut occurrence, the observation about welding solidification pattern was performed in detail and the relation between the cause of the cold shut occurrence and temperature measurement, the spiking phenomenon, etc. was investigated.

About the existence of three types cold shuts in the beam weld was formerly mentioned. Solidification pattern of longitudinal and horizontal section in the adjacent zone where each cold shut existed is shown in **Photo. 9.** a-type cold shut was observed in the comparatively weak spike zone. In this observation in detail about each solidification pattern, cold shuts existed at times among many ripple lines occurred along the spikes as shown in Photo. 9 (a). Besides, rising of the ripple line in the longitudinal section inclined to the opposite welding direction. Occurrence of the cold shuts was few at the position like this in case of iron-based and aluminum alloys.

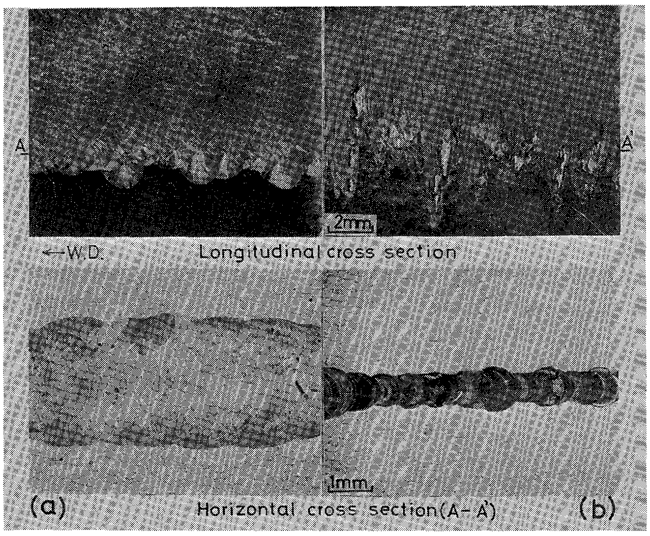


Photo. 9. Macrostructures of longitudinal and horizontal cross section near the root of beam welds. (1200)
(a) $a_b^*=0.50$ (b) $a_b^*=0.75$

b-type cold shut was observed along the porosities existed at the strong spiking portion. It seemed that they occurred for no epitaxial growth by a heat shortage with melted metal inflowed into the porosity at its solidification time. Many b-types were observed in the iron-based alloy.

c-type cold shut occurred in the adjacent zone to the root where strong and needle spikes existed, as shown in Photo. 9 (b), solidification pattern of horizontal section showed the pattern like spot traces probably by an unequal movement of beam compared with (a) and it occupied much rate. Rising of cold shut and ripple line in the longitudinal section coincided with the direction of beam applying unlike a-type. This type occurred most in aluminum alloy.

It was mentioned that the occurrence numbers of cold shuts in aluminum alloy are remarkably much compared with a case of iron-based alloy. It is considered that the reason was based on the remarkably strengthened spike at the adjacent to the root and its excellent heat conductivity as shown in **Photo. 10.** Many uncertain points are remained about this spiking phenomena.[4]

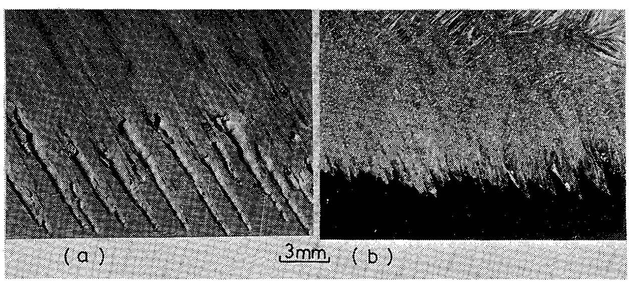


Photo. 10. Macrophotographs of the spike in longitudinal cross section.
(a) 5083 alloy (b) SUS 304

As it was considered that the occurrence of cold shut related closely with the metal vapor behavior and solidification rate that were occurred by the applying of the beam, temperature measurement of the weld was performed using W—W·Re (26%) thermocouple. This result is shown in **Fig. 7.** The welding center had a high temperature of over 3400°C which exceeded boiling point of alloy by far. Solidification rate was estimated as about 5×10^3 °C/sec. Solidification rate at the root was surmised for bigger still more.

It is considered that a striking drilling action was formed by the beam which has very high energitic density when many cold shuts tend to occur. Therefore, according to the few molten metal quantity and a condition of the internal pressure by the produced metal vapor, its inflow to the beam hole became difficult. In addition to this, it was considered that as the former metal had already solidified when the next molten metal was sent in, it didn't weld with inflowed molten metal and separately solidified by the rapid solidification rate.

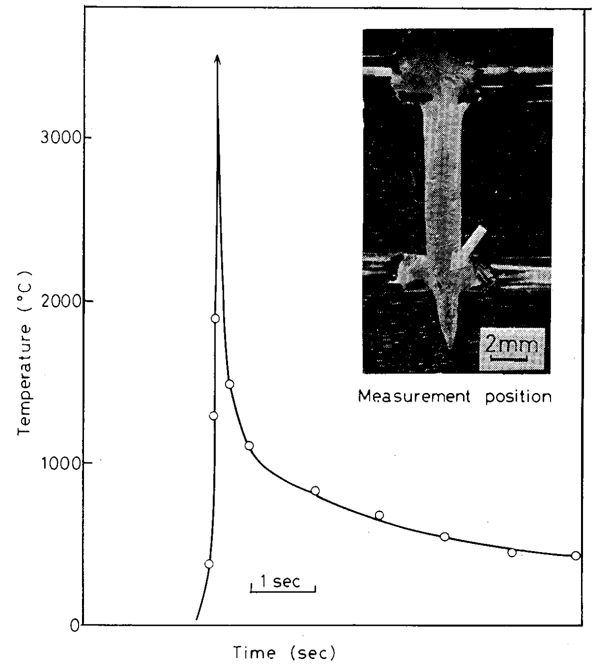


Fig. 7. Results of measured temperature in SUS 304 beam welds.

5. Conclusion

About cold shuts occurred in the electron beam weld metal, the characteristics was investigated by using few kinds of materials like aluminum alloy and some considerations were performed on the cause of its occurrence. The obtained results are as follows.

1) Cold shuts existed in the electron beam weld were classified into three types such as a-type (occurred in the spikes), b-type (occurred in

connection with porosity), c-type (occurred in adjacent of root except a-type and b-type). a-type occurred in the comparatively weak spikes. As opposed to this, b-type and c-type occurred in the strong spikes.

2) It was observed that a great many cold shuts occurred in the aluminum alloy weld compared with iron-based alloy.
3) Cold shuts occurred in the aluminum alloy weld showed a tendency that many of them existed at the adjacent zone of the muximum penetration weld obtained by the slope welding method and corresponded well with the occurring zone of the R-porosity. It seemed that the relation of the occurring tendency of cold shuts and penetration depth was not specially observed about iron-based alloy.
4) In this observation with the results of bending test of the weld including cold shuts and fluctures surface, it was known that the cold shuts unlike the ripple line had a very defective metallurgical combination.
5) It was recognized that the high vapor pressure elements included in the base metal segregated in the cold shuts by the results of an element analysis based on EPMA.
6) It was observed that fatigue intensity had a tendency to be dropped without any constant relation and formed the growing loosening compared with a sound weld as the results of a fatigue test about 5083 alloy weld including cold shuts.

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