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Diffusion Welding of Mild Steel to Aluminium †

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Abstract

Diffusion welding between mild steel and aluminium was carried out under various experimental conditions. Intermetallic layer and the position where fracture occurred were analyzed in each specimen. When nickel interlayer was used in vacuum, the tensile strength of the joint became larger than that of aluminium itself. In other cases, insufficient strengths were obtained.

1. Introduction

Diffusion welding has a benefit that the extent of diffusion of the elements in the weld can be controlled because base metals remain solid state in the process. Therefore, it is thought as a suitable technique to weld metallurgically incompatible dissimilar metals. As for joining between mild steel and aluminium, the following factors, the formation of brittle intermetallic compounds of iron-aluminium and the existence of tenacious oxide film on aluminium, should be kept in mind. Thus, silver or nickel in the form of foil or electroplate was generally used as interlayer to overcome the problems above described.^{1),2)}

In this report, specimens, welded in inert gas or in vacuum were compared because treatment in inert gas is important from the industrial viewpoint. The joint was examined with various methods such as tensile test, metallographic observation, X-ray analysis, electron probe microanalysis and ion probe microanalysis.

2. Experimental procedures

2.1 Specimens

SGD2 mild steel and 1050 commercial pure aluminium were used. Their chemical compositions are given in Table 1. After machined to 19 mm ϕ x 50 mm, the surface of the specimens were ground by emery papers

Table 1. Chemical compositions

Specimen	Chemical composition (wt%)									Tensile strength (kg/mm ²)
	Fe	C	P	S	Si	Mn	Cu	Ti	Al	
SGD2	Bal.	0.15	0.013	0.018	<0.01	0.51	—	—	—	42.2
1050	0.18	—	—	—	0.09	<0.01	0.02	0.01	Bal.	11.3

and buff-polished with 0.3 μ m alumina powder. Then, the specimens were degreased by acetone in a few minutes.

The purity of silver foil used as interlayer was 99.98

%. Silver-beryllium alloy containing 0.5 % beryllium was also used as interlayer. The electroplating conditions are given in Table 2.

Table 2. Electroplating conditions

Treatment		Bath composition	Current density A/dm ²	Bath temperature °C
Degreasing	Mild steel	Na ₂ CO ₃ : 80 g/l, NaOH : 20 g/l	—	80
	Aluminium	NaHCO ₃ : 45 g/l	—	60
Pickling	Mild steel	20% HCl	—	25
	Aluminium	3Vols HNO ₃ , 1Vol 50% HF 3Vols H ₂ O	—	25
Ni plating		NiSO ₄ : 330 g/l, NiCl ₂ : 45 g/l H ₂ BO ₄ : 40 g/l CH ₃ (CH ₂) ₁₁ OSO ₃ Na : 0.4 g/l	2.5	50
Cu plating		CuSO ₄ 5H ₂ O : 200 g/l H ₂ SO ₄ : 120 g/l	3	40

2.2 Welding processes

As shown in Fig. 1, apparatus with resistor type heater was used for diffusion welding in inert gas. Argon gas was flowed into alumina tube at the rate of 5 ml/sec.

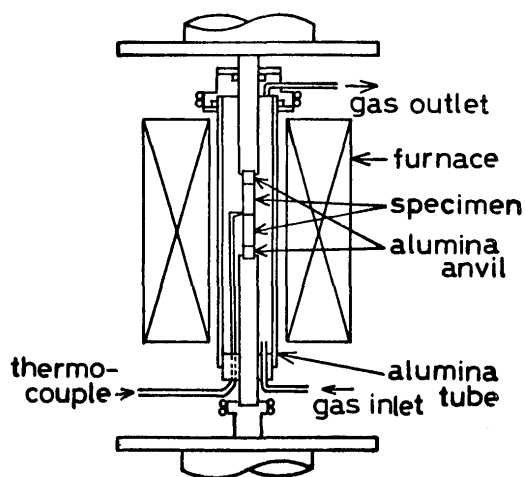


Fig. 1. Schematic diagram of apparatus

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On the other hand, experiment in vacuum was carried out with high frequency induction heater. After setting the samples between anvils in a vacuum chamber, it was evacuated to 10^{-5} torr vacuum.

The temperature of the joint was measured with the CA thermocouple. The welding conditions are given in Table 3. The specimens were cooled down to 150°C in the apparatus after welding.

Table 3. Welding conditions

Interlayer	Atmosphere	Temp. C	Time min.	Pressure kg/mm ²	No.
None	Argon	640	60	0.5	1
	vacuum	625	5	0.5	2
0.2 mm Ag	Argon	575	15	0.5	3
	Vacuum	575	2	0.5	4
0.2mm Ag-0.5%Be	Argon	575	15	0.5	5
	Vacuum	575	2	0.5	6
25 μm Ni plating	Argon	575	15	0.5	7
	vacuum	550	5	0.5	8
Ni-Ag-Cu	Argon	550	60	0.5	9
	Vacuum	550	20	0.5	10

2.3 Analysis

The microstructure of the joint was observed with an optical microscope. Mechanical strength of the joint was measured and the fracture surface was investigated with ion probe microanalyzer (IMA:Hitachi, type IMA-SS). The experimental conditions of IMA are as follows;

primary ion beam diameter: $1\mu\text{m}$
ion source: Ar⁺
accelerating voltage: 10 kV
sample current $2\mu\text{A}$.

Some joints were studied with electron probe microanalyzer (EPMA:Shimadzu, type EMX-SM). X-ray diffraction analysis was made to determine the formation of intermetallic compounds (Rigaku, type D-3F).

3. Experimental results

3.1 Diffusion welding without interlayer

When interlayer was not used, the joint strengths were very poor in every cases. The intermetallic layer formed in the weld was indentified to be Fe_2Al_5 by X-ray and the fracture occurred at the interface between Fe_2Al_5 and aluminium. To know the distribution of trace elements on the fracture surfaces welded in argon gas, IMA technique was applied. Fig. 2 shows the ratios of the output intensities of various secondary ions to Al^+ . Light elements such as carbon, phosphorus and sulphur were enriched on the fracture surface and iron was also detected. It is thought that these elements diffused from mild steel to aluminium and concentrated on the fracture surface. Furthermore, the enrichments of

oxygen, titanium and copper were observed. However, relationship between the enrichment of these elements on the fracture surface and the insufficient strength of the joint remains unclear.

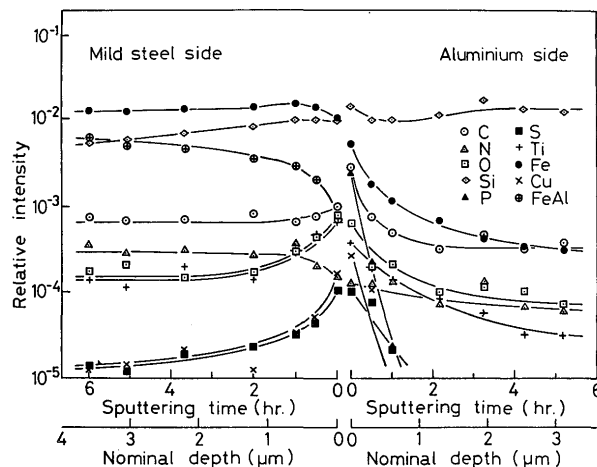


Fig. 2. Relative intensities of various elements on fracture surface vs. sputtering time

3.2 Silver interlayer

When silver interlayer was used, the tensile strength of the joint welded in argon gas ranged from 1.0kg/mm^2 to 1.6kg/mm^2 . On the other hand, the tensile strength of the joint welded in vacuum ranged from 1.9kg/mm^2 to 2.7kg/mm^2 . The microstructure of the joint welded in argon gas is shown in Photo. 1. The results by EPMA

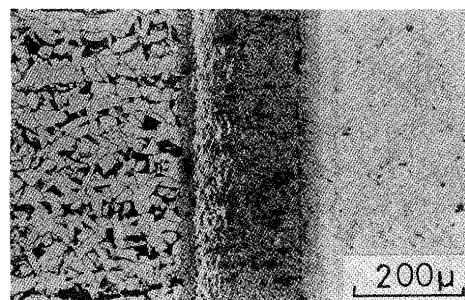


Photo. 1. Microstructure of the joint welded with Ag interlayer

are shown in Fig. 3 and X-ray diffraction patterns are shown in Fig. 4. The results obtained were as follows:

1. Fe_2Al_5 of about $25\mu\text{m}$ thickness was observed in mild steel side.
2. The intermetallic layer of aluminium side was composed of the mixture of Ag_2Al and FeAl_3 .
3. The fracture occurred at Fe_2Al_5 layer.

It is known that beryllium has a controlling effect on the growth of iron-aluminium alloy layers.³⁾ As a trial, silver-beryllium alloy containing 0.5 % beryllium was used as interlayer. Although the addition

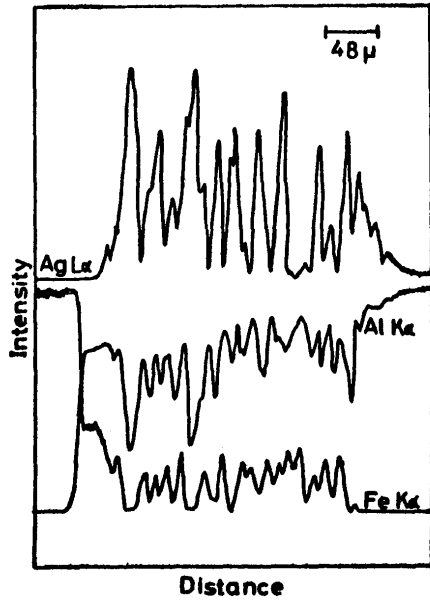


Fig. 3. Elemental distributions in the joint welded with Ag interlayer

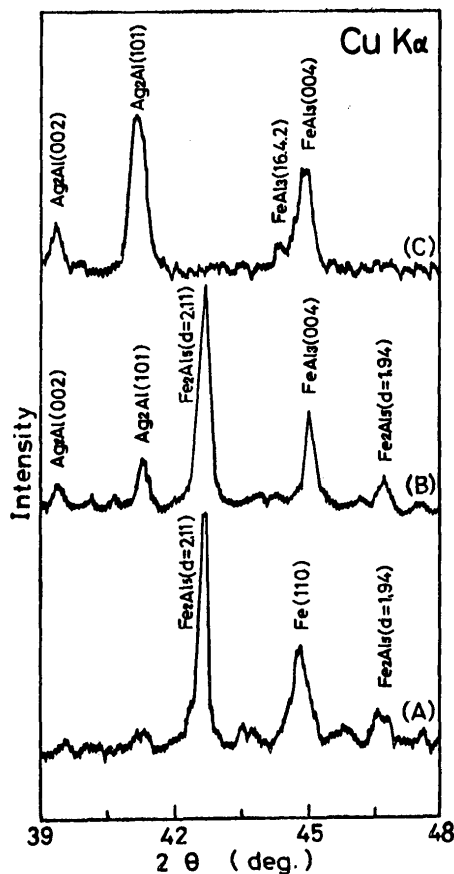


Fig. 4. X-ray diffraction patterns of the specimens welded with Ag interlayer
(A): fracture surface of mild steel side
(B): fracture surface of aluminium side
(C): face exposed after grinding about 50 μm from fracture surface of aluminium side

of beryllium reduced the thickness of Fe_2Al_5 layer to 15 μm, the joint strength was not improved.

3.3 Nickel interlayer

Nickel was electroplated on mild steel surface as interlayer before welding. The microstructure of the joint welded in argon gas is shown in Photo. 2. X-ray diffraction patterns of the fracture surface of aluminium side are shown in Fig. 5. The joint, welded in vacuum, showed the tensile strength larger than that of aluminium. But the tensile strength of the joint ranged from

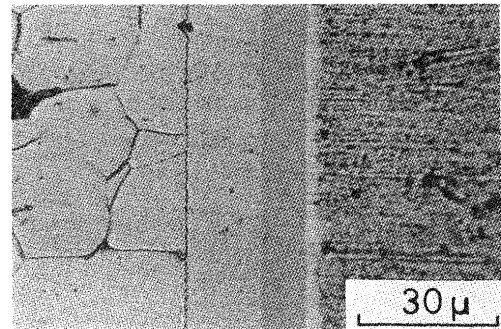


Photo. 2. Microstructure of the joint welded with Ni interlayer

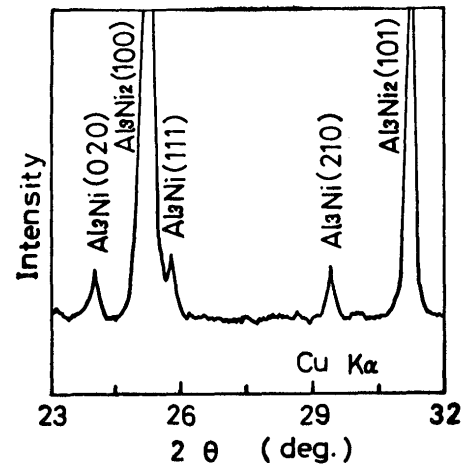


Fig. 5. X-ray diffraction patterns of the fracture surface of aluminium side welded with Ni interlayer

1.4 kg/mm² to 2.0 kg/mm² when welding was carried out in argon gas. The intermetallic layers in the weld were consisted of the following compounds in each joint.

- 1) Al_3Ni_2 of 18 μm thickness and Al_3Ni of 7 μm thickness in the joint welded in argon gas.
- 2) Al_3Ni_2 of 9 μm thickness and Al_3Ni of 2.5 μm thickness in the joint welded in vacuum.

The fracture of the joint welded in argon gas occurred in Al_3Ni_2 layer, partly in Al_3Ni layer and in the interface between Al_3Ni layer and aluminium. Although it was reported that the thickness of Al_3Ni_2 layer affects on the

strength of the joint²⁾, it was difficult to control the thickness of Al_3Ni_2 layer in argon gas.

3.4 Multi-interlayers

As above mentioned, insufficient strength of the joint welded in argon gas could be obtained when a single interlayer was used. As a trial, multi-interlayers consisting of nickel-silver-copper system were used. Nickel of 6 μm thickness was electroplated on mild steel surface. Likewise, copper of 3 μm thickness was electroplated on aluminium surface. Then, these specimens were welded through silver foil of 0.2 mm thickness in argon gas. In comparison with other cases, the joint strength increased to the value ranged from 3.5 kg/mm^2 to 4.9 kg/mm^2 . As an example, the microstructure of the joint is shown in Photo. 3.

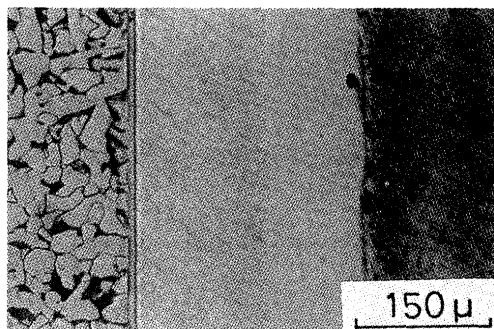


Photo. 3. Microstructure of the joint welded with Ni-Ag-Cu interlayers

4. Summary

Mild steel was diffusion welded to aluminium under various experimental conditions. The conclusions obtained are as follows:

1. Without interlayer: Fe_2Al_5 was formed as intermetallic compound.
2. With silver interlayer: Fe_2Al_5 was formed in mild steel side.
3. With nickel interlayer: Al_3Ni_2 and Al_3Ni were formed in aluminium side.
4. The joint strength was insufficient except when nickel interlayer was used in vacuum.
5. In order to obtain good joint in argon gas, it seems necessary to use multi-interlayer.

Acknowledgment

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