

Development of Laser-arc Hybrid Welding

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Laser-arc hybrid welding combines the laser and arc welding processes to provide advantages not found in either. This process can weld lapped steel sheets that have a larger gap than is possible with laser welding. Blowholes form when lap-welding zinc-coated steel sheets because of the zinc that is vaporized. The laser-arc hybrid welding process can lap-weld zinc-coated steel sheets without causing blowholes. The welding speed of laser-arc hybrid welding is nearly equivalent to that of laser welding. Laser-arc hybrid welding produces high-quality lap joints and is ideal for assembly welding of automotive parts.

1. Introduction

In recent years, laser welding has begun to be used for assembly welding of automotive bodies and parts, although it has not yet to be used widely. One restraint is that in laser lap welding, the gap between the lapped sheets must be controlled very tightly. If the gap is wide, burn-through occurs, and, if the gap is excessive, the two sheets cannot be welded together. For this reason, the gap is generally restricted to 0.1 mm or less for laser welding. Laser lap welding of zinc-coated sheets poses additional problems. Laser lap welding of zinc-coated sheets is performed without any gap, so the zinc that is evaporated between the sheets tends to blow off weld metal, or the zinc vapor tends to remain in the weld metal and form blowholes.

Laser-arc hybrid welding was developed to solve these problems. This method combines YAG laser welding and arc welding, allows a larger gap between lapped sheets than in laser welding, and produces fewer blowholes, even in lap welding of zinc-coated sheets. Therefore, stringent gap control is not necessary for lap welds, and the industrial application of this method is easy. In addition, the welding speed can be equivalent to that of laser welding, so the high efficiency of laser welding can be utilized.

2. Configuration of laser-arc hybrid welding

Fig.1 shows the system configuration for laser-arc hybrid welding. A YAG laser is used for laser welding, and an arc-welding electrode is positioned behind the YAG laser radiation point. The aim position of the arc is about 1

to 3 mm behind the laser radiation point. A YAG laser is used because the plasma does not absorb much of the laser energy. Most of the energy reaches the sheets, so that the YAG laser energy is efficiently utilized for welding. In contrast, energy from a carbon-dioxide laser is strongly absorbed by the arc plasma, so that a sufficient distance must separate the arc and the laser radiation point. Therefore, the combined effect of the laser and arc is not possible with a carbon-dioxide laser.

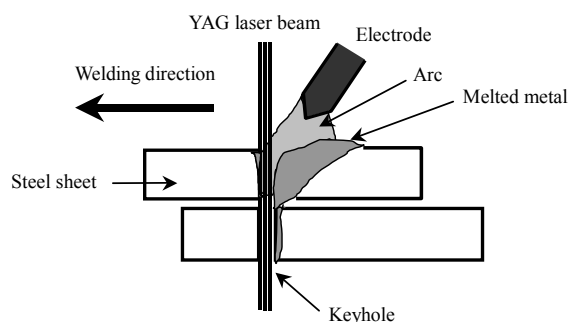


Fig.1 Configuration of laser beam and arc-welding electrode in laser-arc hybrid welding

3. Experiment

3.1 Experimental method

A YAG welding laser manufactured by Luminics with a rated output of 4.5 kW was experimentally combined with metal active gas welding (MAG welding). An 0.8 mm diameter, solid, mild steel wire was used for the welding wire. Cold-rolled steel sheets and hot-dip galvanized (GA) steel sheets with thicknesses of 0.8 to 1.6 mm were used as specimens. All joints were lap welds. The welding conditions are given in Table 1.

Table 1 Welding conditions of laser-arc hybrid welding

Laser resonator	Max. output 4.5kW (lumonics)
Laser output	3kW
Welding speed	1.0 to 5.0m/min
Arc current	60 to 150A
Shielding gas	Ar+20%CO ₂ (20 l/min)
Consumable	Kobe MGS50 (0.8mm ϕ)

3.2 Analysis of hybrid welding phenomena

Time variations of the arc voltage were recorded to investigate arc welding phenomena during hybrid welding.

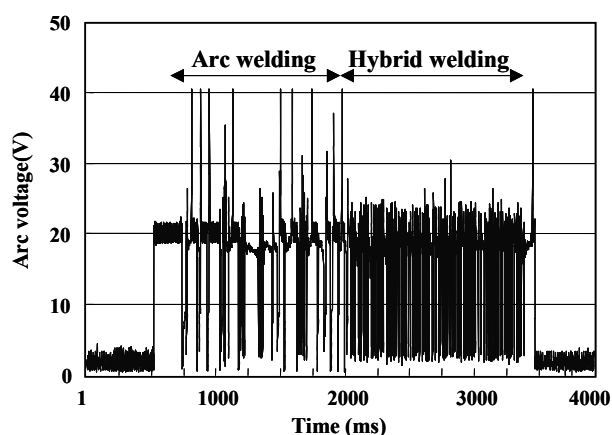
3.3 Evaluation of welded joint performance

The external appearance of the welded joints was visually inspected and evaluated for the presence of welding defects such as blowholes and pits. Further, macrosections were prepared and examined for the formation of the weld beads and existence of blowholes. The strength of the welded joints was determined by tension shear tests.

4. Experimental results

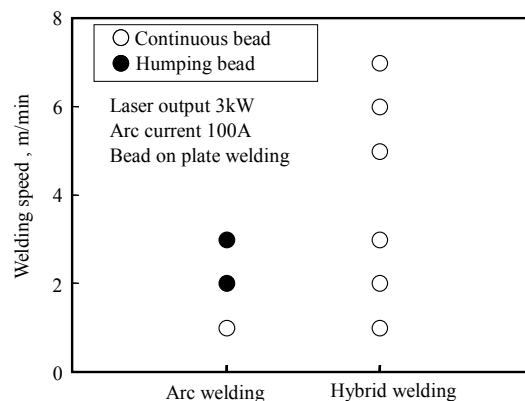
4.1 Welding phenomena

Fig.2 shows the time variation of arc voltage between the welding wire and sheet during hybrid welding. The welding conditions were as follows: laser (working point) output 3 kW, arc current 100 A, and welding speed 2 m/min. The time variation of arc voltage during arc welding is shown in the same figure for comparison. In hybrid welding, the voltage oscillates within the range of 0 to about 20 V at high frequency. Dip transfer of droplets from the wire takes place in a cycle of about 10 ms. In contrast, the voltage during arc welding oscillates over a much wider range, and the dip transfer cycle time is significantly higher at 50 - 100 ms.

**Fig.2** Time variation of arc voltage with and without laser radiation

Generally in arc welding, the bead shape becomes more uneven as the welding speed increases. Hybrid welding can provide uniform beads even when the welding speed is high because droplet transfer from the wire takes place in a very short cycle.

Fig.3 shows the welding speed limit for forming a uniform weld using hybrid and arc welding. The welding speed limit for hybrid welding is at least seven times higher than that for arc welding.

**Fig.3** Welding speed limit for arc welding and hybrid welding that does not cause humping

The arc remains steady in hybrid welding, even at high speeds, as explained below. In arc welding, the arc is maintained by thermionic emission from the sheet. When the welding speed is high, the heating becomes insufficient, and the arc becomes unstable.

In contrast, during hybrid welding, the electron density in a keyhole formed by laser radiation reaches 10^{17} to $10^{20}/\text{cm}^3$. Moreover, the surrounding area is in a molten state, so that thermionic emission takes place very easily. When arc welding is combined with laser welding in this region, a stable arc is maintained even when the welding speed is high.

The reason why the dip transfer cycle time is short in hybrid welding can be explained as follows. In arc welding, the arc is maintained while the thermionic emission points (anode spot and cathode spot) are moving on the sheet, so that the energy is widely dispersed. In contrast, the arc during hybrid welding is discharged from the laser radiation point with a diameter of about 1 mm, which squeezes the arc into a narrow range and concentrates the energy. Therefore, the wire is easily melted, and the arc length is short (potential gradient is large), so that the droplets become small and are transferred to the base metal at a high frequency. The arc discharge mechanisms for arc welding and hybrid welding are shown in Fig.4.

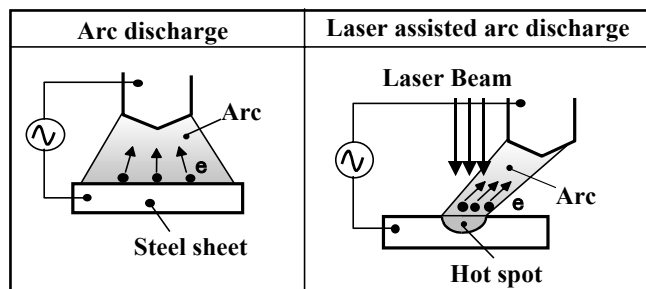
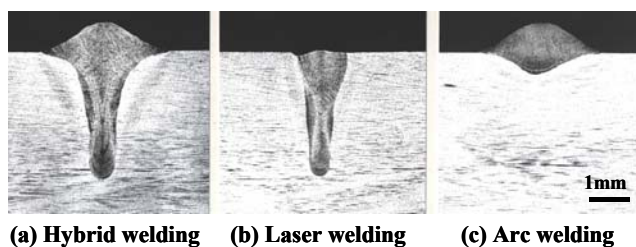


Fig.4 Mechanisms of arc discharge with and without laser beam radiation

Photo 1 compares a macrosection of a hybrid weld bead with those of laser and arc weld beads. The penetration geometry of the hybrid weld bead is a combination of that of the laser and arc weld beads. Near the surface, the arc heat melts the base metal, and the weld bead forms a bulge because weld metal is supplied from the wire. The penetration depth in hybrid welding is approximately equal to that in laser welding. This indicates that laser welding determines the penetration depth, and that, even when the heat input is increased by combining arc welding with laser welding, the arc heat merely melts the surface of the base metal and does not deepen the penetration. However, the fact that the hybrid weld bead contains a larger amount of weld metal than the laser weld bead is advantageous in terms of the gap tolerance and bead width in lap welding.



Laser output; 3kW, Arc current; 100A, Welding speed; 1m/min

Photo 1 Cross sections of hybrid, laser and arc weld beads

4.2 Weld formation

4.2.1 Gap tolerance in lap welding

As described previously, in laser lap welding, the upper sheet melts, and underfill occurs if the gap between lapped sheets is excessive. In the extreme case, a hole is formed. To investigate the gap tolerance for hybrid lap welding, sheets of various thicknesses were lap-welded with varied gaps. The results are shown in Fig.5, and the results for the laser welds are shown in Fig.6 for comparison. These figures show that the gap tolerance for hybrid welding is higher than that for laser welding. Thus, a sound weld bead is formed in hybrid welding, even when the gap is as wide as the sheet thickness.

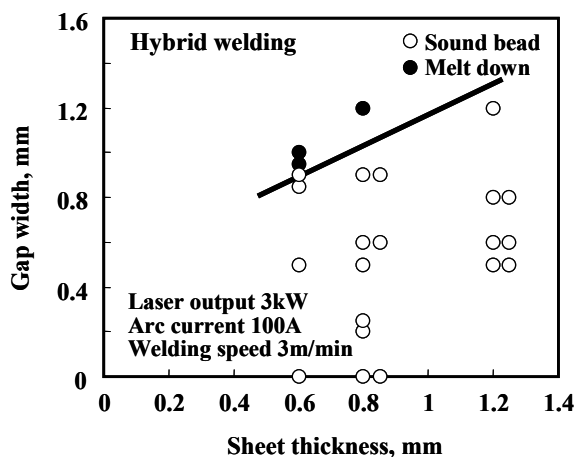


Fig.5 Gap tolerance in hybrid lap welding

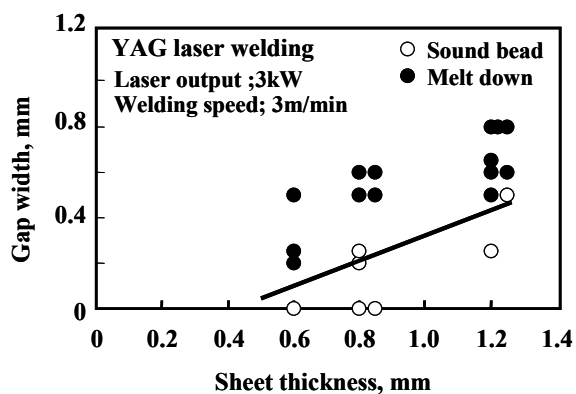


Fig.6 Gap tolerance in laser lap welding

Photo 2 is a macrosection of a hybrid-welded lap joint between two sheets with a gap. It shows that the two sheets are connected completely with no underfill.

The gap tolerance for hybrid lap welding is considerably greater than that for laser welding because the filler wire used in hybrid welding supplies enough weld metal to fill the gap. In contrast, when a gap is present in laser welding with no filler metal, the amount of molten metal tends to be insufficient to fill the gap, resulting in underfill or burn-through.

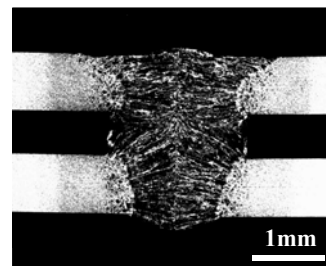


Photo 2 Cross section of hybrid lap-welded joint
(Laser output 3 kW, arc current 100A, welding speed 3.0 m/min)

4.2.2 Increase in bead width in lap welding

Hybrid welding also provides a better bead width than laser welding because of the filler wire. Lap-welded joints were fabricated by laser welding and hybrid welding, and changes in the bead width were measured as a function of the gap between sheets. The results are shown in Fig.7. With a zero gap, the bead width from hybrid welding is approximately equal to or slightly larger than that from laser welding. As the gap width increases, the bead width increases in hybrid welding, while the bead width is almost unchanged in laser welding. This is because, when a gap is present in hybrid welding, the molten weld pool formed by laser welding is supplemented with the additional molten metal formed by arc welding, which fills the gap. In contrast, a sufficient amount of molten metal is not supplied in laser welding, and this effect is not expected.

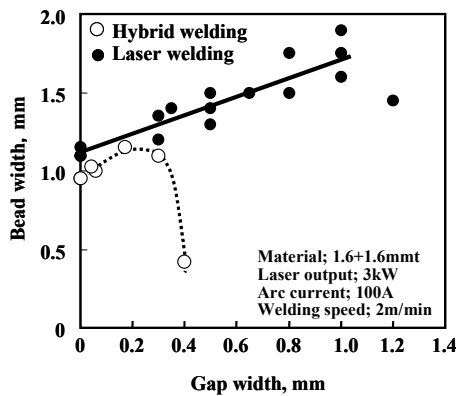


Fig.7 Bead width of laser- and hybrid-lap welding

4.3 Strength of lap-welded joint

The tensile shear strength of hybrid-welded joints was investigated. The shape of the specimen is shown in Fig.8.

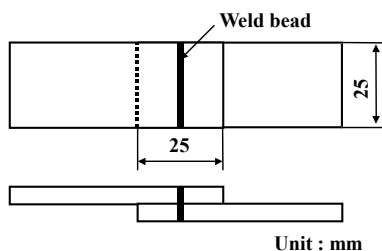


Fig.8 Test specimen for tensile shear strength of lap-welded joint

Table 2 gives the tensile shear strength, bead width, and weld metal hardness of lap-welded joints fabricated from 1.2 mm thick steel sheets with various strengths. The results of laser-welded joints are also shown for comparison. All of the hybrid-welded joints fractured in the base metal, while all of the laser-welded joints fractured in the weld.

Table 2 Tensile strength of lap joints by hybrid and laser welding

Laser or hybrid welding	TS of BM (MPa)	Joint strength (kN)	Failure position	Bead width (mm)	Bead hardness (Hv)
Hybrid	304	9.4	BM	1.6	220
Hybrid	650	18.1	BM	1.5	250
Hybrid	650	18.1	BM	2.0	250
Hybrid	650	17.4	BM	1.6	250
Hybrid	807	21.1	BM	2.1	280
Hybrid	1038	23.4	BM	1.6	380
Laser	650	13.7	WM	1.0	250
Laser	650	10.4	WM	0.8	260
Laser	650	7.8	WM	0.6	260

* BM : Base metal, WM : Weld metal

The fracture strength F_w (N) of a laser lap-welded joint is calculated by Equation (1).³⁾ This equation is also applicable to a hybrid-welded joint.

$$F_w = 1.9W \times h \times H_v \quad \cdots \cdots (1)$$

where, W is the specimen width (mm), h is the bead width (mm), and H_v is the Vickers hardness of the weld metal.

The fracture location in tensile tests of a welded joint is determined by the relation between the strengths of the weld metal and base metal. When the weld metal strength exceeds that of the base metal, the base metal fractures. Otherwise, the weld metal fractures. As is apparent from Equation (1), the strength of the weld increases in proportion to the bead width for a constant bead hardness. The base metal strength is constant and not related to the bead width.

Fig.9 shows the experimental relation between the bead width and tensile shear strength of a welded joint between steel sheets with a tensile strength of 650 MPa. The figure also shows the theoretical relation obtained by Equation (1) for the case where the weld metal hardness is 250. The figure demonstrates that hybrid welding provides a wider bead, and thus a stronger joint, than laser welding, so fracture occurs in the base metal.

4.4 Weldability of zinc-coated steel sheets

The boiling point of zinc is about 900°C, which is significantly lower than the melting point of iron (1500°C). When zinc-coated sheets are lap-welded, the zinc evaporates, and zinc vapor intrudes into the molten metal, so that blowholes are produced, or weld metal is blown off and a hole is formed. Photo 3 shows a longitudinal cross section of a lap-welded joint obtained by laser welding of hot-dip

galvannealed (GA) steel sheets (coating weight: 45 g/m², both surfaces coated). A large number of blowholes are present in the bead.

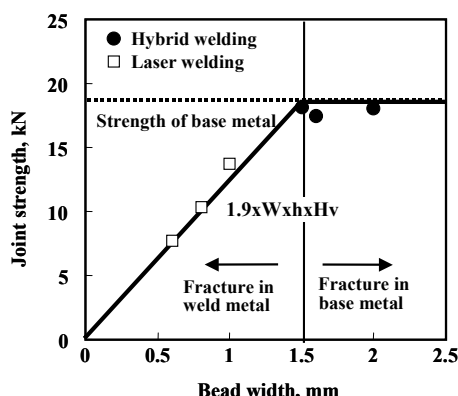


Fig.9 Relation between lap joint tensile strength and bead width

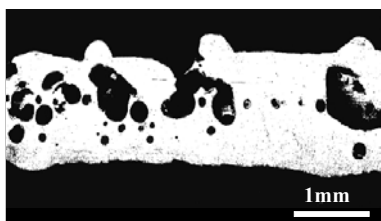


Photo 3 Longitudinal cross section of laser-welded lap joint of GA steel sheets

Photo 4 shows a longitudinal cross section of a hybrid-welded lap joint. No blowhole is observable in the bead, confirming that a sound welded joint is formed.

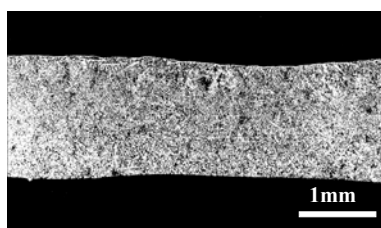


Photo 4 Longitudinal cross section of hybrid-welded lap joint of GA steel sheets

The reasons why hybrid lap welding of zinc-coated steel sheets markedly suppresses the formation of blowholes as compared to laser welding are thought to be as follows. In hybrid welding, arc welding is performed after laser welding, and a much longer time elapses before the molten metal solidifies than with laser welding. This provides sufficient time for the zinc vapor to escape out of the molten metal. In addition, molten metal blown off by the zinc vapor in laser welding is supplemented with metal from the wire feed.

5. Conclusions

The application of laser welding to the assembly of automotive bodies and parts has problems in that the tolerance of the gap between the lapped sheets is low, and blowholes are produced when zinc-coated steel sheets are lap-welded. Laser-arc hybrid welding was developed to solve these problems. This newly developed welding method maintains the features of laser welding, in that it is highly efficient and does not cause much thermal deformation due to its low heat input. Its proven characteristics are as follows:

(1) Large gap tolerance in lap welding

The gap tolerance in hybrid lap welding is nearly equivalent to the thickness of the sheets to be welded, which is significantly larger than with laser welding.

(2) High strength of welded joint

The hybrid lap-welded joint can attain a strength that exceeds that of the base metal because the bead width is wider than that in laser welding.

(3) Excellent lap weldability of zinc-coated steel sheets

In hybrid lap welding of zinc-coated steel sheets, the formation of blowholes is restrained significantly compared to laser welding, even when the gap is 0 mm, so that a sound welded joint can be obtained.

References

- 1) Hamazaki, M. et al, "Effect of TIG Current in Combined Welding of TIG Arc and Laser Welding", Journal of High Temperature Society, Vol. 9, No. 2, pp. 79-83 (1983).
- 2) Dilthey, U. et al, "Prospects by Combining and Coupling Laser Beam and Arc Welding Processes", IIW Doc. XII-1565(1999)
- 3) Ono, M, "Static and Fatigue Strength Characteristics of Laser Welded Lap Joints", Journal of Japan Welding Society, Vol. 14, No. 3, pp. 586-591 (1996).

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