

Laser Roll Welding

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Chapter 1

1.1 Background and Historical aspect

Early 2000s, Automobile industry has been under pressure to improve the fuel efficiency of vehicle for saving fuel as well as minimizing the pollution of environment. This requires the measures such as weight reduction of the vehicle, efficient burning of fuel, use of hybrid systems and alternative energies like electricity, hydrogen fuel cells or solar energy. For reduction of the weight, it is suggested that high strength steels should be used and the amount of steel in the vehicle should be reduced by using replacement of steel parts is not practical owing to its strength. Therefore, use of steel-aluminum hybrid structures has been suggested, particularly in the structural parts. This combination is also widely used in antifriction parts like cylinder liners and bushes. Apart from automobile industry, the combination of dissimilar joint between steel and aluminum also finds its applications in joining of LNG storage tanks and steel supporting structure. The LNG spherical tanks are made from 5083 aluminum alloy and its support is steel skirting. The domestic appliances like electric frying pans, water boilers also use such joints. Therefore, it necessary to join the steel parts to aluminum alloy parts of different shapes. Various joining processes like mechanical clinching, self piercing riveting, adhesive bonding, diffusion bonding, explosion welding, friction welding, resistance spot welding, forge welding and roll bonding have been used for the purpose. So, Development of a reliable dissimilar metal joint was important. M.Kutsuna and M.Rathod at dept. of Material Science and Processing Eng. Nagoya University has started the study on joining of dissimilar metal joint such as Al alloys and carbon steel since 2000 after studying the roll bonding of Aluminum and low carbon steel in 1999.. Patent application of Laser roll welding has been done in Aug.22,2003 to Japanese patent office. The Japanese Patent No.3535152 was issued on March 19,2004. This process was introduced to USA by the Welding Journal Vol. 83-1(2004).p.16s-26s. Not only Al-to steel, but also Steel to Titanium and Al to Titanium joint was investigated using this process.

1.2 Definition of process

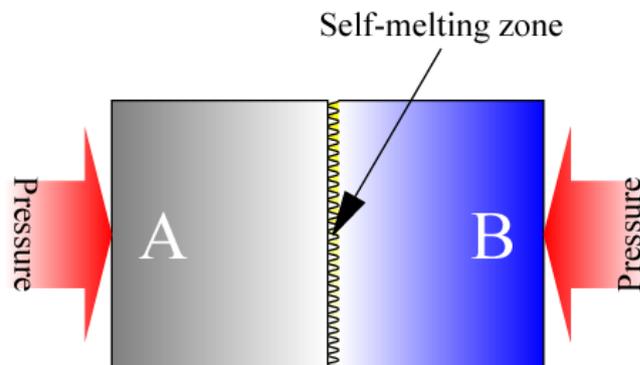
Laser Roll Welding is not fusion welding, brazing and solid state welding. It is defined as a pressure welding with a thin melting interface for lap joint of dissimilar metal sheets using a roller and one side laser heating . In the case of laser roll welding of aluminum to steel, aluminum can be melt only near the interface with steel which is heated upto 1300 °C. In the case of laser roll welding of Titanium to steel, Eutectic phase between Titanium and TiFe intermetallic compound is formed from liquid phase

at the interface above 1180°C. These melting interface and interlayer should be controlled to get a ductile phase at the interlayer.

Chapter 2: Process fundamentals, and Joint Design

2.1 Process principle

Fig.1 shows the process mechanism of laser roll welding in which laser heating of only one base metal and some pressure is applied to make contact with both metals. This contact with both metal allows heat conduction and metal diffusion through the Joint interface. The heating temperature, heating rate and cooling rate should be controlled to make more ductile intermetallic compound such as FeAl or Fe₃Al in the case of AL to steel joint. The heating temperature should be higher than formation temperature of brittle intermetallic compounds like FeAl₂, Fe₂Al₅ and FeAl₃, or the eutectic temperature of high melting point metals such as Ti to Steel joint. As a result, a new joint interface is formed between two metals. The interface can be made by self-melting, formation of intermetallic compound and alloying of both metals. The thickness of the joint interface layer is about 5 μm to 10μm.



By heating and pressurizing only metal A, heat is conducted to metal B, molten phase is formed at the faying surface and jointed

Fig.1 Joining process of Laser Roll Welding

2.2 Process features

This process has following features in the Al-Steel joint ;

- 1) formations of ductile intermetallic compounds such as FeAl and Fe₃Al or eutectic phase after self-melting in the interface layer;
- 2) keeping the intermetallic compound layer thickness less than 10 μm;
- 3) the idea of using a sharp intensified fast moving heat source to just cause wetting and diffusion for a very short period to form a metallic bond.
- 4) Heating is only one metal sheet by laser

Laser is one of such characteristic heat sources, involving a typical thermal cycle of fast heating and cooling. This helps in quickly reaching the temperature of the interface suitable to form ductile compounds like FeAl and Fe₃Al (about 1250°C). This may cause melting of a very thin layer of aluminium – of the order of 10 µm - at the interface. Therefore, though the complete elimination of brittle intermetallic compounds like FeAl₃, FeAl₂ and FeAl is not possible owing to their low free energy; their formation is suppressed to some extent. As this effect of laser heating is taking place, the heated zone is subjected to roll pressure to improve the contact area. This also helps in increasing the cooling rate preventing further diffusion at the interface. Such conditions restrict the intermetallic compound layer thickness to thin levels. The existence of a thin interface layer with some ductile compounds in it is favorable for improved joint strength. In the process suggested by Sepold *et al*, direct melting of aluminium with the feeding of filler metal is involved and no pressure is applied. Whereas in Laser roll bonding process, melting of aluminium is restricted to a thin layer at the interface and pressure is applied with a roll.

2.3 Process parameters

It is observed that this joining process of the dissimilar metal combination of aluminium and steel is quite a complex task. The process parameters discussed by various authors can be summarized in general as shown in Fig.2.

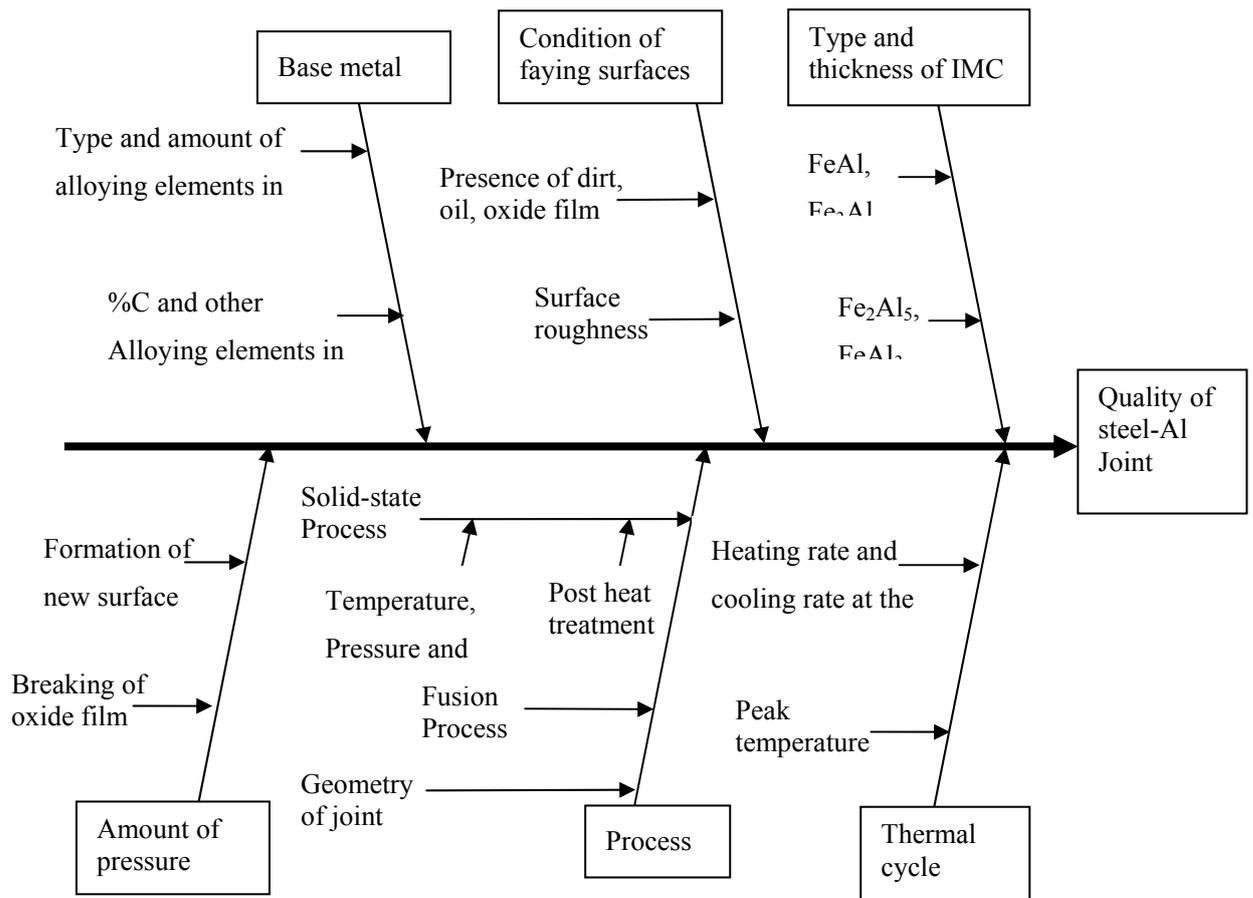


Fig 2 Process parameter for Laser roll welding

2.4 Process variations

Iron and aluminium are not compatible metals as far as fusion welding is concerned. The reason for this is attributed to the great difference between their melting points (660°C for Al and 1538°C for Fe), almost zero solid-solubility in each other and formation of brittle intermetallic compounds like FeAl₂, Fe₂Al₅ and FeAl₃. Therefore, the fusion welds of iron and aluminium are brittle. The differences in the thermal properties - like thermal expansion coefficients, thermal conductivities and specific heats – lead to high welding stresses in fusion welding.

In laser roll welding of steel and titanium joint, steel sheet is heated upto 1200°C to make an eutectic phase between Titanium and TiFe intermetallic compound which thickness is less than 20 µm in the interface layer. The heating temperature is lower than melting points of both metals, Steel and Titanium.

2.5 Applicable materials

In the research, dissimilar metal joints such as steel to copper, steel to aluminum, steel to titanium, stainless steel to, aluminum, galvanized steel to aluminum alloy, aluminum alloy to titanium are possible to get higher strength than that of base metals. Other combination of dissimilar metal is possible. Binary phase diagram may give the possibility.

Chapter 3: Equipment and Supplies

3.1 Laser roll welding equipment developed

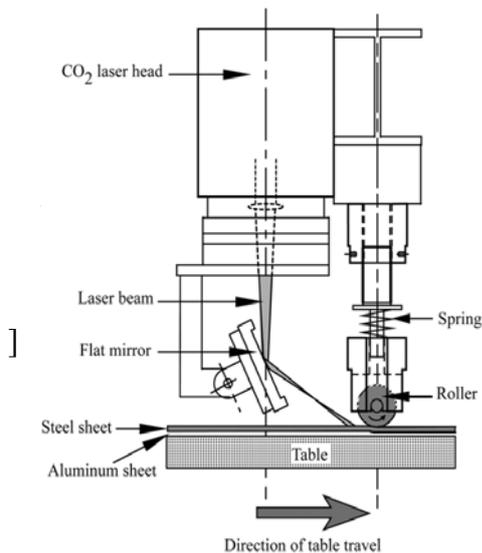


Fig.3 Schematic drawing of Laser Roll Bonding process

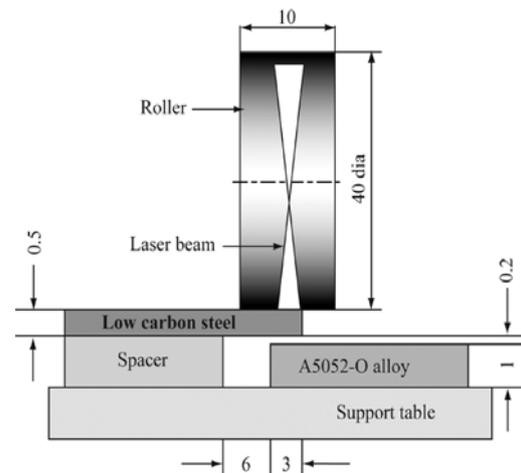


Fig.4 Setup of test specimens on X-Y

Many kinds of high power lasers can be used for laser roll welding. In the research, 2kW CO₂ laser and 2kW fiber laser were used for dissimilar metal joints. The diameter of beam spot is about 3mm x 5mm on the metal sheet and 10mm far from the bottom of

roller. Incident angles of laser beam were 45 ° in CO2 laser and 30 ° in fiber laser, respectively.. Figs.3 and 4 show the facility and setup of test specimens on X-Y table. Fig.5 shows the actual facility using 1 2kW fiber laser. Ar shielding and brazing flux are applied to remove the oxide film during welding.



Fig. 5 Laser roll welding facility using a 2kW fiber laser.

3.2 Welding condition for laser roll welding

Table 1 shows the welding condition for joining of aluminum alloy to low carbon steel

Table 1 Experimental conditions for laser roll bonding

Laser Power	1.0 kW ~ 2.0kW
Travel Speed	1.0 ~ 3.2 m/min
Beam spot dia.	3mm ~ 5mm
Roll Pressure	100 ~ 202 MPa
Shielding Method	Argon Gas shielding
Insert Material used	Aluminium brazing flux, KAlF ₄ :K ₂ AlF ₆ .H ₂ O

Welding thermal cycle at the interface is very important to minimize the thickness of interface layer which should be less than 10µm to get ductile intermetallic compounds.

Chapter 4: Applications for dissimilar metal joints

4.1 Joining of Aluminium and Al alloys to Low Carbon Steels

4.1.1 Introduction

The new automobile industry has a continuous requirement for weight reduction to increase efficiency and reduce air pollution. One way suggested is the use of the combined structure consisting of Aluminum alloy and steel sheet. Therefore, it is necessary to join these dissimilar metals together for different shapes in large continuous production suitable for the modern automobile industry. Attempts of using resistance spot welding with inserts for this purpose have been already made [1]. Major problem appeared during joining these dissimilar metals are the formation of intermetallic brittle compounds like FeAl₃ & Fe₂Al₅ in the interface layer. It has been reported that if the thickness of the intermetallic compound layer is limited below 10µm, the joint strength is improved [2].

In the present work CW and pulsed CO₂ laser welding were used, CW CO₂ laser were used to weld the steel sheet with aluminum A5052, and pulsed CO₂ laser used to weld the pure aluminum A1050. Using of laser beam welding of steel and aluminum were also reported [3].

An attempt is made to identify and estimate the thickness of the intermetallic compounds after diffusion bonding with different conditions of pressure, travel speed, and laser power. Due to laser heating, the material experiences fast heating and cooling rates. It has been found that the formation of the brittle compounds takes place by diffusion process, which involves slow heating and cooling rates. Therefore, a process combining laser heating and roll bonding is suggested. It is intended that the laser heating of steel in such a way that the interface reaches the temperature sufficient to form the bond while it being pressed. It was aimed to control the joining process by varying laser power, travel speed, and roll pressure so that to promote the formation of brittle intermetallic compounds in the interface layer. The joint strength and formability were determined by tensile shear test and Erichsen test respectively.

4.1.2 Experimental Procedure

(1) Materials used

The common materials used in automobile industry for structural components are low carbon steel and aluminum alloys. The sheet thickness for both types aluminum A5052 and A1050 is 1mm, and for steel sheet is 0.5mm used in this study. The chemical composition is shown in Table 2.

Table 2 Chemical Composition of Materials used(in mass %)

Alloy	Mg	Cr	Si	Fe	Cu	Mn	Zn	Others
A1050	0.05max	-----	0.25max	0.4max	0.05max	0.05max	0.05max	0.03
A5052	2.5	0.23	0.25max	0.4max	0.1max	0.1max	0.1max	0.05

SPCC	C	Mn	P	S
steel	0.12 max	0.5 max	0.04 max	0.045 max

(2) Laser Roll welding

A lap joint was used to combine the steel sheet with the aluminum alloys as shown in Fig. 6-(a), the steel was placed on the top of the aluminum in order to absorb the heat from the incident laser beam without melting and conduct the heat to the interface. The over lap was 9mm, and the Gaussian beam was defocused to give elliptical spot of 2.5mm minor and 3.5mm major diameter on the steel surface.

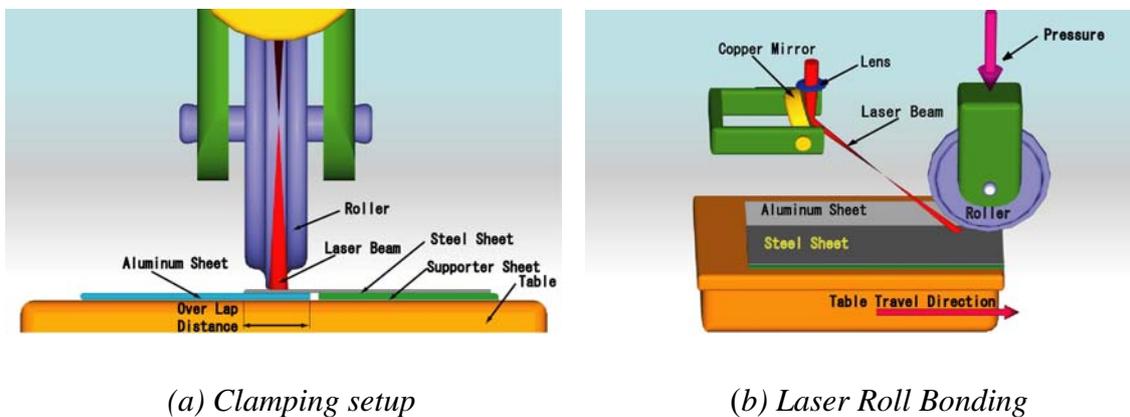


Fig.6 Schematic drawing

In order to heat the interface between the steel and aluminum to a suitable temperature by laser beam and apply pressure to this interface at the right time, the laser roll-welding fixture used in this study is made as shown in Fig.6-(b).

A spring is used to press the joint against the table through the roll; this pressure can be determined by the spring deflection. Prior to joining, the faying surfaces of both sheets were cleaned by using the suitable way, for Aluminum sheets, ultrasonic cleaning was applied to remove the hard aluminum oxide film, then it was merged with brazing flux ($KAlF_4:K_2AlF_5.H_2O$) to prevent further oxidation and remove any if exist.

Laser Roll welding with varying travel speed, laser power, and roll pressure were carried out. The joints were cut transversely to observe the macrostructure and microstructure. The same were used to identify and estimate the intermetallic compounds through the interface layer by EPMA with WDX method. Based on the EPMA results the thickness of the interface layer was divided into ductile compounds ($FeAl+Fe_3Al$) and brittle compounds thickness ($FeAl_3+Fe_2Al_5$). For estimating the

strength and formability of the joints, three samples were prepared for tensile shear test and one specimen for Erichsen test.

4.1.3 Experimental results

The main purpose of using CO₂ Laser Roll welding is to achieve fast heating and fast cooling, which may suppress the formation of the brittle intermetallic compounds. To increase the possibility of formation of the ductile intermetallic compounds (FeAl+Fe₃Al), the interface temperature should be in the range 1100°-1300°C as shown in Fig.7[4] for Iron-Aluminum phase diagram. Temperature is the most influential variable since it, together with pressure, determine the extent of contact area during diffusion bonding and it alone determine the rate of diffusion that governs void elimination.

Changing pressure values with interface temperature (by varying the laser power or travel speed), we can control the interface layer thickness until the optimum is reached, in which the brittle compounds layer thickness

will be the minimum and the ductile one will be the maximum. In addition to these parameters, a pulsed laser welding is used in welding the pure Aluminum A1050, which enable us for more control of the heating and cooling rates by changing the pulse.

As the interface layer temperature reaches the required range, a thin surface region of aluminum undergoes melting. Bonding was achieved as shown in the macrostructure samples in Fig.8. A typical microstructure of laser roll bonding joints is shown in Fig.9.

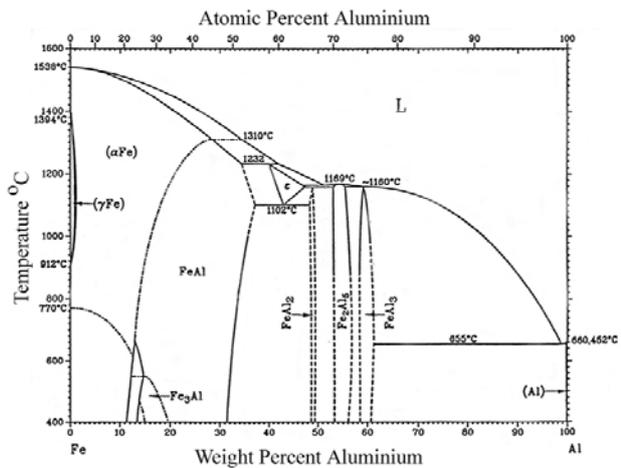
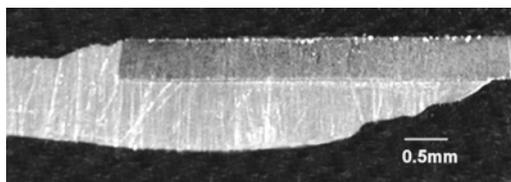
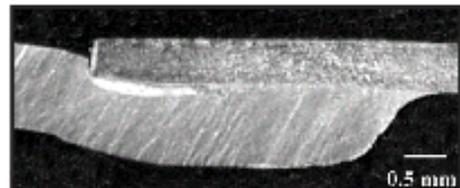


Fig.7 Iron-Aluminum Phase diagram

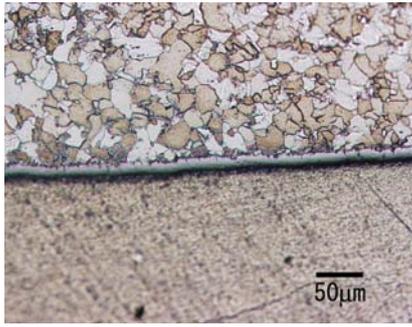


1.5kW-1.5m/min-150MPa
(a) SPCC-A1050

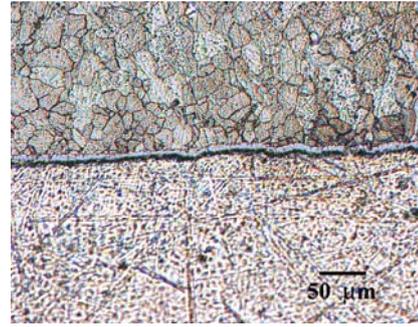


1.5kW-2.2m/min-202MPa
(b) SPCC-A5052

Fig. 8 Macrostructure Samples

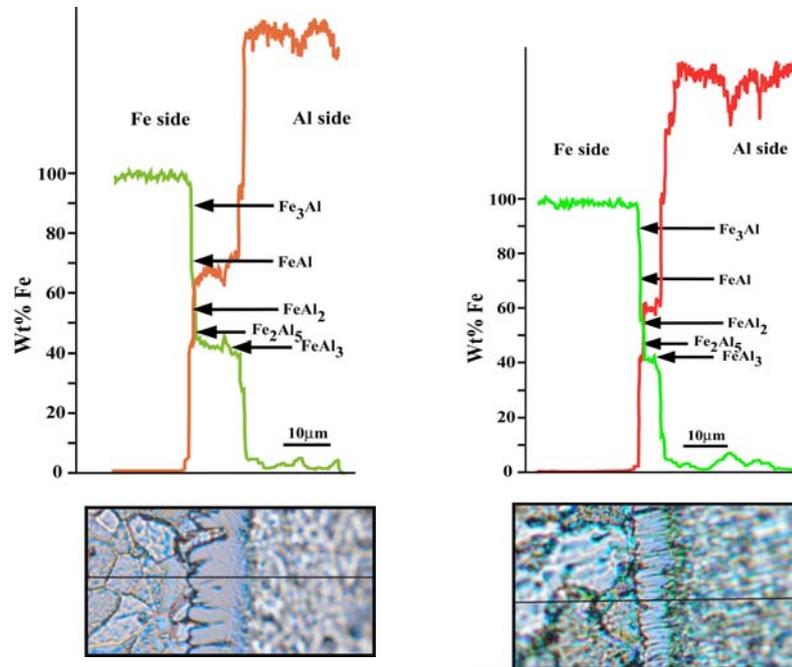


1.5kW-150MPa-4.0m/min
(a) SPCC- A1050



1.5kW-150MPa-2.0m/min
(b) SPCC- A5052

Fig. 9 Macrostructure Specimens

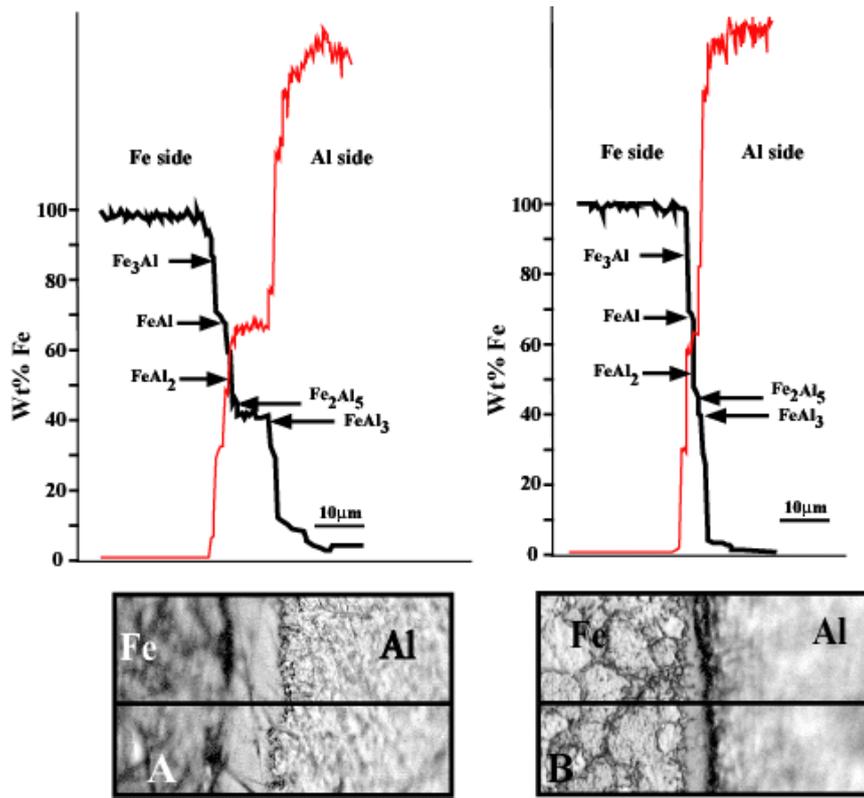


(a) 1.5kW-150MPa-2.25m/min

(b) 1.5kW-150MPa-6.0m/min

Fig.10 EPMA analysis for SPCC-A1050

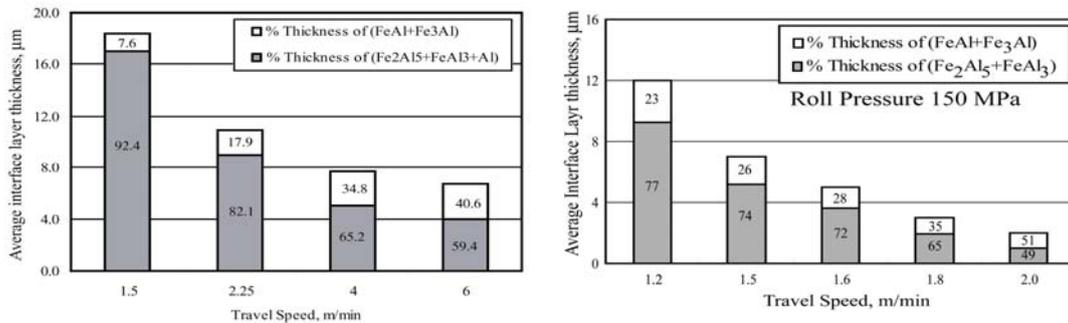
The interface layer was analyzed by using EPMA method; the EPMA traces in Fig.10 for A1050 and Fig.11 for A5052 show the existence of the ductile compound on the steel side and brittle compound on the aluminum side for a constant pressure, and laser power for two travel speeds. These figures also show the fraction thickness for both ductile and brittle compounds through the interface layer is changing with travel speed. In general, for a constant laser power and pressure, starting with a low speed, will offer a longer time for the diffusion process to take place in which in turn produces a thicker layer with higher percentage of the brittle compounds as shown in Fig.12.



(a) 1.5kW-150MPa-1.2m/min (b) 1.5kW-150MPa-2.0m/min
 Fig.11 EPMA analysis for SPCC-A5052

The higher the interface thickness, the higher percentage of brittle compounds exist. With increasing the travel speed the percentage thickness of the ductile compounds increases from 23% to 51% for A5052 and from 7.6% to 40.6% for A1050. The reason is related to “as discussed earlier “ controlling the diffusion rate by changing heating and cooling rates with the travel speed.

In this experiment, different laser’s powers and pressures were used to study their



(a) SPCC- A1050 (1.5kW-150MPa) (b) SPCC- A5052 (1.5kW-150MPa)
 Fig. 12 Composition of IMC in the interface layer

effect on the interface compounds. Increasing the power has the same effect of decreasing the speed, but if power reaches to high values, it will cause melting of the

steel sheet, and if it reaches to low values, the heat input may not be sufficient to produce bond. As for the pressure, it is necessary for increasing the contact area directly after heating for a short time to allow diffusion process to take place, and help in increasing the cooling rate of the joint by heat conduction.

Fig.13 shows the relation between tensile shear strength and interface layer

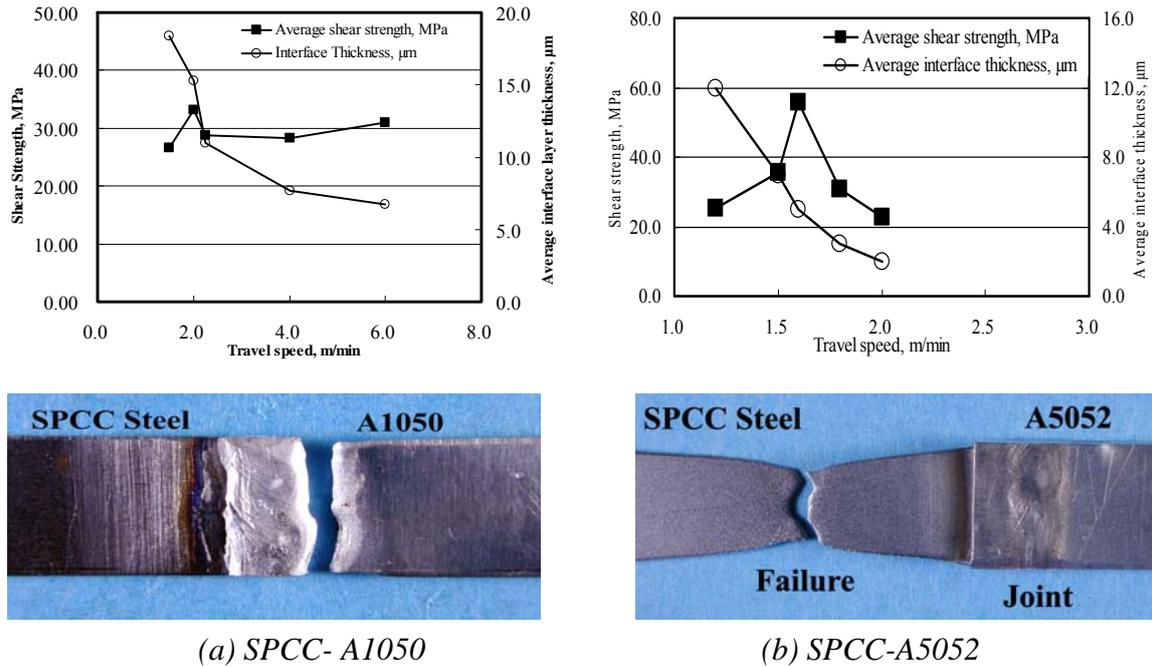
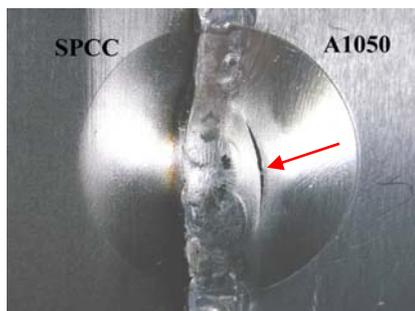
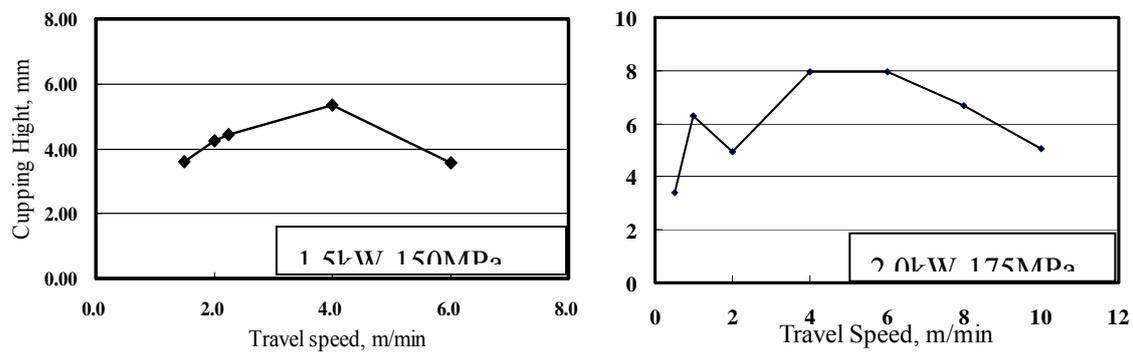


Fig.13 Effect of travel speed on shear strength

thickness with travel speed.

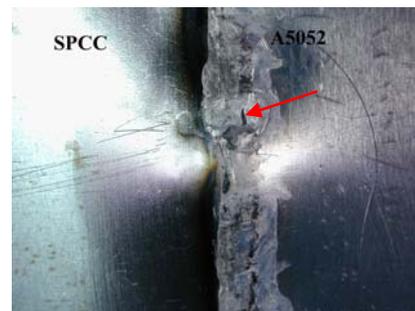
By increasing the travel speed, the interface layer thickness decreases, at the same time shear strength increases up to 33.1MPa for A1050 and to 55.9MPa for A5052. Although in higher speeds, the percentage of ductile compounds is relatively high, the shear strength drops down for fast travel speed, owing to insufficient temperature due to the lack of heat energy at the interface layer.

To detect the formability of these joints, which it is a major characteristic of the sheets used in automobile industry, Erichsen test was carried out and evaluated with different speeds as shown in Fig.14. The cupping height increases with speed until it reaches a maximum value then starts to decrease almost in the same manner with shear strength analysis. The maximum cupping value is related to the existence of the optimum thickness of the interface layer, which is responsible of relatively high percentage of ductile compounds with a sufficient heat for satisfactory strong bonding.



1.5kW-150MPa-1.5m/min

(a) SPCC-A1050



2.0kW-175MPa-2.0m/min

(b) SPCC-A5052

Fig.14 Results of Erichsen Test performed on laser roll bonded joints

4.1.4 Conclusions

1. It is possible to joint the aluminum alloys to steel by using laser roll welding. Moreover, by controlling the parameters such as laser power, travel speed, roll pressure and pulse; we can get 55.9MPa shear strength for A5052 and about 30MPa for A1050.
2. With good contact of the faying surfaces by roll pressure, heat conduction can be accomplished from steel to the aluminum. Laser heating provides high energy density in the beam spot and rapid heating and cooling cycle. Therefore, diffusion bonding takes a place for a short period because of the short thermal cycle.
3. For both joints made from A1050 and A5052 aluminum alloys with SPCC steel after laser roll bonding, the EPMA analysis shows that interface layer consist of brittle intermetallic compounds – $FeAl_3$ and Fe_2Al_5 – on aluminum side and ductile one – $FeAl$ and Fe_3Al - on the steel side. As the travel speed increased, the total thickness of the interface layer decreased with increasing of the thickness of ductile compounds.

4.2 Joining of Al Alloys and Zinc coated steel

There is an issue to reduce the weight of car body by aluminum alloys replace steel as some structural body parts for improving fuel consumption and CO₂ generation. As one of the solutions, the multi material car body concept using aluminum alloys and high strength steels is discussed recently. Therefore, new welding processes by which these dissimilar materials can be joined in high reliability and productivity are demanded. Laser Roll Welding was developed for joining of dissimilar metals by M.Kutsuna and M.Rathod in 2002. In this section, Laser Roll Welding of zinc coated steel and aluminum alloy was investigated, and the process parameters were studied. Otherwise, the influences of process parameters on the weldability, the formation of intermetallic compound layer and the mechanical properties have been investigated. When intermetallic compound layer thickness was less than 10 μm, failure of tensile-shear test specimen occurred in the base metal of the zinc coated steel.

The car industry has subjects to improve fuel efficiency. One of the solutions is to reduce the weight of car body such as car panels shown in Fig.23. To be replaced steel parts by aluminum alloys is very effective to achieve large weight reduction.



Fig.15 Example of laser roll welding application : Car panel

The technology for joining of steel to aluminum with high reliability and productivity is necessary to realize this "hybrid body structure". However, it is difficult to join steel to aluminum by fusion welding. The reason is attributed to the formation of intermetallic compounds such as FeAl₃ and Fe₂Al₅. Shown in Fig.7 [4].

The intermetallic compounds presented on it are grouped as Fe-rich compounds (FeAl and Fe₃Al) and Al-rich compounds (FeAl₂, Fe₂Al₅ and FeAl₃). Mechanical properties of cast intermetallic compounds by compressive test are shown in Fig.16 [1]. While Al-rich intermetallic compounds are brittle, iron-rich intermetallic compounds show slight ductility and high strength. Then, it is desirable that the brittle intermetallic compound could be controlled by application of Laser Roll Welding.

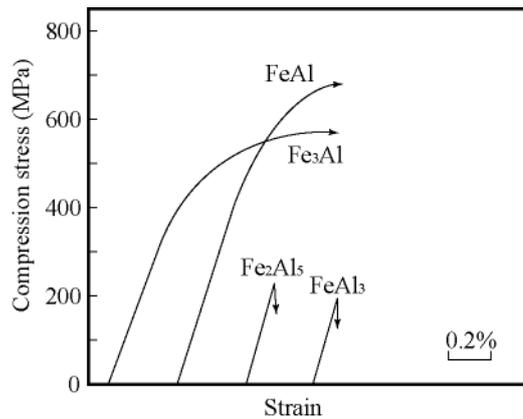


Fig16 Stress-Strain Curve in compressive test of Fe-Al intermetallic compounds [1]
 In the present work, Laser Roll Welding of the zinc coated steel and the aluminum alloy was investigated, and the process parameters were studied. Otherwise, the influences of the process parameters on the weldability, the formation of intermetallic compound layer and the mechanical properties of joints.

4.2.2 Experimental Procedure

(1) Materials used

Zinc coated steel sheet (GI) and aluminum alloy 6000 sheet (Al-0.5Mg-1.0Si) were used for joining. The dimension of the steel sheet was 180 x 125 x 0.55 mm and that of the 6000 series aluminum alloy was 180 x 125 x 1 mm.

(2) Laser Roll Welding Facility

A schematic diagram of Laser Roll Welding process is shown in Fig.3. A pressure roller was mounted on a 2.4 kW pulse CO₂ laser facility. It is desirable that thermal cycle for joining can be shortened by heating of the laser. Therefore, the formation of the brittle intermetallic compound can be easily controlled. Furthermore, good contact of steel sheet and aluminum sheet and rapid heat transfer from a steel sheet to an aluminum alloy sheet are conducted by a pressure roller.

(3) Process Parameters of Laser Roll Welding

Process parameters are shown in Table 3. Travel speed was varied from 0.2 to 0.7 m/min. The steel surface exposed to the laser beam was coated with graphite to increase the absorption of laser beam. The faying surface was coated aluminum brazing flux. Argon gas with 25 l/min flow rate was used for shielding of joint.

4.2.3 Experimental results and discussions

(1) Bead Appearance and Cross-Section of Laser Roll Welded Joints

Bead appearance of Laser Roll Welded specimen with travel speed of 0.5 m/min is shown in Fig.17. Top bead is shown in Fig.17 (a). Cockles are observed on the zinc

Table 3 Process parameters for Laser Roll Welding for Zinc coated steel to Al alloy

Laser type	Pulse CO ₂ Laser
Laser peak power	2.0 kW
Duty cycles	75%
Frequency	150 Hz
Travel speed	0.2~0.7 m / min
Overlapped width	3 mm
Roll pressure	150 MPa
Center shielding gas	Ar : 25 l / min
Side shielding gas	Ar : 25 l / min

coated steel near the weld bead. Bottom bead is shown in Fig.17 (b), and cross-section of the weld bead is shown in Fig.18. These figures show partial melting and spreading of molten metal on steel sheet occurs in aluminum sheet.

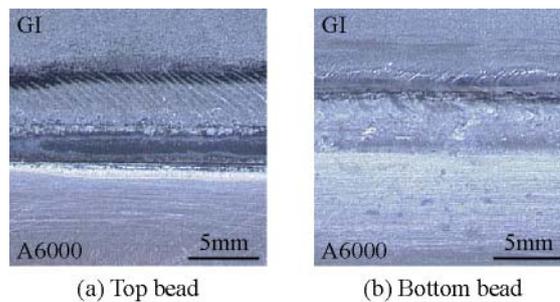


Fig. 17 Bead appearance of laser roll welded joint of GI steel to A6000 alloy



Fig. 18 Macro-section of laser roll welded joint of GI steel to A6000 alloy

(2)Effect of travel speed on intermetallic compound layer thickness at the interface

Interface microstructures of Laser Roll Welded joint with travel speed of 0.5 m/min is shown in Fig.19.

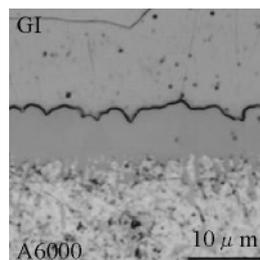


Fig. 19 Microstructure of laser roll welded joint of GI steel to A6000 alloy

Existence of intermetallic compound layer was confirmed at the weld interface between GI and A6000. Effect of travel speed on intermetallic compound layer thickness is shown in Fig.20. Intermetallic compound layer thickness decreases significantly from 22 to 5 μm as the travel speed is increased from 0.3 to 0.6 m/min.

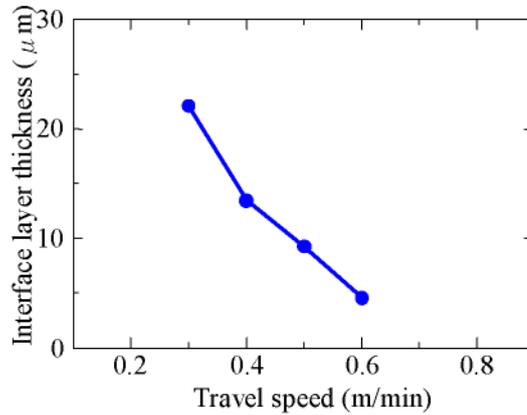


Fig.20 Effect of travel speed on intermetallic compound layer thickness

(3) Electron-probe microanalysis (EPMA)

As the optical microstructure does not reveal the details of the interface layer, EPMA of iron, aluminum and zinc across it were made to identify intermetallic compounds and existence of zinc. Three such traces for specimens welded with travel speed of 0.5 m/min are shown in Fig.21.

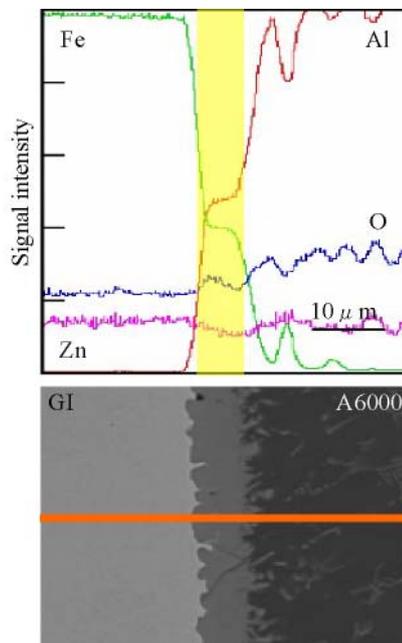


Fig. 21 EPMA result of interface layer of laser roll welded joint
Variation in composition of the intermetallic compound layer is observed as stepped lines. Intermetallic compound layers are indicated by yellow color zone.

From the position of stepped lines, it is suggested that most intermetallic compound layer is formed mainly by brittle FeAl₃. When the travel speed is faster than 0.6 m/min, zinc is confirmed in aluminum alloy.

(4) Tensile shear test

Tensile shear test was done to investigate the influence of the travel speed on the weldability. Effect of travel speed on tensile load and intermetallic compound layer thickness is shown in Fig.22. Failure in base metal of zinc coated steel is shown as the blue circle in the figure, and failure in interface is shown as a solid blue mark. When intermetallic compound layer thickness was less than 10 μm, failure of specimen occurred in base metal of zinc coated steel. When intermetallic compound layer was less than 10 μm, failure of specimen occurred in the base metal of the zinc coated steel. Therefore, it is thought that the intermetallic compound layer thickness should be less than 10 μm to get a good Laser Roll Welded joint.

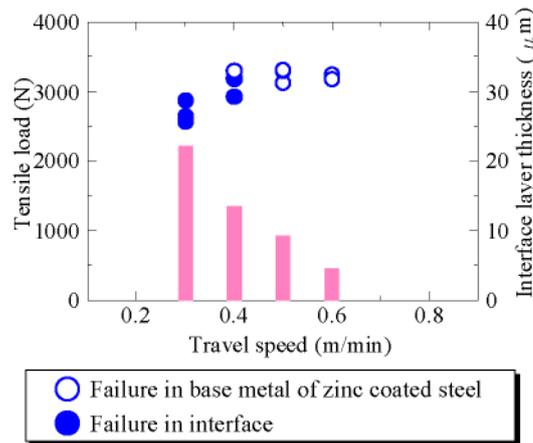


Fig. 22 Results of tensile shear test of laser roll welded joint of GI steel to A6000 alloy

4.2.4 Conclusions

In this section, joining of a dissimilar metal joint of zinc coated steel and 6000 series aluminum alloy by laser roll welding is discussed. The following conclusions can be drawn.

- 1) Increase in travel speed of the table led to decrease the thickness of the intermetallic compound layer at the interface.
- 2) Increase in travel speed led to lowering of the peak temperature and shortening of the holding time more than 500 °C at the interface.
- 3) It is suggested that intermetallic compound layer that is formed mainly is brittle FeAl₃. As the travel speed is faster than 0.6 m/min, zinc is confirmed in aluminum alloy.

- 4) When intermetallic compound layer was less than 10 μm , failure of specimen occurred at the base metal of zinc coated steel in tensile shear test.

4.3 Joining of Ti and Low carbon steel

4.3.1 Introduction

Titanium is one of structural materials. It has several advantages such as high corrosion resistance and high strength-to-weight ratio. The demand of titanium structural panel and the dissimilar joint has been increased in industry. It is well known that joining of steel and titanium is difficult because of generating the brittle intermetallic compound. In this section, the laser roll welding of dissimilar metals, titanium to low carbon steel is discussed. Using a 2.4kW CO₂ laser and a 2kW fiber laser, the effects of process parameters on the formation of intermetallic compound at the interlayer and on the mechanical properties were investigated to get a sound dissimilar metal joint.

In this section, the laser roll welding of dissimilar metals, titanium to low carbon steel been investigated using a 2.4kW CO₂ laser and a 2kW fiber laser. It is easy to control intermetallic compound by this welding process. When welding speed, laser power and roll pressure were controlled, interlayer thickness and intermetallic compound(IMC) was minimized. In order to estimate joint performance, tensile-shear test and EPMA analysis were done.

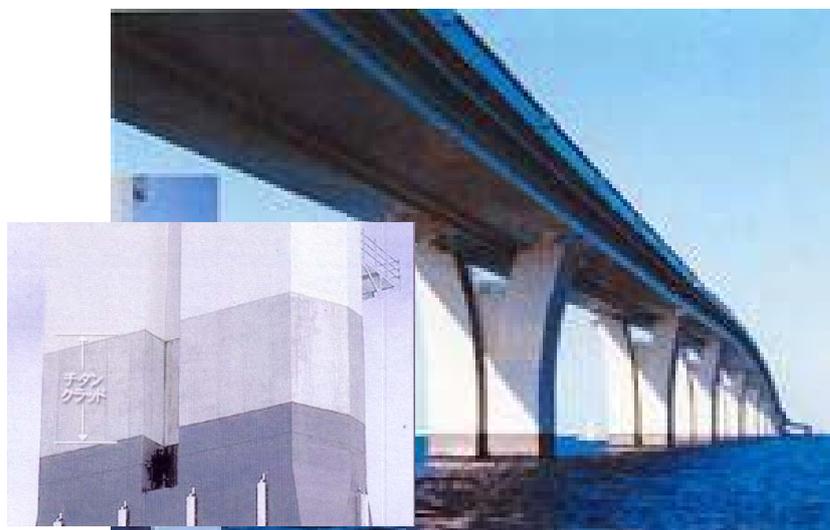


Fig.23 Application of Ti-Fe dissimilar metal panel for the leg of bridge

4.3.2 Experimental Procedure

(1) Materials.

Pure titanium sheet (JIS H4600-TP340C) and low carbon steel (JIS SPCC) sheet were used for joining. The dimension of the titanium sheet and the steel sheet were 40 x 200 x 0.5 mm. The equilibrium diagram of Ti-Fe binary alloys is shown in Fig. 24. The eutectic point is 1085°C. So, laser heating temperature at the interface should be higher than 1085°C.

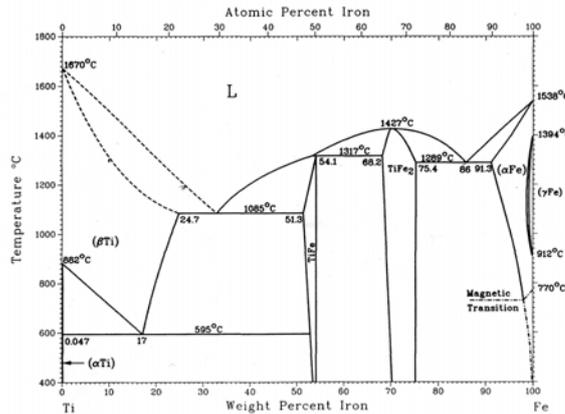


Fig. 24 The equilibrium diagram of Ti-Fe binary alloys

(2) Laser Roll Welding Process.

A schematic diagram of Laser Roll Welding process is shown in Fig.3. A pressure roller, bonding mirror, and a 2.4kW pulse CO₂ laser facility were used for the joining. It is desirable that thermal during the joining should be shortened by rapid heating of laser. Therefore, the formation of the brittle intermetallic compound can be easily controlled. Furthermore, good contacts of steel sheet to titanium sheet and rapid heat transfer from a steel sheet to a titanium sheet are conducted by a pressure roller.

Table 4 Process parameters for laser roll welding

Type of laser	Pulsed CO ₂ laser
Laser power	1.6 ~ 2.0 kW
Duty cycles	80 %
Frequency	150 Hz
Travel speed	1.2 ~ 1.7 m/min
Overlap width	3 mm
Roll pressure	76 ~ 128 MPa
Center shielding gas	Ar: 25 l/min
Side shielding gas	Ar: 25 l/min

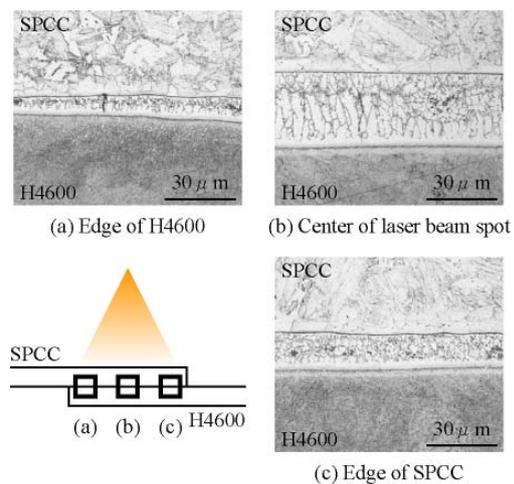


Fig.25 The microstructures of Welded joint

(2) Process Parameters of Laser Roll Welding.

Process parameters are shown in Table 4. Travel speed was varied from 1.2 to 1.7 m/min. The steel surface exposed to the laser beam was coated with graphite to increase the

absorption of laser beam. The faying surface was polished and degreased. Argon gas at the flow rate of 25 L/min was used for shielding of joints.

4.3.3 Experimental Results

4.3.3-1 Laser Roll Welding Using a CO₂ Laser

(1) Microstructures of Joint interface.

The microstructures of Welded joint with laser average power of 2.0 kW and travel speed of 1.4 m/min is shown in Fig.25. The interlayer thickness at the center of laser beam spot is the thickest and at the edge of steel to titanium is the thinnest.

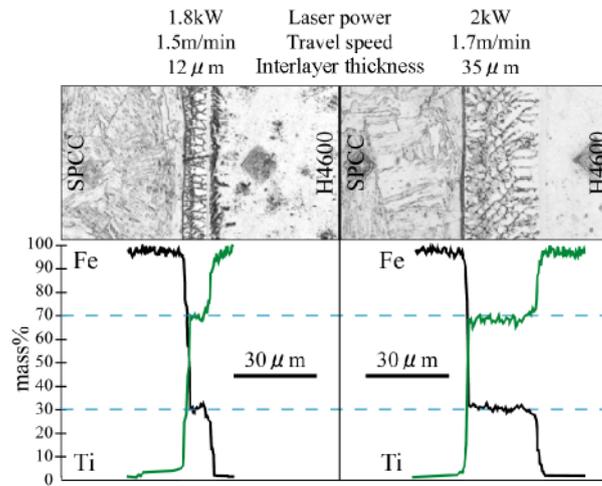


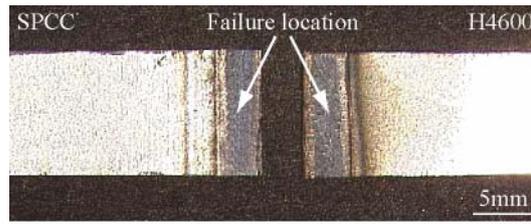
Fig.26 Result of EPMA Analysis of welded joint interface

(2) EPMA Analysis.

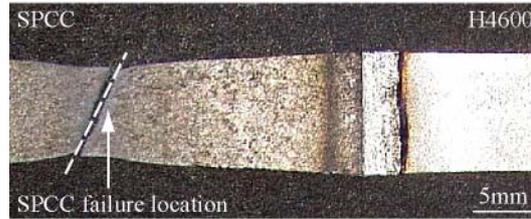
As the optical microstructure does not reveal the details of the interface layer, EPMA of iron and titanium across it were made to identify phases of interlayer. Two such traces for specimens are shown in Fig.26. The interlayer thickness was 17 μm with laser power of 1.8 kW and travel speed of 1.5 m/min, 33 μm with laser average power of 2.0 kW and travel speed of 1.7 m/min. From the EPMA results, it is suggested that the mixed layer of β-Ti and TiFe intermetallic compound is formed at the interface.

(3) Tensile Shear Test.

Tensile shear test was done to investigate the joint performance of welded joint. Tensile shear specimens after testing of Laser Roll Welded joints are shown in Fig.27. Some specimens were broken in the interface (a), others were broken in the base metal of steel sheet (b). When interlayer thickness was less than 25 μm, failure of specimen occurred in the base metal of steel sheet



(a) Failure in interface



(b) Failure in base metal of SPCC

Fig.27 Tensile shear specimens after testing of Laser Roll Welded joints of Titanium to low carbon steel

4.3.3-2 Laser Roll Welding Using a Fiber Laser

(1) Process parameters

2KW fiber laser has more higher power density of beam. It is used for laser roll welding in this section. The process parameters are shown in Table 5. The steel surface heated by laser beam was coated with graphite to increase the absorption of laser beam. The faying surface was polished and degreased. Argon gas was used for shielding of joints at a flow rate of 15 L/min.

Table 5 Process parameters for laser roll welding

Type of laser	cw fiber laser
Laser power	2.0kW
Travel speed	0.6~2.4m/min
Overlap width	5mm
Roll pressure	128MPa
Shielding gas	Ar:15L/min

(2) Microstructures of Welded Joint.

Macro-section of Laser Roll Welded joints are shown in Fig.28. A thin intermetallic compound layer is observed as shown in Fig.28(a), However, too much heating makes very thick interface layer which thickness is 200~300 μm as shown in Fig.28(b). Fig.29 shows the Microstructures of Laser Roll Welded joints. In the interface layer, titanium layer ($\beta\text{-Ti}$), eutectic phase between $\beta\text{-Ti}$ and TiFe and TiFe intermetallic compound can be observed.

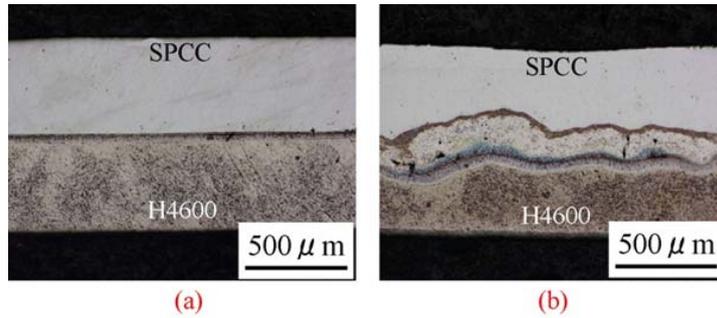


Fig. 28 macro-sections of laser roll welded joint.

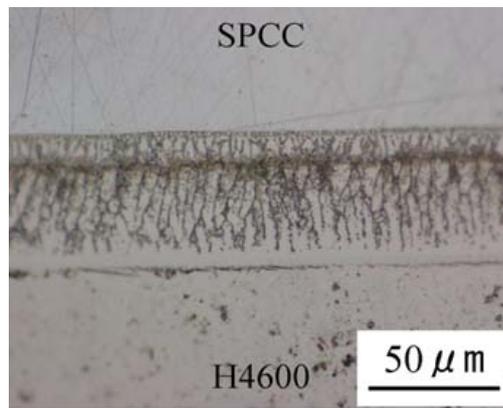


Fig.29 Microstructures of Laser Roll Welded joints

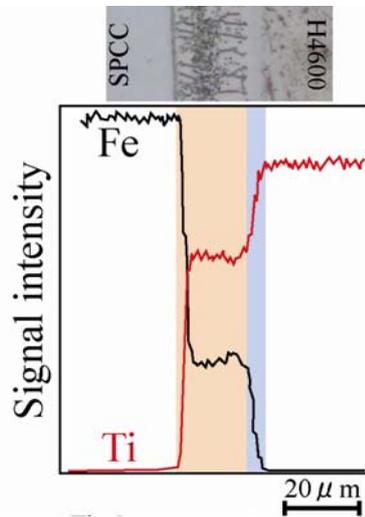


Fig. 30 Result of EPMA analysis of interface layer

(3) EPMA line analysis. EPMA line analysis of iron and titanium across the interface were made to identify interlayer. Composition penetration plots of chemical species for specimen that the interlayer thickness was 30 μm with laser average power of 2.0 kW and travel speed of 2.1 m/min is shown in Fig.30. From the EPMA results, it is suggested that the mixed layer of $\beta\text{-Ti}$ and TiFe is formed at 21

the interface. This layer is eutectic structure composed of β -Ti and TiFe. When there are very thick 200~300 μm intermetallic compound layers, a number of intermetallics TiFe, TiFe₂ and β -Ti have been identified.

(3) Tensile Shear Test.

Some specimens were broken in joint interface, others were broken in the base metal of steel sheet in tensile shear test as shown in Fig.27. Even when interlayer thickness was measure up to 200 μm , some specimens were broken in the base metal of steel sheet.

4.3.3 Conclusion

The effect of laser power and travel speed on the formation and composition of interlayer have been investigated in laser roll welding of titanium to low carbon steel using a pulsed CO₂ laser or cw fiber laser. As a result, laser roll welded joint showed enough tensile strength each type of laser. The composition of thin intermetallic compound layer was eutectic structure composed of β -Ti and TiFe. However, thicker intermetallic compound layer is composed of β -Ti, eutectic structure of β -Ti and TiFe, TiFe or TiFe₂ IMC. Most of welded joints were broken at the base metal in the tensile shear test.

Acknowledgement:

Author are thankful to METI of Japan for the financial help in this research, Laser X co. , Chuoseiki Co. Horie Metal Co and my students, M.J.Rathod, A. Ammar, N.Yamagami, H.Ozaki, R.Ichioka et al at dept. of Material Processing Eng, Nagoya University for their works to develop Laser roll welding process.

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