Proposal of New Bonding Technique "Instantaneous Liquid Phase (ILP) Bonding" †

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Abstract

A new bonding technique named "Instantaneous Liquid Phase (ILP) bonding" suitable mainly for welding dissimilar materials was proposed by which instantaneous melting of one or two of the faying surfaces is utilized. The processes of ILP bonding are mainly consisted of three stages, namely the first stage forming thin liquid layer by rapid heating, the second stage joining both specimens by thin liquid layer, and the third stage cooling the specimens rapidly to avoid the formation of brittle layer. The welding temperatures of the specimens to be welded in ILP bonding are generally differentiated from each other.

ILP bonding was applied for a variety of combinations of dissimilar materials of aluminum, aluminum alloys, titanium, titanium alloy, carbon steel, austenitic stainless steel, copper and tungsten, and for similar materials of stainless steel and nickel-base alloy. There were no microvoids in these welding joints, and the formation of brittle layer at the bonding interface was suppressed. The welded joints of Al + Ti, Cu + carbon steel and Cu + austenitic stainless steel showed the fracture in base metal having lower tensile strength. Further, the welded joints of Al + carbon steel, Al alloy + Ti, Al alloy + carbon steel or + austenitic stainless steel, Ti + carbon steel or + austenitic stainless steel showed better tensile properties in the comparison with diffusion welding. Furthermore, ILP bonding was available for welding same materials susceptible to hot cracking. Because of the existence of liquid layer, the welding pressure required was extremely low, and preparation of faying surface by simple tooling or polishing by #80 emery paper was enough. The change in specimen length before and after welding was relatively little, only depending on the thickness of liquid layer. The welding time was very short, and thus high welding efficiency was obtained.

KEY WORDS: (Dissimilar Materials) (Diffusion Welding) (Solid Phase Welding) (Austenitic Stainless Steels) (Aluminum) (Aluminum Alloys) (Copper) (Titanium) (Titanium Alloy) (Inconel) (Carbon Steel)

1. Introduction

Welding dissimilar materials has wide spread industrial application particularly in the aerospace and nuclear industries. Brazing and diffusion welding are often utilized to join dissimilar materials and thus avoid various problems of fusion welding, e.g. brittle layer of compounds due to the liquid-state mixing of elements from both materials. Even in the diffusion welding of some kinds of dissimilar materials, however, brittle layer is formed sometimes due to long reaction time. Another problem of diffusion welding is the formation of voids which occur more easily in gas atmosphere than in vacuum, and sometimes Kirkendall voids[1)] are caused by the difference in diffusion coefficients of elements. Further, evacuating system and loading apparatus must be equipped, and exacting mating surfaces are required, resulting in a low welding efficiency and a high welding cost.

Therefore in this report, the authors propose a new bonding technique, called "Instantaneous Liquid Phase (ILP) bonding", by which instantaneous melting of one or two of the faying surfaces is utilized. The main processes of ILP bonding are: Both materials are heated in inert gas atmosphere as rapidly as possible up to the temperatures where generally the faying surface of lower melting point is melted to make the bonding both materials accomplished instantaneously by the liquid phase. Then, at this moment the materials are cooled rapidly so as not stagnate in the temperature region where liquid layer exists and thus brittle layer is easily formed. Therefore, ILP bonding has several advantages as follows: Neither usual microvoids nor Kirkendall voids are formed, and also the brittle layer at the bonding interface is suppressed. Because of the existence of liquid layer, the welding pressure required during ILP bonding is extremely low, and preparation of faying surface by simple tooling or polishing by #80 emery paper is enough. Because creep deformation hardly occurs due to short welding time and low welding pressure, the change in specimen length before and after welding is relatively little, only depending on the thickness of liquid layer. Moreover, ILP bonding is also available for welding of similar materials.

Also in the field of diffusion welding, several techniques utilizing liquid phase have been proposed, e.g. the use of eutectic liquid[2–5)], the use of solid-liquid coexistent region[6,7)] and TLP bonding[8)], and their welding time is generally as long as in diffusion welding. On the other hand, ILP bonding, in which also eutectic liquid is

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available if it were, has several unique characteristics compared with them. Namely, the processes of instantaneous melting and rapid cooling results in short welding time. Moreover, the welding temperatures of the specimens to be welded in ILP bonding are generally different from each other, and rather the difference in the melting point is utilized positively as mentioned later, whereas the welding temperatures of specimens to be welded in diffusion welding are the same as each other.

In this report, ILP bonding has been applied for a variety of combination of dissimilar materials of aluminum, aluminum alloys, titanium, titanium alloy, carbon steel, stainless steel, copper and tungsten, and for similar materials of stainless steel and nickel-base alloy. Consequently, the welded joints by ILP bonding have shown better tensile properties and a higher welding efficiency than those by diffusion welding.

2. Principle of ILP Bonding Processes

2.1 Principle for welding dissimilar materials

Principally, there are three types of methods of ILP bonding for welding dissimilar materials, which are illustrated in **Fig. 1** where A and B are the specimens having lower and higher melting point, respectively. Both the specimens are heated in inert gas atmosphere. In the method I, the faying surfaces of A and B are touched with each other throughout the welding and are heated together. Just after the melting of either of faying surfaces, the specimens are cooled rapidly by He gas, which results in rapid solidification and in suppression of the formation of brittle layer near the bonding surface. In the methods II and III, A is set away from B, then both are heated separately and independently. In the method II, the faying surface of B is heated to a peak temperature near the melting point of A, and the faying surface of A is heated to the melting point. Just after the melting of faying surface of A, A is touched with B, and the gap between A and B is filled with the thin liquid layer. Simultaneously, the specimens are cooled rapidly by He gas. In the method III, neither A nor B is melted before the touching of both materials. However, B is heated to a peak temperature higher than the melting point of A. When A is touched with B, the faying surface of A is melted by heat conduction from B with or without reaction between the faying surfaces of A and B. Simultaneously both are cooled by He gas. If A makes eutectic with B, it is available in all methods.

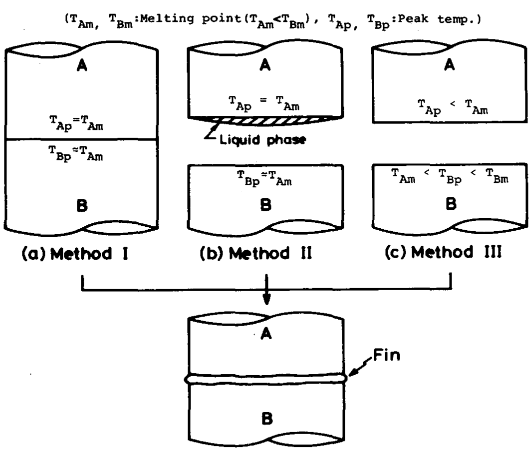


Fig. 1 Principles of ILP bonding

For the rapid cooling, He gas is usually useful, but also heat conduction due to thermal gradient in the specimen is useful. In this sense, it is desirable to get a steep thermal gradient by rapid heating, and this results in short welding time.

As above mentioned, the processes of ILP bonding are mainly consisted of three stages, namely, the first stage forming thin liquid layer by rapid heating, the second stage joining both specimens by the instantaneous thin liquid layer, and the third stage cooling the specimens rapidly. According to these stages, ILP bonding has many advantages as follows; the joining is done without any microvoids even in inert gas, the brittle layer can be suppressed, the influence of oxide film is reduced, and the joining time is very short which causes no Kirkendall voids. Furthermore any strict preparation of faying surface is not required, and very low welding pressure is enough.

2.2 Principle for welding similar materials

As well known, welding some kinds of materials is very difficult with not only fusion welding but also diffusion welding. In such case, TLP bonding[8] is applicable. However, the selection of suitable insert material and long welding time are required in TLP bonding.

Now, ILP bonding is also available for similar materials welding, in which only the methods I and II can be utilized. Because the brittle layer does not occur in the joining of similar materials, rapid cooling is not required. This technology has some advantages as follows: The insert materials required in TLP bonding is not needed. Welding time is much shorter than TLP bonding. Hot cracking may be suppressed because of small amount of liquid layer formed. Relatively little change in length of the specimens before and after bonding is obtained.

3. Experimental Materials and Methods

3.1 Materials used

The materials used and their compositions are listed in **Table 1**. The specimen was columnar and had 10 mm in diameter and 40 to 50 mm in length. The faying surface of specimen was tooled (VV) or polished by #80 emery paper, then was degreased by acetone. After that, the specimen was set in the apparatus of ILP bonding, which will be mentioned later in detail.

The combinations of dissimilar and similar materials welding used are shown in **Table 2**. Among the combinations of welding dissimilar materials, it is well known that the welding Al especially Al-Mg alloy to carbon steel or stainless steel and the welding Ti to carbon steel is very difficult by diffusion welding[9–19] and that the welding Cu to carbon steel or stainless steel is easy by diffusion welding. Among the combinations of welding same materials, fully austenitic stainless steel SUS 310S and Inconel 713C are very susceptible to hot cracking.

Table 1 Chemical compositions of materials used

(a) Commercially pure aluminum(A1050) and aluminum alloy (A5052, A2024, A7075)

	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	Al
A1050	0.02	0.12	0.11	---	---	---	0.01	0.01	99.73
A5052	0.02	0.09	0.15	0.03	2.30	0.01	0.23	0.01	Bal.
A2024	4.64	0.12	0.30	0.69	1.58	0.20	0.07	0.01	Bal.
A7075	1.60	0.10	0.19	0.03	2.50	5.42	0.23	0.01	Bal.

(b) Tough pitch copper(C1100): Cu; 99.95%

(c) Commercially pure titanium(TB35) and titanium alloy(Ti-6Al-4V)

	C	H	O	N	Fe	Al	V	Ti
TB35	0.0007	0.0003	0.101	0.004	0.062	-----	-----	Bal.
Ti-6Al-4V*	≤0.10	≤0.015	≤0.30	≤0.07	≤0.40	5.5~6.75	3.5~4.5	Bal.

* Standard of B265-58T in ASTM

(d) Plain carbon steel and austenitic stainless steel(SUS304, SUS310S)

	C	Si	Mn	P	S	Ni	Cr
Carbon steel	0.16	0.24	0.40	0.024	0.031	----	----
SUS304	0.06	0.29	1.67	0.035	0.026	8.32	18.75
SUS310S	0.025	0.31	1.14	0.031	0.001	19.35	24.25

(e) Commercially pure tungsten(YWP)

Fe	MO	NVR*	W
0.002	0.002	0.010	99.98

*NVR: Nonvolatile residue

(f) Inconel alloy 713C

C	Cr	MO	Al	Ti	Nb+Ta	Zr	B	Ni
0.10	13.08	4.51	5.98	0.75	2.07	0.06	0.012	Bal.

*Almost all the designations follow JIS(Japan Industrial Standard)

Table 2 Material combinations for ILP bonding

Welding dissimilar materials	Al(A1050) + Ti(TB35)
	Al(A1050) + Carbon steel
	Al alloy(A5052) + Ti(TB35)
	Al alloy(A5052) + Carbon steel
	Al alloy(A5052) + SUS304
	Al alloy(A2024) + Ti-6Al-4V
	Al alloy(A7075) + Ti-6Al-4V
	Cu(C1100) + Ti(TB35)
	Cu(C1100) + Carbon steel
	Cu(C1100) + SUS304
	Cu(C1100) + Tungsten
	Ti(TB35) + Carbon steel
	Ti(TB35) + SUS304
Welding same materials	SUS304 + SUS304
	SUS310S + SUS310S
	Inconel 713C + Inconel 713C

3.2 Method for welding dissimilar materials

The apparatus of ILP bonding are shown in **Fig. 2**, which also gives the setting manner of specimens with the method II or III. Generally, the specimens of higher and lower melting point were set in the lower and upper positions, respectively, and the lower end of specimen in the lower position was cooled by water throughout the welding. A thermocouple was welded to the side surface at 1 mm apart from the faying surface for both the lower and the upper specimens. The specimens were heated in 99.999% Ar atmosphere by high frequency induction heating. In the method I, both the specimens were heated by touching each other. Just when the liquid layer occurred in the bonding interface, the power was turned off and He gas was flowed by a relay. In the method II, at the beginning both the specimens were kept at some distance from each other and were heated separately in Ar gas. When the faying surface of the specimen set in the upper position was melted, this specimen was lowered soon and touched with the specimen set in the lower position. Simultaneously, the power was turned off and the specimens were rapidly cooled by He gas. In the method III, initially both the specimens were kept at some distance from each other and heated separately in Ar gas. Just when they were heated to the peak temperatures in the manner mentioned in 2.1, they were touched rapidly with each other. Simultaneously, the power was turned off and the specimens were cooled rapidly by He gas. In any method above mentioned, welding pressure by which the specimens were touched with each other was very low (generally less than 0.05 MPa).

The conditions of peak temperature Tp in ILP bonding

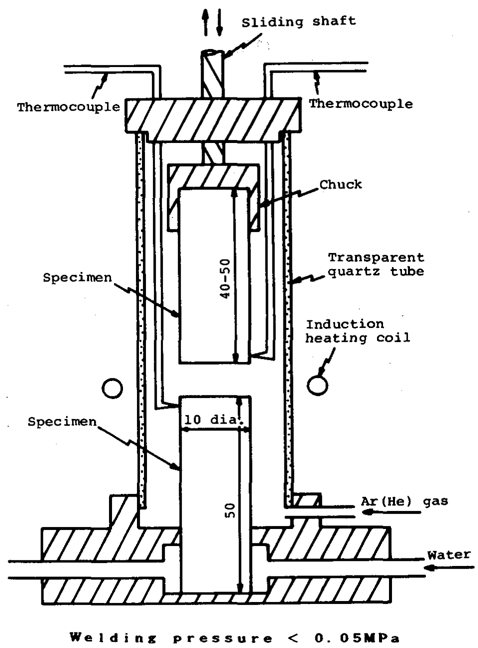


Fig. 2 Illustration of apparatus used for ILP bonding

Table 3 Conditions of ILP bonding for welding dissimilar materials

Combination	Method	Peak temp., Tp(°C)
Al(A1050) + Ti(TB35)	III	A1050: 620, Ti : 850
Al(A1050) + Carbon steel	III	A1050: 620, steel: 850
	III	500, 1100
Al alloy(A5052) + Ti(TB35)	III	A5052: 600, Ti : 850
Al alloy(A5052) + Carbon steel	III	A5052: 600, steel: 850
	III	500, 1100
Al alloy(A5052) + SUS304	III	A5052: 530, SUS304: 1000
	III	500, 1100
Al alloy(A2024) + Ti-6Al-4V	III	A2024: 580, Ti-6Al-4V: 850
Al alloy(A7075) + Ti-6Al-4V	III	A7075: 600, Ti-6Al-4V: 850
Cu(C1100) + Ti(TB35)	I	Ti: 1100
	II	Cu:Melting point, Ti : 800
Cu(C1100) + Carbon steel	II	Cu:Melting point, steel: 1200
Cu(C1100) + SUS304	II	Cu:Melting point, SUS304: 1200
Cu(C1100) + Tungsten	III	Cu> 800, W : 1300
Ti(TB35) + Carbon steel	I	steel: 1140
	III	Ti: 1200, steel: 1100
Ti(TB35) + SUS304	I	SUS304: 1120
	III	Ti: 1200, SUS304: 1000

Tp in method I is shown only for materials with thermocouple

for dissimilar materials welding is shown in **Table 3**, where the method I, II or III was selected according to preliminary experiments. The method I was not generally available for the welding dissimilar materials which have large difference in melting point, e.g. Al or Al alloy + Ti and Al or Al alloy + carbon steel, because nonbonded part generally occurred. The reason is considered that thermally activated state of Ti or carbon steel at the melting point of Al or Al alloy is not enough for their bonding because the difference in the melting point between these materials are too large. For the welding Cu to other material, the method II was mainly used where Cu was heated to the melting temperature, because welding thermocouple to Cu was very difficult. Generally speaking with some exceptions, the method III was mostly available for various combinations of dissimilar materials. The availability of method III was clear in the point that Tp conditions could be widely changed, although the disadvantage of the method III is the necessity of welding thermocouples to both specimens. In ILP bonding, Tp is very important, and thus was selected on the basis that there should be no nonbonded part at the bonding interface. In Table 3 two Tp conditions are shown for some combinations, which were used to study the effect of improved wettability of liquid layer at higher Tp on the tensile strength. By the way, for the combinations of Cu + Ti, Ti + carbon steel and Ti + SUS 304 eutectic reaction located at about 890°C, 1085°C and near 1085°C, respectively was utilized. Moreover for these combinations in the method I, welding pressure was increased up to about 0.25 MPa. It is also thought about the combination of Al + Fe that eutectic reaction at 652°C near the melting point of Al acted.

A typical welding thermal cycle for the combination of Al + carbon steel is shown in **Fig. 3**. The welding time was very short, namely about 30 sec at shortest, and generally about 60 sec.

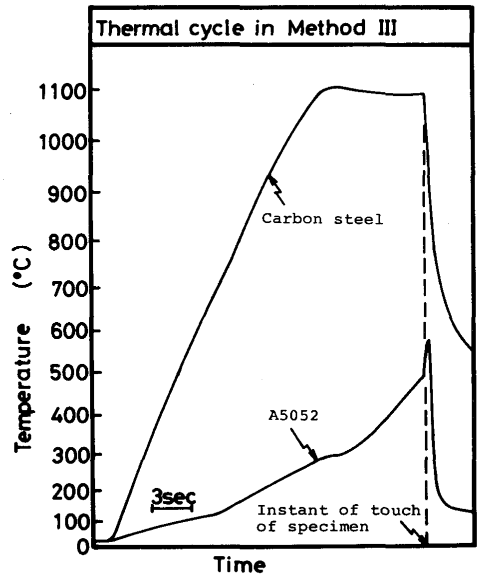


Fig. 3 An example of thermal cycle in Method III

3.3 Method for welding similar materials

The apparatus and the setting manner of specimens for welding similar materials are the same as those shown in Fig. 2. Because there is no difference in melting point between two materials to be welded, the method III can not be utilized in principle. The methods I and II were available for welding similar materials, but the nonbonded part occurred at the center of the bonding interface in the method I. Therefore, only the method II was used. The welding conditions are shown in **Table 4**. The time from the start of heating to the touching specimens was about 60 sec, and Ar gas was used for cooling specimens. When two specimens of Inconel 713C or SUS310S were welded to each other, the power was turned off at delay time of

Table 4 Conditions of ILP bonding for welding same materials

Material	Method	Peak temp., Tp(°C)
SUS304	II	Upper specimen: Melting point Lower specimen: 1300
SUS310S	II	Upper specimen: Melting point Lower specimen: 1300
Inconel 713C	II	Upper specimen: Melting point Lower specimen: 1250

0.2 to 0.3 sec after touching of specimens in order to improve the wettability between both specimens during the touching time.

3.4 Tensile test

Specimen configuration used for the tensile test is shown in **Fig. 4**, and cross-head speed of 1 mm/min was used for this test. By the way, the welded joints containing A2024 or A7075 was heat-treated before the tensile test for age hardening, namely under 190°C × 12 hr for A2024 and 120°C × 24 hr for A7075.

4. Experimental Results and Discussions

4.1 Applicability for the welding dissimilar materials

4.1.1 General appearance of specimen welded and change in length of specimen before and after welding

An example of appearance of specimen after ILP bonding is shown in **Fig. 5**. Fin occurred a little and the amount increased with either the Tp of the specimen of lower or higher melting point. Therefore, when the Tp of the specimen of higher melting point was raised in the method III, the amount of fin could be kept constant by lowering the Tp of the specimen of lower melting point. When the Tp of Ti or carbon steel for the combinations of A5052 + Ti, Al + carbon steel and A5052 + carbon steel was raised from 850°C to 1100°C, the wettability of liquid layer against the opposite solid faying surface was improved, especially in A5052 + Ti.

In this study, the proper Tp was selected so that the change in specimen length due to the fin might be within 0.3 to 0.7 mm, or at longest 1.2 mm after welding. This change corresponds to about 0.3 to 1.2% of whole length of specimens welded, and nearly equal to or less than that

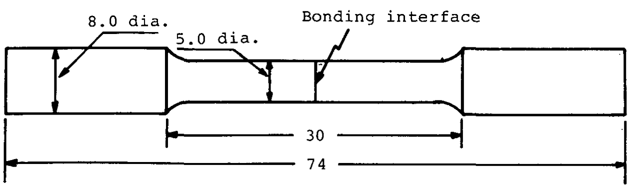


Fig. 4 Configuration of tensile test specimen

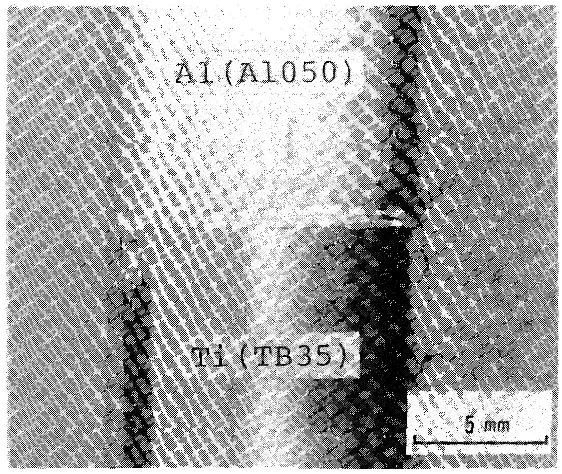


Fig. 5 An example of general appearance of welded joint of dissimilar materials by ILP bonding

in diffusion welding. Because not only the touching time during welding is very short but also welding pressure is very low in ILP bonding, it seems that creep deformation can not occur and only the fin influenced the length of specimen.

4.1.2 Results of tensile test

(a) Welding Al or Al alloys to other materials

Results of tensile test are shown in **Fig. 6**, where solid mark means fracture occurred in the base metal of Al or Al alloy and semisolid mark does it occurred at or near the bonding interface with plastic deformation in the base metal of Al or Al alloy. For the combinations of Al + Ti, all the welded joints fractured in the base metal of Al. The appearances of the tensile test specimens fractured are shown in **Fig. 7 (a)**.

As well known, welding Al especially Al-Mg alloy to carbon steel or stainless steel is generally very difficult by diffusion welding[9–13]. For this reason, the use of insert materials is studied from several viewpoints[11–16]. However, it should be noticed that the tensile strength in the combination of Al + carbon steel by ILP bonding shown in Fig. 6 was higher than that obtained by diffusion welding without insert materials. Namely, all the specimens of Al + carbon steel fractured at the bonding interface, but plastic deformation occurred to some extent in the base metal of Al. Especially under the Tp of 1100°C for carbon steel, large plastic deformation occurred in the base metal of Al as shown in Fig. 7 (b), and consequently the tensile strength was nearly equal to that of Al base metal. The fracture surface in Tp of 1100°C was dimple as shown in **Fig. 8** and endorses the excellent tensile property.

For the combination of A5052 + Ti, when the Tp for Ti was set to 850°C, one of the specimens fractured in base metal of A5052, and other fractured near the bonding interface after plastic deformation occurred considerably in the base material of A5052. Under the condition of

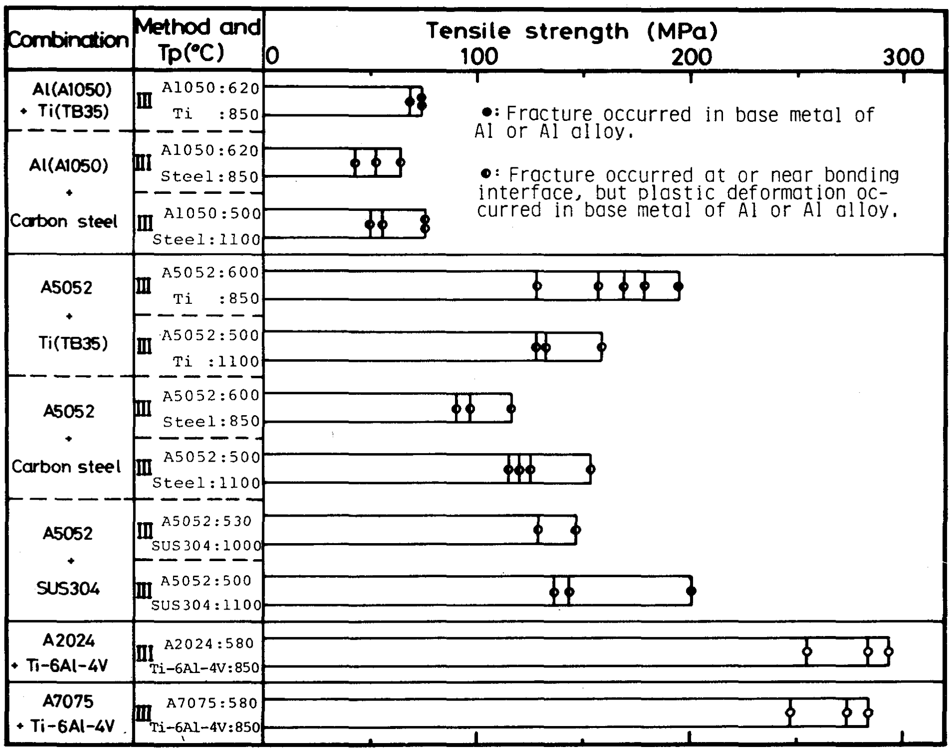
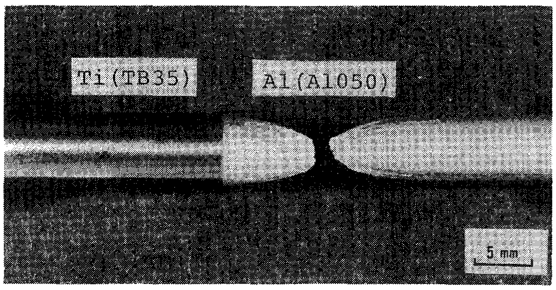
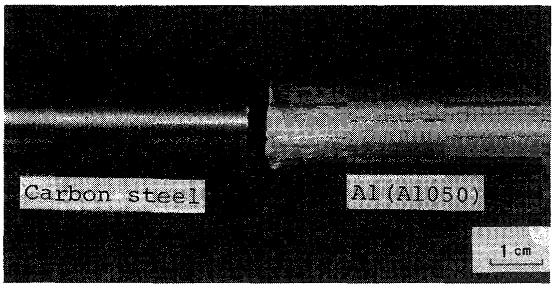


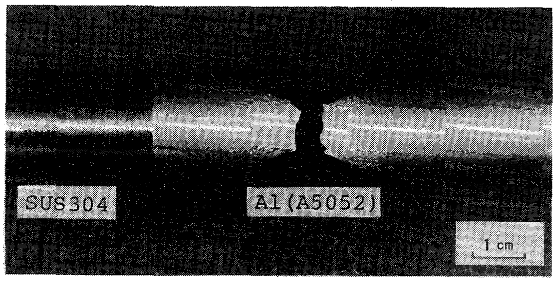
Fig. 6 Tensile strength of welded joints of Al or Al alloy + other materials



(a) Al (A1050) + Ti (TB35)



(b) Al (A1050) + carbon steel



(c) Al (A5052) + SUS 304

Fig. 7 Appearance of tensile tested specimens in Fig. 6.

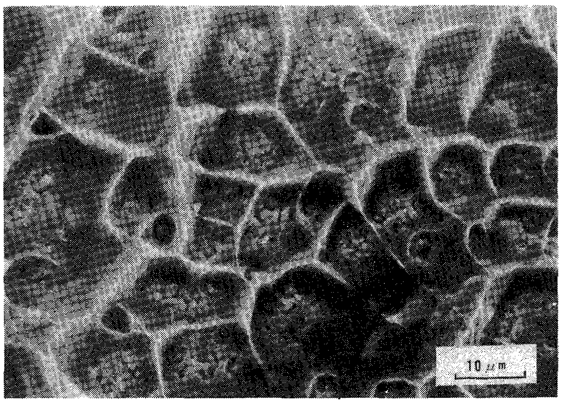


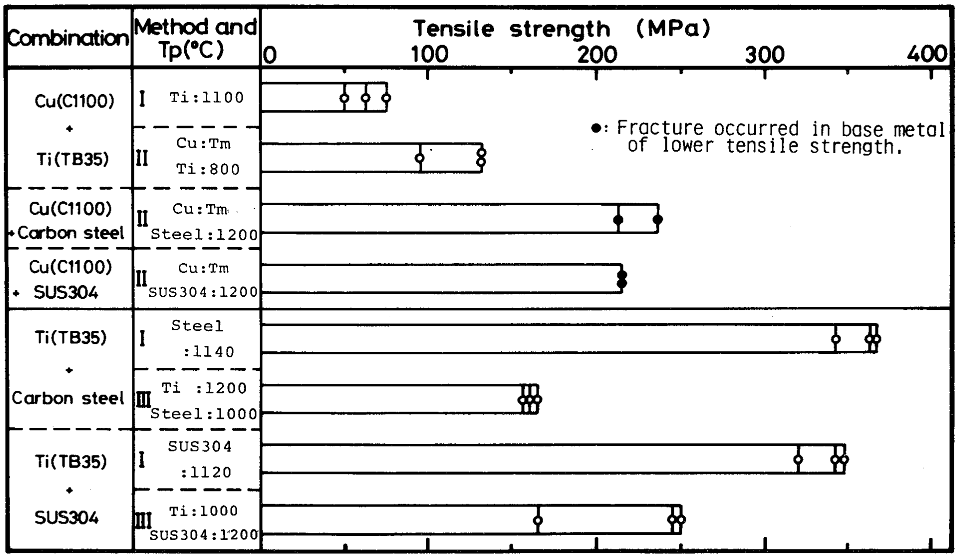
Fig. 8 Fractograph in Al (A1050) + carbon steel combination

Tp = 1100°C for Ti the tensile strength was generally lowered a little, although the wettability of liquid layer was improved remarkably.

The fracturing feature of the combination of A5052 + carbon steel was similar to that in Al + carbon steel. Also in this case, the tensile strength under the Tp of 1100°C for carbon steel was higher than that under the Tp of 850°C.

The fracturing feature in the combination of A5052 + SUS 304 was similar to Al + carbon steel mentioned above. Especially when the Tp for SUS 304 was set to 1100°C, one of the specimens fractured in base metal of A5052. The appearance of the tensile test specimen fractured in base metal of A5052 is shown in Fig. 7 (c).

The welded joints of A2024 + Ti-6Al-4V and A7075 + Ti-6Al-4V gave the tensile strength of about 250 to



T_m : Melting point
T_p in method I is shown for only the specimen with thermocouple

Fig. 9 Tensile strength of welded joints of Cu or Ti + other materials

280 MPa, which were maxima in the welded joints containing Al or Al alloy by ILP bonding. However, any plastic deformation was not observed in the base metal of A2024 and A7075, because they were heat-treated for age hardening. On the other hand, it is shown[21] that the welded joint of high strength aluminum alloy A2017 + Ti by diffusion welding utilizing solid-liquid coexisted state gave tensile strength of about 240 MPa in the best condition.

Therefore, ILP bonding is judged to be generally excellent for the welding Al or Al alloy to other materials.

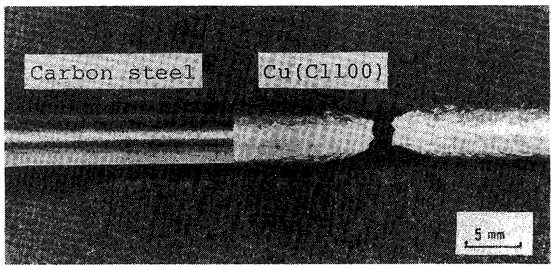
(b) Welding Cu or Ti to other materials

Results of tensile test are shown in **Fig. 9**. For the combination of Cu + Ti, the tensile strength of about 100 to 130 MPa was obtained in the method II. The tensile strength in the method I was worse than that in method II. In any case, the tensile strength was not enough, probably due to brittle eutectic product.

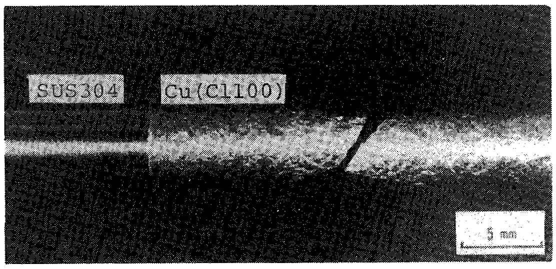
For the combinations of Cu + carbon steel and Cu + SUS 304, all the welded joints fractured in the base metal of Cu as shown in **Fig. 10**. As well known, the diffusion welding for those combinations is easy, but ILP bonding is far excellent in the viewpoint of welding efficiency.

For the combination of Cu + W, only the bending test was done. The appearance of the bended specimen is shown in **Fig. 11**, and it is considered that the good bonding was obtained.

It is shown[17–19] that welding Ti to carbon steel or stainless steel by diffusion welding is difficult. The welded joint even with the specimens polished very smoothly gave only the tensile strength of about 250 MPa[17,18]. How-



(a) Cu + carbon steel



(b) Cu + SUS 304

Fig. 10 Appearance of tensile tested specimens fractured in base metal in Fig. 9.

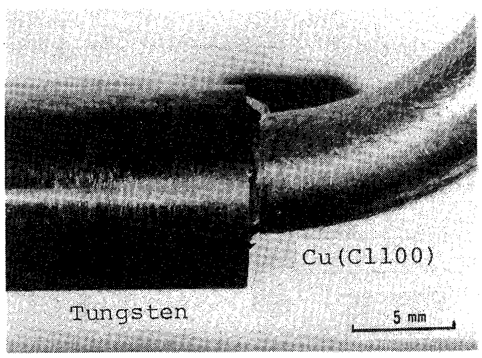


Fig. 11 Appearance of bending tested specimen of Cu + W combination

ever, the tensile strength of Ti + Carbon steel and Ti + SUS 304 by ILP bonding in the method I showed tensile strength of about 350 MPa which nearly corresponds to the lower limit strength of Ti (TB35) specified in JIS. The tensile strengths in the method III were worse than in the method I. Interestingly in welding Ti to carbon steel or SUS 304, Ar gas cooling gave nearly the same tensile strength as He gas cooling.

Therefore, ILP bonding is more excellent in also welding Ti to carbon steel or to austenitic stainless steel than diffusion welding.

4.1.3 Microstructure near bonding interface.

The SEM microstructure and the distribution of Al and Ti in the combination of Al + Ti are shown in **Fig. 12**, where no layer of compound is seen at the bonding interface and also the diffusion layer is very narrow. The hardness distribution is shown in **Fig. 13**, where no hard layer is seen. On the other hand, it is reported[20] that hard layer of Al_3Ti is formed in the combination of Al + Ti in diffusion welding. Making a comparison between diffusion welding and ILP bonding, ILP bonding is better than diffusion welding also in this point.

Also in the combination of A5052 + Ti, no layer of compound was seen, and there was also no hard layer as shown in **Fig. 14**. Therefore, there may be better Tp condition under which fracture always occurs in the base metal of A5052.

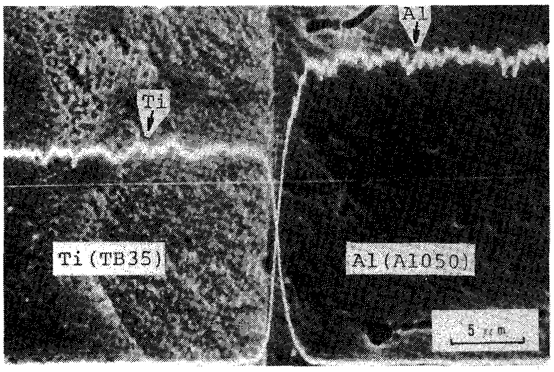


Fig. 12 SEM microstructure and distribution of Al and Ti in A (1050) + Ti combination

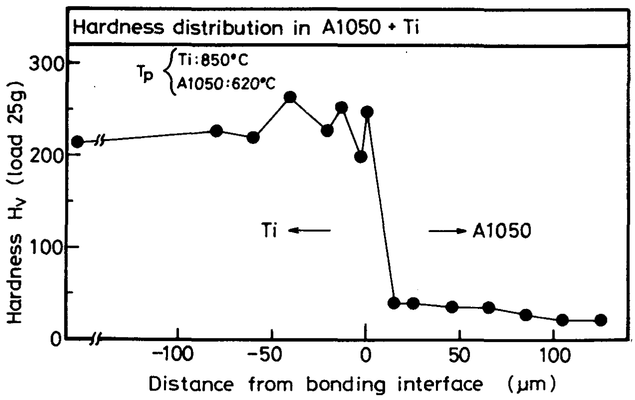


Fig. 13 Hardness distribution in Al (A1050) + Ti combination

The SEM microstructure and the distribution of Al and Fe in the combination of Al + carbon steel are shown in **Fig. 15**, where a layer of compound is seen in both conditions of Tp, but has not been identified, though is considered to be Al_3Fe according to Fe-Al phase diagram. It is noteworthy that the width of the layer is nearly constant independently of Tp condition. The hardness distributions are shown in **Fig. 16**. Hard layer giving Hv of about 280 is seen in Tp of 850°C for carbon steel, but not seen in Tp of 1100°C. Also the combination of A5052 + carbon steel gave nearly the same layer of compound at the bonding interface. The hardness distributions in Tp of

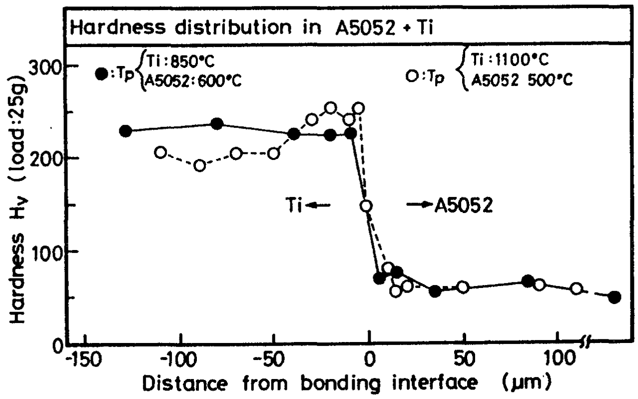
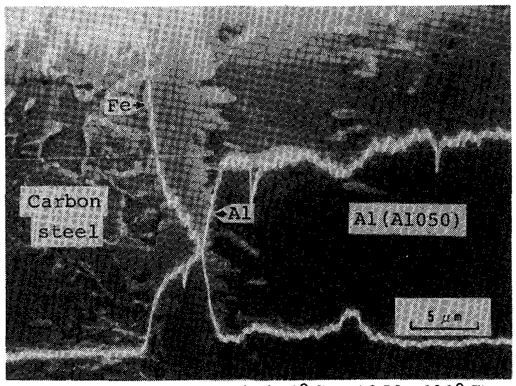
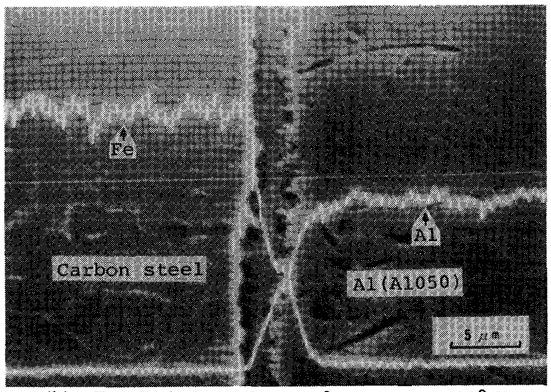


Fig. 14 Hardness distribution in A5052 + Ti combination



(a) Tp (Carbon steel: 850°C, A1050: 620°C)



(b) Tp (Carbon steel: 1100°C, A1050: 500°C)

Fig. 15 SEM microstructure and distribution of Al and Fe in Al (A1050) + carbon steel combination

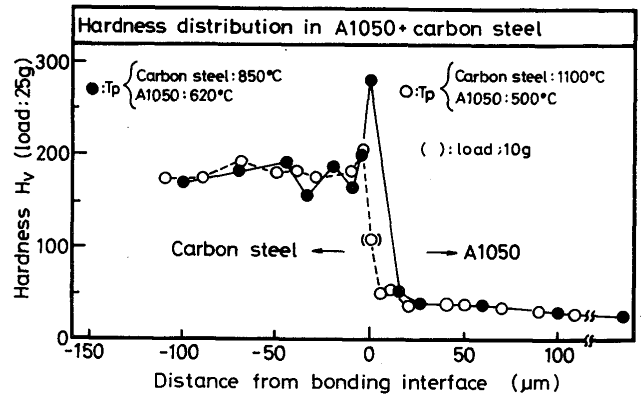


Fig. 16 Hardness distribution in carbon steel + Al combination

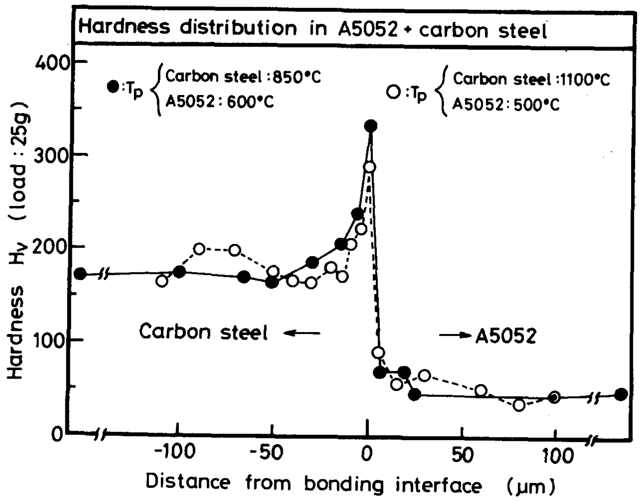


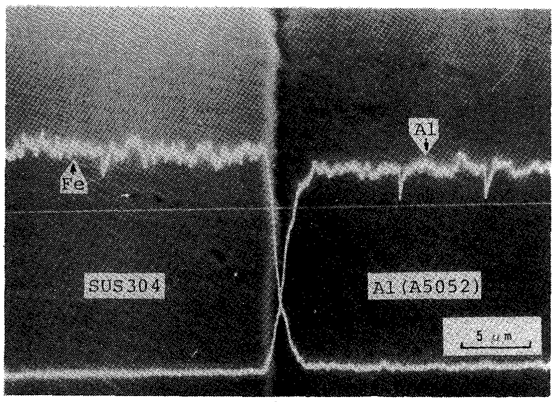
Fig. 17 Hardness distribution in A5052 + carbon steel combination

850 and 1100°C for carbon steel are shown in **Fig. 17**, where the hard layers at the bonding interface give somewhat higher Hv than in Fig. 16.

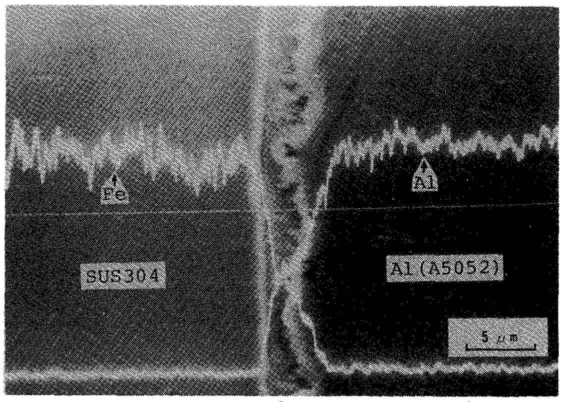
The SEM microstructures and the distribution of Al and Fe in the combination of A5052 + SUS 304 are shown in **Fig. 18**, where also layer of compound is seen in both Tp conditions. The hardness distributions are shown in **Fig. 19**. It is noticed that there is no noticeable hard zone in both conditions.

The SEM microstructure and the distribution of Cu and Fe in the combination of Cu + carbon steel are shown in **Fig. 20**, where no layer of compounds is seen at the bonding interface and the diffusion layer is very narrow. Moreover, Cu penetration into the grain-boundary of carbon steel is not seen. The hardness distribution is shown in **Fig. 21**, which also confirms that there was no layer of hard compound.

The optical microstructure in the combination of Cu + W is shown in **Fig. 22**, which shows no defects near the bonding surface. The SEM microstructure and the distribution of Cu and W is shown in **Fig. 23**, where no layer of compound is seen and the diffusion layer is narrow. The hardness distribution is shown in Fig. 24, where there is



(a) Tp (A5052: 530°C, SUS 304: 1000°C)



(b) Tp (A5052: 500°C, USS 304: 1100°C)

Fig. 18 SEM microstructure and distribution of Al and Fe in A5052 + SUS 304 combination

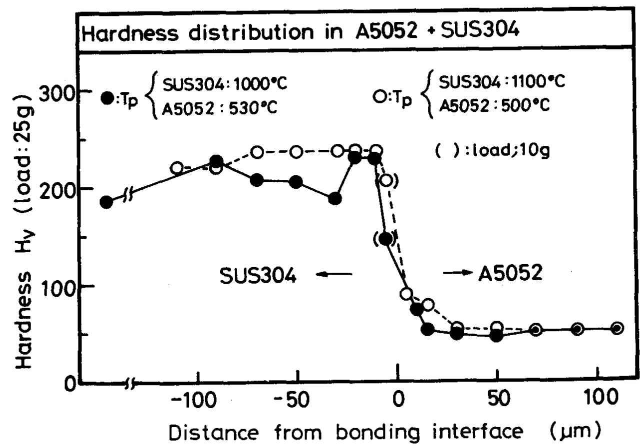


Fig. 19 Hardness distribution in A5052 + SUS 304 combination

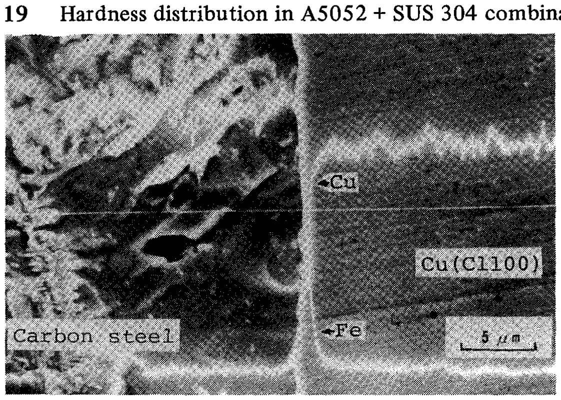


Fig. 20 SEM microstructure and distribution of Cu and Fe in Cu + carbon steel combination

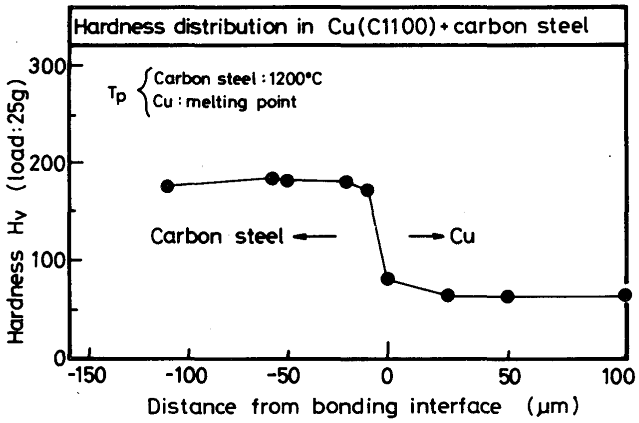


Fig. 21 Hardness distribution in Cu + carbon steel combination

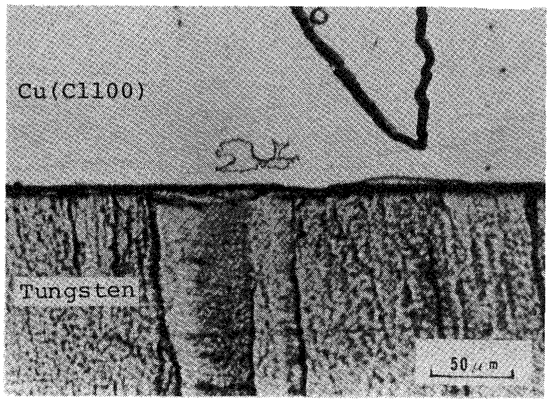


Fig. 22 Optical microstructure in Cu + W combination

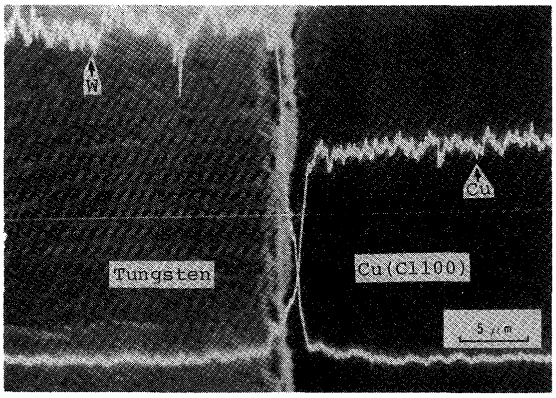


Fig. 23 SEM microstructure and distribution of Cu and W in Cu + W combination

no hard zone.

The SEM microstructure in the combination of Ti + carbon steel is shown in **Fig. 25**, where compound layer at the bonding interface and decarburized zone in carbon steel adjacent the interface are observed. The hardness distribution is shown in **Fig. 26**, which means the compound layer was very hard.

4.1.4 Microvoids

There was no voids as seen in the microstructures mentioned above. Therefore also in this point, it is judged that ILP bonding is an excellent bonding technique.

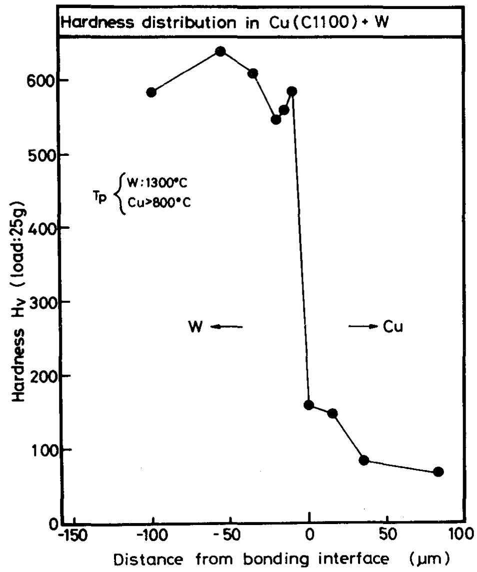


Fig. 24 Hardness distribution in Cu + W combination

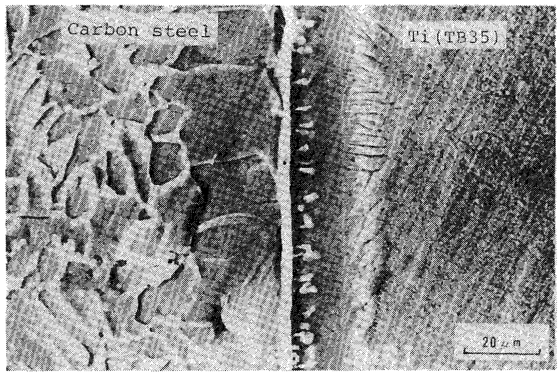


Fig. 25 SEM microstructure in the combination of Ti + carbon steel

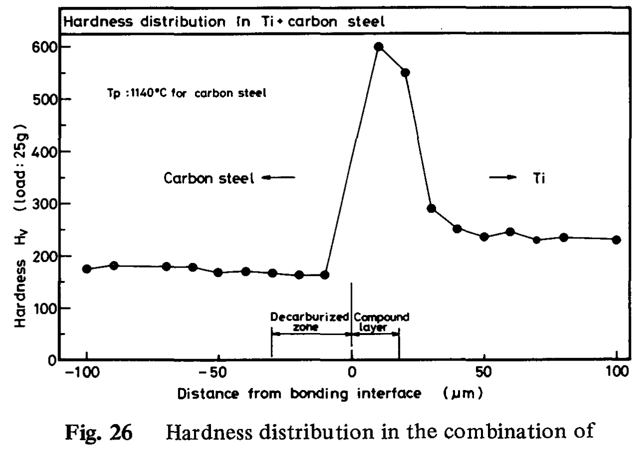
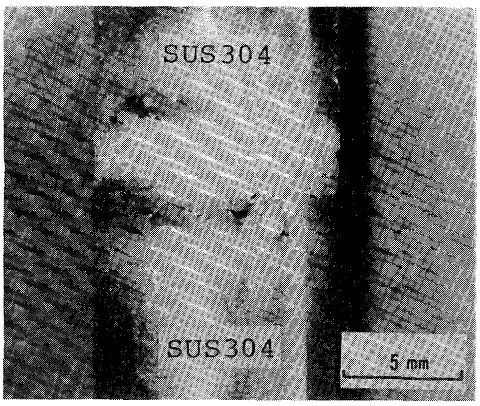


Fig. 26 Hardness distribution in the combination of Ti + carbon steel

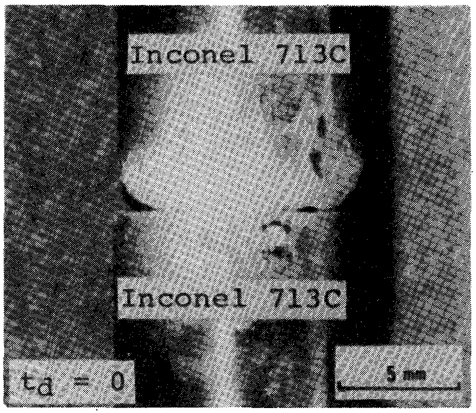
4.2 Applicability for the welding similar materials

4.2.1 Macroscopic feature of specimen bonded

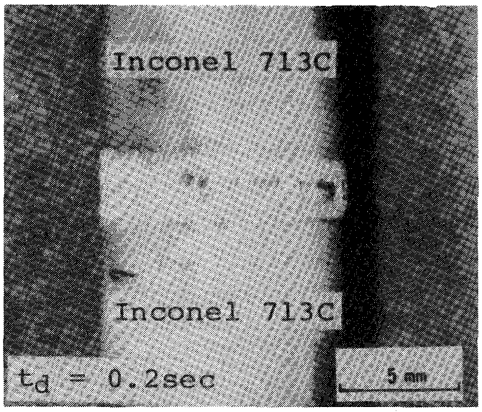
Examples of general appearances of joint of same materials are shown in **Fig. 27**, where (a) gives the joint of SUS 304, (b) does the joint of Inconel 713C cooled simul-



(a) SUS 304



(b) Inconel 713C (t_d = 0 sec)



(c) Inconel 713C (t_d = 0.2 sec)

Fig. 27 General appearance of joint of same materials by ILP bonding (t_d is delay time from the instant of touch of specimens to the start of cooling)

taneously with the touching upper and lower of specimens eacher other, and (c) does the joint of Inconel 713C cooled at delay time of 0.2 sec after the touching specimens each other. The appearance of SUS 304 was good in simultaneous cooling with the touching, because the wettability of the liquid layer was relatively good. On the other hand, in Inconel 713 C, the specimen kept for 0.2 sec after the touching gave better appearance than that with no delay time, because of the less wettability of liquid layer. Also for the welding SUS 310S, the delay time of 0.3 sec improved the wettability and thus the macroscopic appearance of the joint.

Table 5 Tensile strength of welded joint of same materials

Material	t_d (sec)	Tensile strength (MPa)	Remarks
SUS304	0	627	Reduction of area:46%
	0	659	Reduction of area:70%
SUS310S	0.3	470	Reduction of area:82%
	0.3	462	Reduction of area:82%
Inconel 713C	0	809	Fractured near bonding interface
	0	863	Fractured in base metal
	0.2	599	Fractured near bonding interface
	0.2	599	Fractured nearbonding interface

* t_d: Delay time from the instant of touch of specimens to the cooling

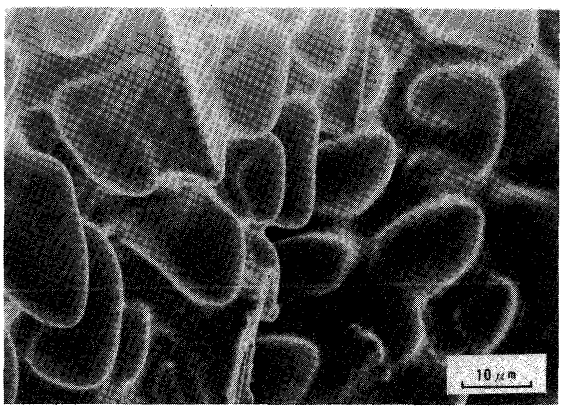


Fig. 28 Fractograph of welded joint of Inconel 713C, showing liquation cracking

The change in specimen length before and after welding was less than about 0.1 mm, which is comparable to that in TLP bonding.

Microstructure showed that the width of melted zone was about 50 to 150μm in Inconel 713C and about 250μm in SUS310S.

4.2.2 Results of tensile test

The results of tensile test are shown in **Table 5.** The tensile strength of welded SUS 304 satisfied the standard of JIS and good reduction of area was obtained. Also the welded SUS 310S gave good tensile strength and enough reduction area, although the tensile strength was a little lower than the standard of JIS, perhaps due to coarsened grain size. For the welded Inconel 713C shown in Fig. 27 (b), whose appearance was not good, the tensile strength was high so that one of the specimens fractured in base metal. For another kind of the welded Inconel 713C shown in Fig. 27 (c), whose appearance was good, the tensile strength was lower than that in (b). The SEM microfractograph shown in **Fig. 28** gives dendritic feature of liquation cracking, and means that liquation cracking occurred by the delay time of 0.2 sec caused the somewhat lower tensile strength. It can be expected that an increase of the welding pressure may prevent the liquation cracking. Because the change in specimen length was less than 0.1 mm as mentioned in 4.2.1, a little increase in welding pressure may have only a little influence on the change in specimen length.

5. Conclusions

The principle, the procedures and the applicability of newly developed Instantaneous Liquid Phase (ILP) bonding was discussed. Main conclusions are as follows;

(1) The ILP bonding is suitable mainly for welding dissimilar materials, and the welding time required is very short comparing with diffusion welding.
(2) The ILP bonding is composed of three stages, namely (i) melting of thin faying surface of the material of lower melting point by rapid heating, (ii) bonding with solid faying surface of the material of higher melting point and (iii) rapid cooling to prevent the formation of brittle compound layer. If there were eutectic reaction between two materials to be welded, it should be utilized in stage (i) and/or (ii).
(3) As the procedures to practice the three stages, three methods namely the methods I, II and III were proposed.
(4) The advantages of ILP bonding are: Welding time is short. Very low welding pressure is enough. No voids occur in spite of the welding process in Ar gas. Any strict preparing of faying surface is not required to get good weldability. The change in specimen length before and after welding is little.
(5) In welding commercially pure Al to commercially pure Ti, the fracture occurred in the base metal of Al. In welding commercially pure Al to plain carbon steel, the fracture mainly occurred at or near the bonding interface after the plastic deformation to some extent in the base metal, and thus the best data gave nearly the same tensile strength as the Al base metal.
(6) In welding Al-Mg alloy A5052 to commercially pure Ti, carbon steel or austenitic stainless steel, the fracture mainly occurred at or near the bonding interface after the plastic deformation to some extent in the base metal of A5052, and partly occurred in the base of A5052. Therefore the tensile strength was higher than those by diffusion bounding.
(7) In welding high strength Al alloy (A2024, A7075) to Ti-6Al-4V alloy, the welded joint showed tensile strength of about 250 to 280 MPa.
(8) In welding Al or Al alloy to other materials mentioned in (5) to (7), the method III was useful.
(9) In welding tough pitch copper to plain carbon steel or austenitic stainless steel (SUS 304), the fracture occurred in the base metal of Cu. In these welding, the method II was useful.
(10) In welding commercially pure Ti to carbon steel, the welded joint showed tensile strength of 360 to 370MPa which is higher than by diffusion welding. In welding commercially pure Ti to austenitic stainless steel (SUS 304), the welded joint showed tensile strength of 320 to 340 MPa. In these welding, eutectic reaction was utilized and the method I was useful.
(11) In bonding tough pitch Cu to commercially pure W, good bending property was obtained.
(12) SEM microstructure, EDX microanalysis and hardness measurement showed there was no hard compound layer at the bonding interface between Al and Ti, A5052 and Ti, tough pitch Cu and carbon steel, Cu and W. There observed a compound layer between Al and carbon steel, A5052 and carbon steel, A5052 and austenitic stainless steel, but the hardness was not so high unexpectedly.
(13) The ILP bonding was shown to be available also for same materials welding, by applying it to austenitic and fully austenitic stainless steels and Inconel alloy (713 C). The joint of austenitic and fully austenitic stainless steel gave enough tensile strength and good reduction of area. The joint of Inconel 713C gave tensile strength which was comparable to or about 70% of that in base metal, and the lower value was caused by micro liquation cracking. It was guessed that a little higher welding pressure may prevent the cracking.

Acknowledgement

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