

# Roll Welding and Laser Roll Welding\*

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DISSIMILAR METALS in sheet or strip are joined for a variety of product applications. Domestic appliances such as electric frying pans and water boilers, for example, use combinations of dissimilar metals. Steel-aluminum sheet has structural application in automobiles and in antifriction parts such as cylinder liners and bushes. Dissimilar joining between steel and aluminum sheet also finds applications in liquefied natural gas storage tanks and steel supporting structure. Besides joining steel to aluminum to obtain higher strength than that of the base metals, other combinations of interest include:

- Steel to copper
- Steel to titanium
- Stainless steel to aluminum
- Galvanized steel to aluminum alloy
- Titanium to aluminum alloy

Joining for this purpose can be done in various ways, such as mechanical clinching, self-piercing riveting, adhesive bonding, diffusion bonding, explosion welding, friction welding, resistance spot welding, forge welding, and roll bonding.

This article describes two methods based on rolling of sheet. The first is roll welding, where two or more sheets or plates are stacked together and then passed through rolls until sufficient deformation has occurred to produce solid-state welds. The other process is laser roll welding, which is a hybrid process based on a thin-melting interface for a lap joint of dissimilar-metal sheets using a roller and one-sided laser heating.

## Roll Welding

Two types of roll welding are common. In the first, the parts to be welded are merely stacked and passed through the rolls. The second method, usually termed pack rolling, involves sealing the parts to be rolled in a pack or sheath and then roll welding the pack assembly.

The first method is more generally employed in the cold welding of ductile metals and alloys.

Sometimes the stack to be welded is first tack welded at several locations to ensure alignment during rolling. Also, when using this method, the deformation during the first rolling pass must exceed the threshold for welding (typically greater than 60% for cold rolling) to keep the parts together. The required first pass reduction can be reduced by hot rolling, if the metals to be rolled can tolerate preheating without excessive oxidation. Once the first pass has been accomplished, the reduction per pass can be decreased, as is often desirable because roll-separating forces increase as the parts to be rolled become thinner. However, the nonuniform stress distribution that builds up during a sequence of very light passes can cause the weld to open up or “alligator.” Therefore, the reduction for subsequent passes is generally a compromise between applying excessive separating forces and “alligating.”

In pack roll welding, the parts to be welded are completely enclosed in a pack that is sealed (typically by fusion welding) and often evacuated to provide a vacuum atmosphere. This may be accomplished by a frame that surrounds the parts to be welded, which is sandwiched by two lids, or may simply consist of two covers formed to encapsulate the parts to be welded (Fig. 1). Semikilled or killed low-carbon steel is a common material for the pack but is not suitable for all alloy and temperature combinations. Although the preparation costs of pack roll welding are significant, the process has the following advantages:

- Provides atmospheric protection, which may be particularly important for reactive alloys such as those of titanium, zirconium, niobium, and tantalum
- Permits welding of complex assemblies involving several layers of parts.

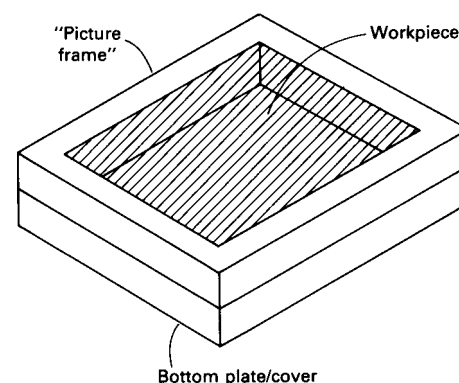
A significant limitation of the process is that packs become difficult to process when their length exceeds several feet.

Titanium and titanium alloys are considerably more difficult to pack roll than are either steels or copper and aluminum alloys because most titanium alloys have very narrow working

temperature ranges. To overcome this problem, titanium alloys that are pack rolled are sometimes encased in a steel envelope, or can. The can is evacuated to minimize oxidation of the work metal, and it also serves to minimize heat loss to the relatively cold rolls upon deformation. The narrow working temperature range of titanium alloys makes the rolling of these materials labor-intensive. Rolling passes are done by hand on relatively small pieces, and many intermediate reheating steps are required. Some  $\beta$ -titanium alloys, however, are continuously rolled on hot and cold strip mills.

Nonpack rolling, of course, can employ continuous strip rolling. A seldom-used hybrid version of roll welding is to seal the edges of the parts to be welded by fusion welding prior to rolling. This method does not provide atmospheric protection to the outer surfaces, as in pack roll welding, but does occlude air from the more critical inner surfaces.

In roll welding, successful welding depends not only on the total amount of deformation but also on the pressure during rolling. A high isostatic pressure component during rolling is promoted by large reductions per pass, large roll diameters, and rough roll surfaces. A nonuniform distribution of normal stresses, referred



**Fig. 1** Pack used for roll welding. The top cover, which would be welded in place before rolling, is not shown.

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to as pressure hill effects, is caused by frictional and mechanical restraint and results in lower pressure near the outer edges of the parts being rolled. Therefore, rolling conditions must be such to ensure sufficient pressure near the edges to avoid weak welds in these regions.

Copper, aluminum, and their alloys are often cold roll welded. Hot rolling is applicable to a wide spectrum of alloys. Typically, hot rolling is performed above recrystallization temperatures. In practice, weldability is often improved by raising the temperature to the region where oxygen mobility becomes significant to promote oxide assimilation by diffusion. Also, welded assemblies are often postheat treated to cause recrystallization (in cold rolling), oxygen diffusion, and/or sintering. In welding dissimilar metals, selection of temperatures for rolling and postheating must take into consideration the possibility of intermetallic compound formation, eutectic melting, and/or porosity due to Kirkendall diffusion. The most common metals that are roll welded are low-carbon steels, aluminum and aluminum alloys, copper and copper alloys, and nickel. Low-alloy steels, high-alloy steels, nickel-base alloys, and titanium and titanium alloys have also been roll welded.

### Roll-Welded Heat Exchangers

One of the more important applications of roll welding is the fabrication of heat exchangers. This process is used to fabricate flat solar collectors. In another method of heat-exchanger fabrication, three plates are stacked, with the middle plate containing the flow channels. The stacked plates are initially held together by tack fusion welds or resistance spot welds. This approach has been employed for both aluminum and steel heat exchangers. A second important application of this process is in the cladding of sheet metal products.

A principal application of roll welding is the production of heat-exchanger panels with flow tubes as an integral part of the composite. Millions of refrigerator evaporator plates have been formed by this process. A cross section of a similar application, solar collector panels, is illustrated in Fig. 2. Roll-welded heat-exchanger panels are most often made of aluminum, although copper and stainless steel panels have also been produced commercially.

The first major step in the production of roll-welded heat exchangers is to thoroughly clean the surfaces of the sheets to be joined by combinations of solvent cleaning, chemical cleaning, and wire brushing. Next, a stop-weld pattern is reproduced on one of the sheets that will later form the passageways in the heat exchanger. This is accomplished by transferring ink onto the surface by silkscreen processing. These stop-off inks contain materials such as graphite or titanium oxide.

The prepared plates are placed together and temporarily joined by spot welding to form a sandwich that is then roll welded, with at least

partial welding occurring during the first rolling pass. The sandwich sometimes is heated prior to this first rolling pass. Whether hot rolling or cold rolling is employed, the major reduction takes place in this first pass (50 to 80%). Subsequently, cold rolling may be employed to reduce the panel to final gage. Also, panels are generally given a postweld heat treatment. This heat treatment results in an annealed part and, particularly in the case of cold rolled panels, may improve the weld quality through recrystallization and diffusion. Finally, the passageways are formed by inflating them with air pressure while the sandwich is held between platens. The panel is then ready for trimming, additional forming, and painting, as required for the application.

The process has been used to produce heat exchangers for refrigerators, solar panels, poultry incubators, electronic equipment temperature controllers, industrial heat exchangers, and special applications such as thermal control of spacecraft. Modifications of the process permit as many as six sheets to be welded at one time and inclusion of passageways oriented along different principal directions at the different layers. Also, it is possible to produce panels where the passageways are expanded on one side only.

### Cladding of Metals by Strip Roll Welding

The common early application of strip roll welding was the fabrication of bimetallic strips for thermostats. This remains an important application, with thermostats taking many complex forms and finding use in furnaces, color televisions, cars, and numerous industrial controls.

A key cladding application is the production of coins by the U.S. Mint. Silver shortages in the 1960s and 1970s resulted in the introduction of coins made from new materials. These coins required a unique set of properties for acceptance by the general public and use in automatic vending machines. Copper clad with cupro-nickel was found to meet these requirements (Fig. 3). The cladding process is relatively simple, although stringent in its requirement for surface preparation. Cladded strips are produced by continuous rolling, with the surfaces prepared just prior to rolling by processes such as wire brushing. Welding typically is accomplished in a single rolling pass. Subsequent heat treatments may be employed to improve the weld quality by processes such as sintering, diffusion, and recrystallization.

The starting material for the U.S. quarter is two outer layers of 75Cu-25Ni, each 1.2 mm (0.048 in.) thick, with an inner layer of pure copper that is 5.1 mm (0.20 in.) thick. To obtain good bond strength, the surfaces are chemically cleaned and wire brushed. The strips are then roll welded to a combined thickness of 2.29 mm (0.090 in.) (Fig. 4). A second rolling operation reduces the final thickness 1.36 mm (0.0535 in.). The strips thus undergo a total reduction of 82% (Ref 1).

Similar processing is applied to many new products, including electrical contacts, conductive springs, automotive windshield wiper sockets, automotive trim, clad cookware, wrap for underground cable, and electromagnetic shielding (Table 1).

Essentially all combinations of ductile metals and alloys can be clad by roll welding, although the oxides of some metals may make welding

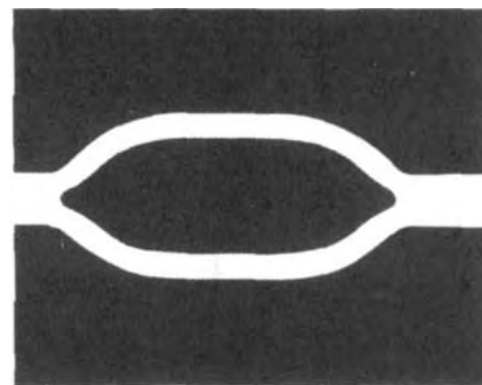


Fig. 2 Cross section of an aluminum solar collector panel produced by the roll welding process



Fig. 3 Metallographic cross section of the edge of a cupronickel-clad copper coin

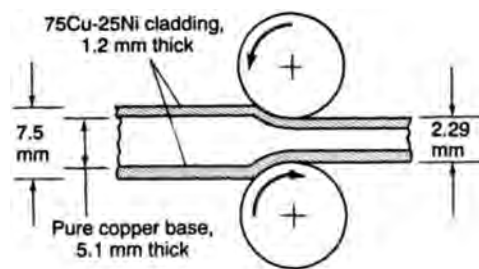


Fig. 4 Schematic showing 70% reduction in cross section of a U.S. Mint quarter coin (composed of an inside layer of pure copper sandwiched between two thin layers of cupronickel material) as it undergoes an initial roll welding operation. A second rolling operation further reduces the material to a final thickness of 1.36 mm (0.0535 in.) for a total reduction of 82%. Source: Ref 1

difficult and other combinations may suffer from intermetallic compound formation on heating. Most engineering metals and alloys can be processed into clad-laminate form, but some cannot (Table 2, Ref 2). One characteristic that makes some metals difficult or impossible to combine by deformation is low ductility. Such metals cannot be co-reduced to the extent necessary to achieve a metallurgical bond. Another characteristic that can cause problems is the tendency of some metals to form a tenacious oxide film that inhibits weld formation. Finally, some metals are thermally unstable; they form brittle intermetallic compounds when heated above a certain temperature. Those metals that are readily processed into clad laminates have opposite characteristics. They are ductile and easily cleaned of oxides, and they form no intermetallic

compounds. In most cases, when a metal is named, alloys of that metal also apply.

### Laser Roll Welding

As noted, laser roll welding is a hybrid welding process—neither a fusion welding process nor completely a solid-state welding process. It is best described as a pressure welding process with a thin layer of melting from laser heating on one side of a lap joint. Using a roller and laser heating, it is typically used to join dissimilar-metal sheets. In the case of aluminum to steel with laser roll welding (Fig. 5), for example, the steel sheet is heated to 1300 °C (2370 °F) so that aluminum melts only near the interface with the steel.

The advantage of laser heating is the sharp focusing of energy for fast heating and cooling. Rapid heating and cooling minimizes the time for formation of brittle intermetallics by diffusion processes. The process of combining laser heating with roll bonding is intended to reach sufficient temperatures quickly, to form a bond while being pressed. Some basic process variables (Fig. 6) include laser power, travel speed, and roll pressure. By control of welding speed, laser power, and roll pressure, the interlayer thickness and formation of brittle intermetallic compounds can be minimized.

Different types of high-power lasers (on the order of 2 kW) can be used for laser roll welding of dissimilar-metal joints. A schematic of roll welding with a CO<sub>2</sub> laser is illustrated Fig. 5(a), and a setup with a fiber-optic laser

**Table 1 Typical properties of common roll-welded clad laminates**

Materials system	Composite ratio, %	Thickness		Width		Tensile strength		Yield strength		Elongation, %	Applications
		mm	in.	mm	in.	MPa	ksi	MPa	ksi		
Copper 10300/low-carbon steel	50:50	0.25–2.54	0.010–0.100	12.7–50	0.5–2	260(a)	38(a)	215(a)	31(a)	40(a)	Typically used for commutators in electric motors, replacing copper 10400. The lower conductivity of steel causes less heat loss during welding, resulting in faster, better-quality welds. The added strength of steel allows thickness reduction.
Deoxidized copper/carbon steel/deoxidized copper	5:90:5, 10:80:10, 15:70:15	0.25–2.54	0.010–0.100	≤610	≤24	420(b)	61(b)	250(b)	36(b)	35(b)	Used in heat exchangers, replacing brazing shim material. One-piece manufacturing eliminates separate shims and reduces assembly cost. Because no ferrous surfaces are exposed, no flux is needed.
Type 434 stainless/5052 aluminum	40:60	0.56–0.76	0.022–0.030	≤610	≤24	395	57	360	52	12	Widely used for automotive body moldings, drip rails, rocker panels, and other trim components, often replacing solid stainless steel or aluminum. Stainless steel provides bright appearance; the hidden aluminum base provides cathodic protection, corroding sacrificially to the body steel.
Copper 11000/1100 aluminum	50:50	0.51–2.54	0.020–0.100	50–510	2–20	180(c)	26(c)	12(c)	1.7	35(c)	Developed specifically for transition joints between copper and aluminum in refrigeration equipment. Usually used in the form of deep-drawn tubing.
C1008 steel/type 347 stainless steel/C1008 steel	43:10:45	0.36	0.014	305	12	393	57	195	28	35	Used in hydraulic tubing in vehicles, replacing terne-coated carbon steel tubing. The outer layer of carbon steel cathodically protects the stainless core of the tube, extending its life significantly.
Nickel 201/type 304 stainless steel/nickel 201	7.5:85:7.5	0.20–2.41	0.008–0.095	25–64	1–2.5	...	...	310	45	40	Used in formed cans for transistor and button cell batteries, replacing solid nickel at a lower cost.
Copper 10300/type 430 stainless steel/copper 10300	17:66:17, 20:60:20, 33:34:33	0.10–0.15	0.004–0.006	12.7–150	0.5–6	415(d)	60(d)	275	40	20(d)	Replaces heavier gages of copper and bronze in buried communications cable. The stainless steel provides resistance to gnawing by rodents, which is a serious problem in underground installations.
Phosphor bronze 51000/carbon steel/copper	10:85:5	0.38–1.52	0.015–0.060	≤610	≤24	455(e)	66(e)	435	63	16(e)	Used in automotive applications, such as windshield-wiper bearings. The bronze provides the bearing qualities, the steel provides strength, and the copper aids tooling life and provides corrosion resistance in service.

(a) In eighth-hard temper. (b) 10:80:10 material. (c) In three-quarter-hard temper. (d) 20:60:20 material. (e) In quarter-hard temper. Source: Ref 2

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Table 2 Relative weldability of selected dissimilar metals and alloys roll welded into clad-laminate form

Base metal No. 1	Base metal No. 2																				
	Ag	Al	Al alloys	Au	Carbon steel	Co	Cu	Mn	Mn-Ni	Nb	Ni	Pt	Stainless steel	Steel	Sn	Ta	Ti	U	Zr		
Ag	...	...	...	...	...	...	A	B	...	...	...	...	...	B	...	...	...	...	...	...	
Al	...	...	A	C	B	C	B	...	...	...	B	...	B	...	...	...	...	...	...	C	
Alfesil	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	
Be	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	
Carbon steel	...	B	...	...	...	...	...	...	...	...	...	...	B	...	...	...	...	...	...	C	
Cu	A	B	...	A	...	...	...	B	B	B	A	B	B	A	A	B	B	...	...	B	
Mn	B	...	...	...	...	...	B	...	...	...	A	B	...	...	...	...	...	...	...	...	
Ni	...	B	...	A	...	...	A	...	...	...	...	B	...	B	A	...	...	...	...	...	
Nb	...	...	...	...	...	...	B	...	...	...	...	...	...	...	...	B	...	...	...	...	
Stainless steel	...	B	...	...	B	...	B	...	...	...	...	...	...	...	...	...	B	...	...	B	
Steel	B	...	...	...	...	...	A	...	...	...	B	...	...	...	...	...	...	...	...	B	
U	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	B

A, easy to weld; B, difficult but possible to weld; C, impractical to weld; D, impossible to weld. Source: Ref

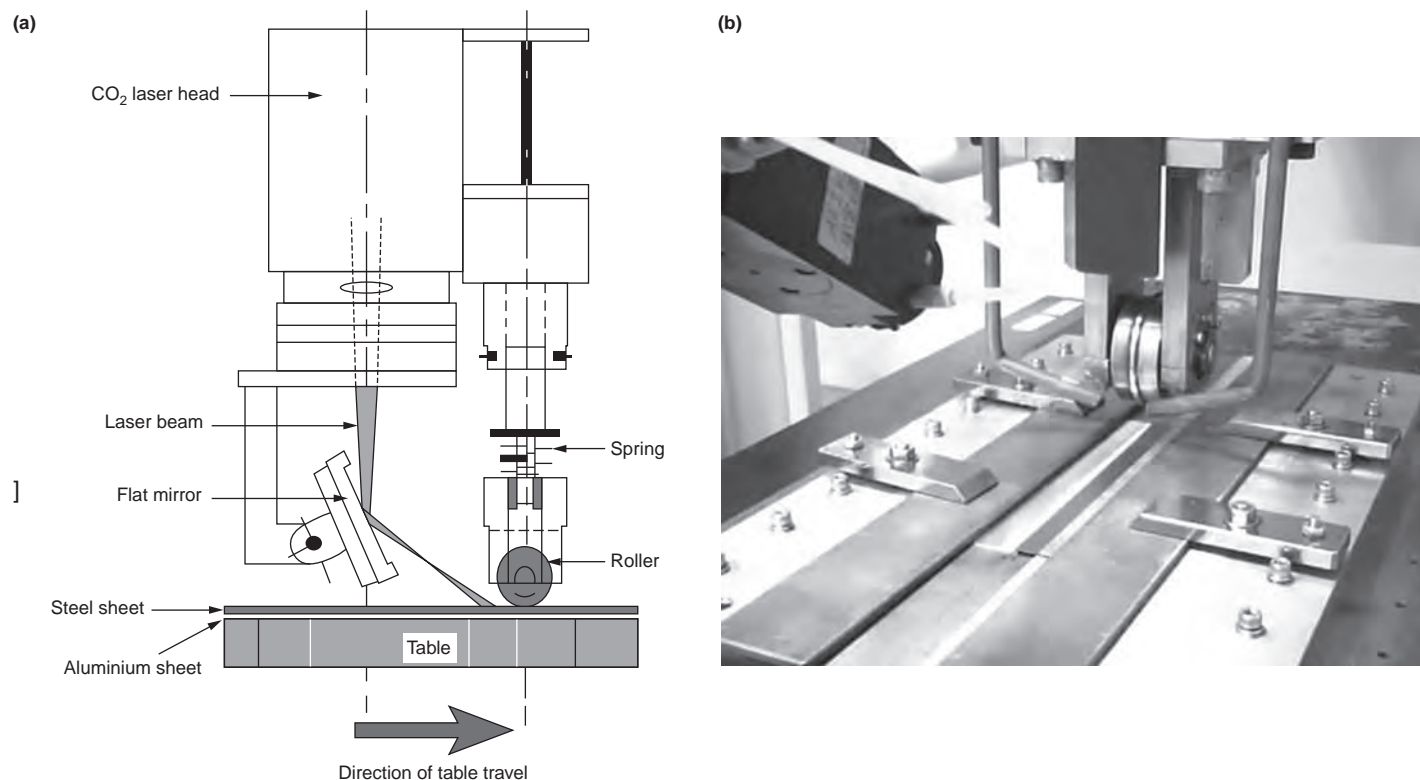


Fig. 5 Laser roll welding. (a) Schematic of laser roll welding process with aluminum and steel sheet. (b) Using a 2 kW fiber laser

is illustrated in Fig. 5(b). The diameter of the beam spot is approximately 3 by 5 mm (0.12 by 0.2 in.) on the metal sheet and 10 mm (0.4 in.) distance from the bottom of the roller. Incident angles of the laser beam were 45  $\mu$ m. CO<sub>2</sub> laser and 30  $\mu$ m. fiber laser, respectively.

## Laser Roll Welding of Dissimilar Metals

### Steel and Aluminum Sheet Joining

Fusion welding of aluminum to steel is impractical, because brittle intermetallic compounds such as FeAl<sub>2</sub>, Fe<sub>2</sub>Al<sub>5</sub>, and FeAl<sub>3</sub> can

form during the melting and subsequent solidification. The reason for this is attributed to the great difference between their melting points (660  $^{\circ}$ C, or 1220  $^{\circ}$ F, for aluminum and 1538  $^{\circ}$ C, or 2800  $^{\circ}$ F, for iron), almost zero solid solubility in each other, and formation of brittle intermetallic compounds.

In the iron-aluminum system (Fig. 7), intermetallic compounds are grouped as iron-rich compounds (FeAl and Fe<sub>3</sub>Al) and aluminum-rich compounds (FeAl<sub>2</sub>, Fe<sub>2</sub>Al<sub>5</sub>, and FeAl<sub>3</sub>). Mechanical properties of cast intermetallic compounds under compressive test are shown in Fig. 8. While the aluminum-rich intermetallic compounds are brittle, iron-rich intermetallic compounds show slight ductility and high

strength. The objective is to minimize formation of the brittle intermetallic compounds.

Although the complete elimination of brittle intermetallic compounds such as FeAl<sub>3</sub>, FeAl<sub>2</sub>, and Fe<sub>2</sub>Al<sub>5</sub> is not possible due to their low free energy, their formation can be suppressed to some extent. Laser heating of the steel quickly reaches the temperature of the interface suitable to form ductile compounds such as FeAl and Fe<sub>3</sub>Al (approximately 1250  $^{\circ}$ C, or 2280  $^{\circ}$ F). This results in melting of a very thin layer of aluminum—on the order of 10  $\mu$ m—at the interface. 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

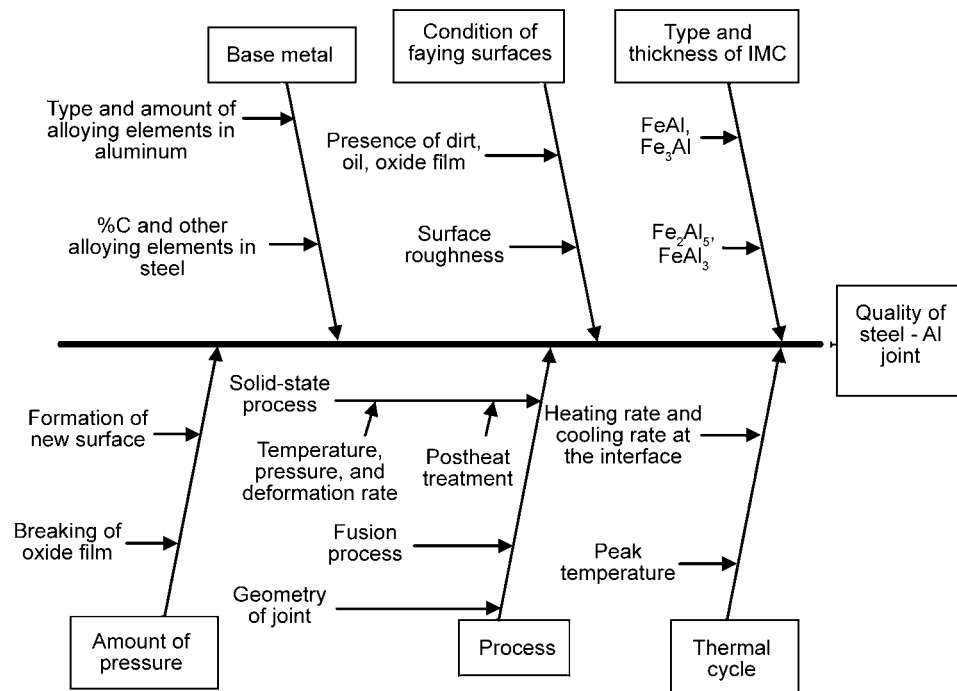


Fig. 6 Process parameter for laser roll welding. IMC, intermetallic compound

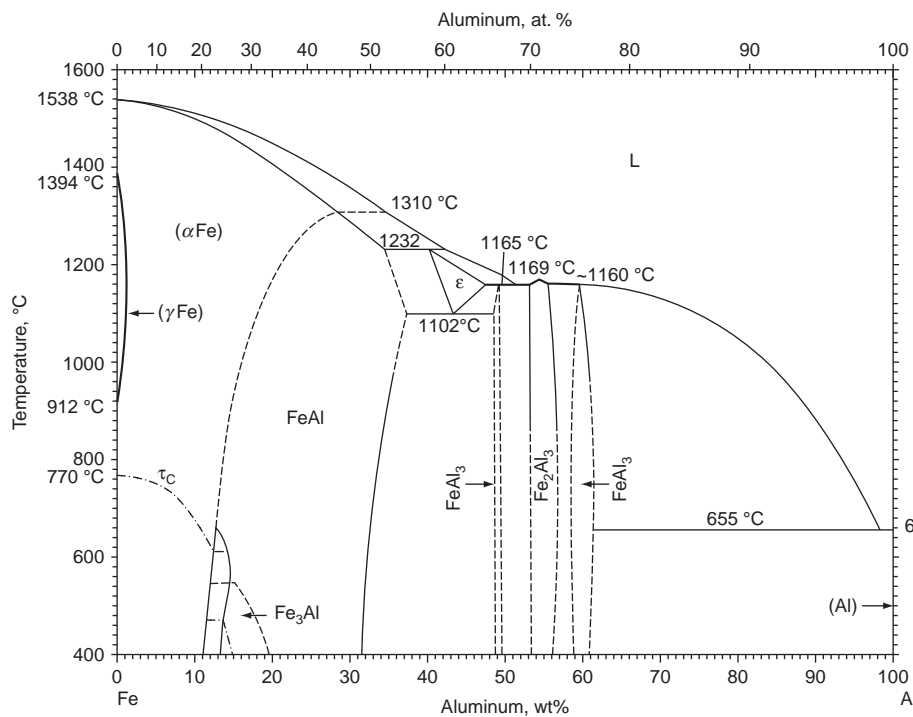


Fig. 7 Aluminum-iron phase diagram

further diffusion at the interface. Such conditions restrict the intermetallic compound layer thickness to thin levels. The existence of a thin interface layer containing some ductile compounds is favorable for improved joint strength.

**Welding Uncoated Steel Sheet with Aluminum Sheet.** Low-carbon steel and aluminum alloy sheet products are common in the automobile industry for structural components. For weight reduction, one method is to use

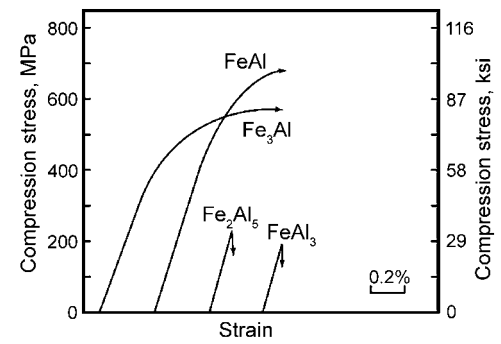


Fig. 8 Stress-strain curve in compressive test of iron-aluminum intermetallic compounds. Source: Ref 3

combined sections consisting of steel sheet with aluminum or aluminum alloy sheet. Attempts to use resistance spot welding with inserts for this purpose have already been made (Ref 3), with the major problem being the formation of brittle intermetallic compounds such as FeAl<sub>3</sub> and Fe<sub>2</sub>Al<sub>5</sub> in the interface layer. It has also been reported that if the layer thickness of the intermetallic compound is limited to below 10  $\mu\text{m}$ , the joint strength is improved (Ref 4).

In an example of laser roll welding, a low-carbon steel (JIS-SPCC, 0.12 C max, 0.5 Mn max, 0.04 P max, S 0.045 max) with a sheet thickness of 0.5 mm (0.02 in.) was joined with a 1 mm (0.04 in.) thick sheet of aluminum (A1050) and aluminum-magnesium alloy (A5052). A continuous-wave CO<sub>2</sub> laser was used to weld the steel sheet to the A5052 alloy, while a pulsed CO<sub>2</sub> laser was used to weld the steel sheet to the unalloyed aluminum sheet (A1050).

A lap joint was used, and the steel was placed on top of the aluminum to absorb the heat from the incident laser beam without melting and to conduct the heat to the interface. The overlap was 9 mm (0.36 in.), and the Gaussian beam was defocused to give an elliptical spot of 2.5 mm (0.10 in.) minor and 3.5 mm (0.14 in.) major diameter on the steel surface. A spring was used to press the joint against the table through the roll. Prior to joining, the faying surfaces of both sheets were cleaned ultrasonically to remove the hard aluminum oxide film, then treated with a brazing flux (KAlF<sub>4</sub>·K<sub>2</sub>AlF<sub>5</sub>·H<sub>2</sub>O) to prevent further oxidation.

Laser roll welding was conducted with varying travel speed, laser power, and roll pressure. The range of conditions was as follows:

- *Laser power:* 1.0 to ~2.0 kW
- *Travel speed:* 1.0 to 3.2 m/min (3.3 to 10.5 ft/min)
- *Beam spot diameter:* 3 to 5 mm (0.12 to 0.2 in.)
- *Roll pressure:* 100 to 200 MPa (14.5 to 29 ksi)
- *Shielding method:* Argon gas

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In addition to these parameters, pulsed laser welding is used to weld the unalloyed aluminum A1050, which enables more control of the heating and cooling rates by changing the pulse.

The joints were cut transversely to observe the macrostructure and microstructure. Macrostructure examples are shown in Fig. 9. Specimens were used to identify and estimate the intermetallic compounds through the interface layer by electron probe microanalysis (EPMA) with wavelength-dispersion analysis. Based on the EPMA results, the thickness of the interface layer was divided into ductile compounds (FeAl and Fe<sub>3</sub>Al) and brittle compounds (FeAl<sub>3</sub> and Fe<sub>2</sub>Al<sub>5</sub>). The EPMA analysis showed that the interface layer consisted of brittle intermetallic compounds (FeAl<sub>3</sub> and Fe<sub>2</sub>Al<sub>5</sub>) on the aluminum side and ductile ones (FeAl and Fe<sub>3</sub>Al) on the steel side. As the travel speed increased, the total thickness of the interface layer decreased with increasing thickness of the ductile compounds.

Thickness of the interface layer could be controlled by changing pressure values and interface temperature (by varying the laser power or travel speed). Increasing the power has the same effect as decreasing the speed, but if the power reaches high values, it will

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

Figures 10 and 11 illustrate the effect of travel speed on interface layer thickness and shear strength. By increasing the travel speed, the interface layer thickness decreases at the same time shear strength increases up to 33 MPa (4.8 ksi) for A1050 and to 56 MPa (8.1 ksi) for A5052. With higher speeds, the percentage of ductile compounds is relatively high, but the shear strength drops for fast travel speed, owing to insufficient temperature due to the lack of heat energy at the interface layer. To evaluate the formability of the joints, the Erichsen test was carried out and evaluated with different speeds, as shown in Fig. 12. The cupping height increases with speed until it reaches a maximum value, then starts to decrease almost in the same manner as the shear strength analysis.

**Welding Galvanized Steel Sheet with Aluminum Sheet.** Laser roll welding of dissimilar-metal-joint zinc-coated steel with 6000-series aluminum alloy (A6000) has also been

evaluated. Like the uncoated steel sheet, the following conclusions were observed:

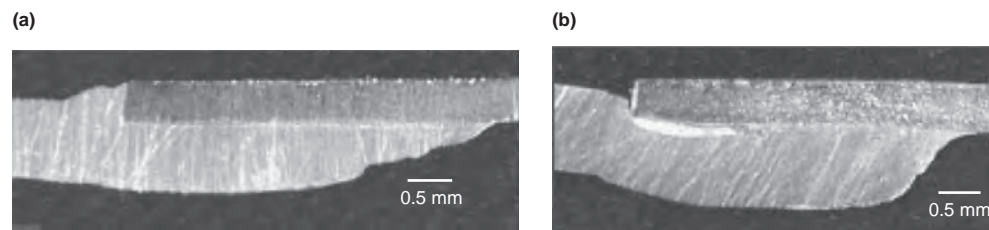
- Increase in the travel speed of the table led to decrease in the thickness of the intermetallic compound layer at the interface. Increase in travel speed led to lowering of the peak temperature and shortening of the holding time more than 500 °C (900 °F) at the interface.
- It is suggested that the intermetallic compound layer formed is mainly brittle FeAl<sub>3</sub>. Because the travel speed is faster than 0.6 m/min (2.0 ft/min), zinc is confirmed in the aluminum alloy.
- When the intermetallic compound layer was less than 10 μm, failure of the specimen occurred at the base metal of the zinc-coated steel in tensile shear test.

### Steel and Titanium Sheet Joining

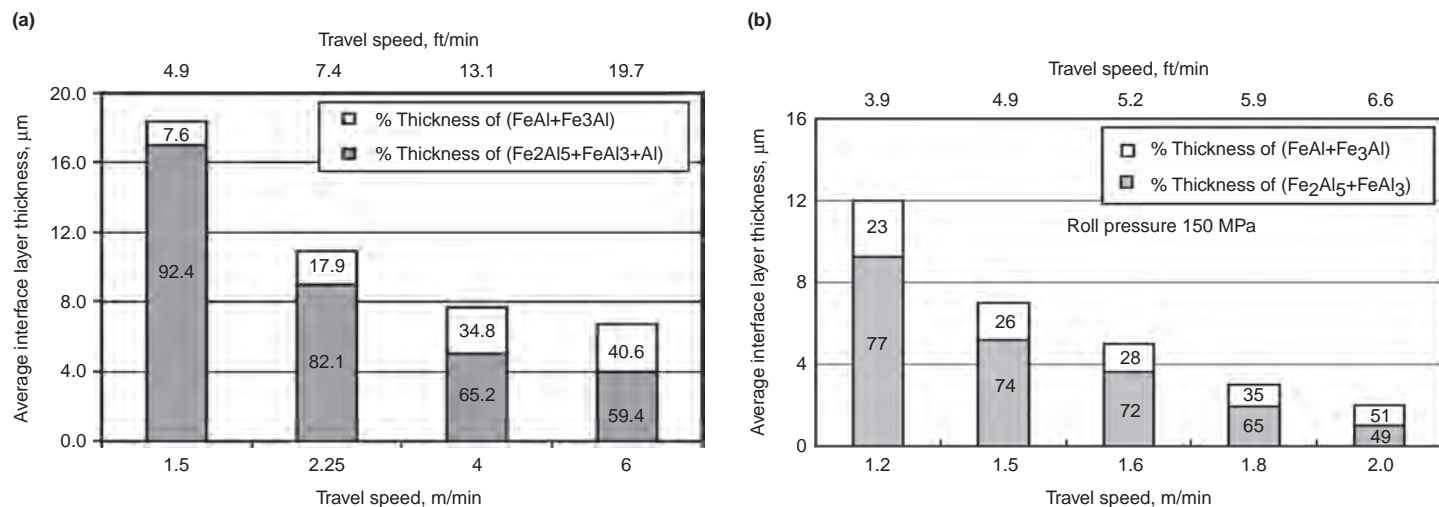
Fusion welding of steel and titanium is difficult because of generating the brittle intermetallic compound, but laser roll welding allows some control over the formation of intermetallic compounds. In the case of laser roll welding of titanium to steel, the eutectic phase between titanium and TiFe intermetallic compound is formed from the liquid phase at the interface above 1180 °C (2155 °F). The melting interface and interlayer should be controlled to obtain a ductile phase at the interlayer.

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 by 200 by 0.5 mm (1.6 by 8 by 0.02 in.).

Process parameters are shown in Table 3. Travel speed varied from 1.2 to 1.7 m/min (3.9 to 5.6 ft/min). The steel surface exposed to the laser beam was coated with graphite to increase the absorption of the laser beam.



**Fig. 9** Macrostructure samples from joints after laser roll welding of low-carbon steel sheet (JIS-SPCC) with (a) A1050 aluminum and (b) aluminum-magnesium alloy A5052. Laser power, welding speed, and roll pressure were: (a) 1.5 kW, 1.5 m/min (4.9 ft/min), and 150 MPa (22 ksi) for A1050, and (b) 1.5 kW, 2.2 m/min (7.2 ft/min), and 200 MPa (29 ksi) for A5052



**Fig. 10** Composition of intermetallic compounds in the interface layer. (a) SPCC-A1050 at 1.5 kW, 150 MPa (22 ksi). (b) SPCC-A5052 at 1.5 kW, 150 MPa (22 ksi)



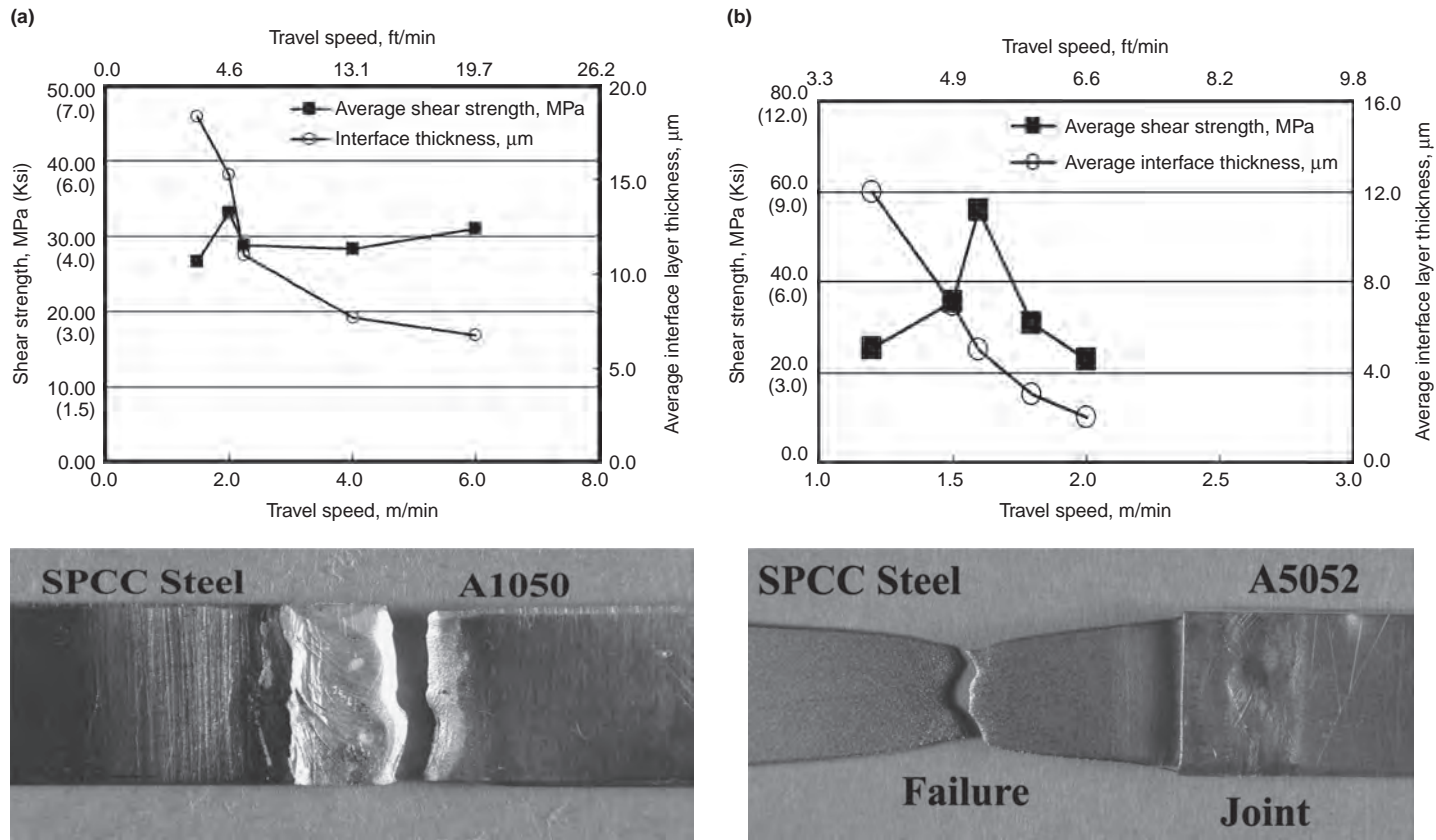


Fig. 11 Effect of travel speed on shear strength. (a) SPCC-A1050. (b) SPCC-A5052

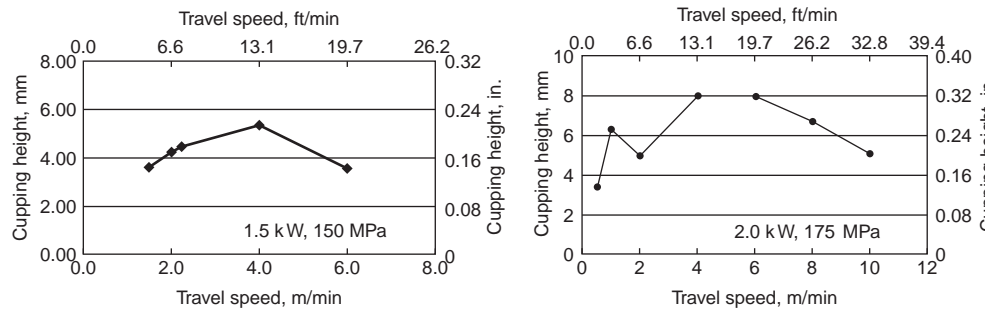


Fig. 12 Results of Erichsen test performed on laser roll-bonded joints. (a) A1050 at 1.5 kW, 150 MPa (22 ksi), 1.5 m/min (4.9 ft/min). (b) A5052 at 2.0 kW, 175 MPa (25 ksi), 2.0 m/min (6.6 ft/min)

Table 3 Process parameters in laser roll welding of commercially pure titanium with steel sheet

Type of laser	Pulsed CO <sub>2</sub> laser
Laser power	1.6–2.0 kW
Duty cycles	80%
Frequency	150 Hz
Travel speed	1.2–1.7 m/min (3.9–5.6 ft/min)
Overlap width	3 mm (0.12 in.)
Roll pressure	76–128 MPa (11–18.5 ksi)
Center shielding gas	Ar: 25 L/min
Side shielding gas	Ar: 25 L/min

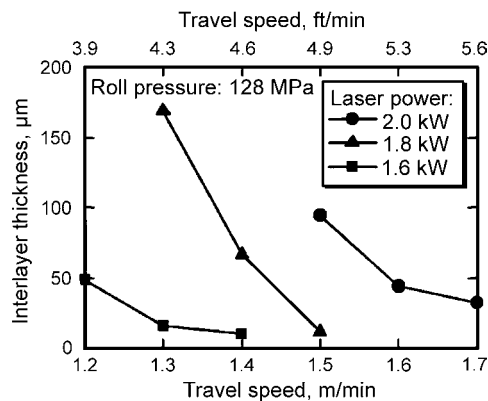


Fig. 13 Effect of power and speed on interlayer thickness

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

The effect of laser power and travel speed on interlayer thickness is shown in Fig. 13. Interlayer thickness decreases significantly from 170 to 10 μm as the travel speed is increased from 1.3 to 1.5 m/min (4.3 to 4.9 ft/min) at a laser power of 1.8 kW.

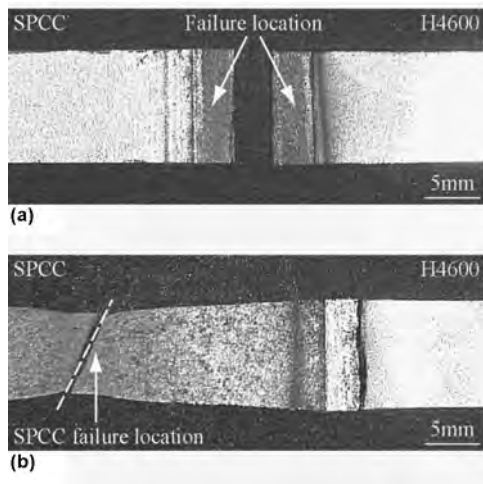
A tensile shear test was done to investigate the performance of the welded joint. Tensile shear specimens after testing of laser roll-welded joints are shown in Fig. 14. Some

specimens were broken at the interface (Fig. 14a), and others were broken in the base metal of the steel sheet (Fig. 14b). When the inter-layer thickness was less than 25 μm, failure of the specimen occurred in the base metal of the steel sheet.

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**Fig. 14** Tensile shear specimens from steel-titanium joint after laser roll welding. (a) Failure at interface. (b) Failure in base metal of SPCC

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