



Mechanism of Gap Bridgeability in Lap-Fillet Laser-Arc Hybrid Welding

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Abstract

Laser-arc hybrid welding is known for its superior joint strength relative to arc welding and its ability to fill the gap that laser welding cannot otherwise fill. The role of laser-arc interaction in filling the lap-fillet joint is the point of investigation in this article. The effect of the laser and arcing parameters on the weld's formation is tested experimentally with the variable gap between the plates. The arc and laser parameters play a significant role in bridging the gap. For example, appropriate process parameters, such as low welding speed and moderate to high welding current, can bridge the gap up to 1 mm. Sufficient laser power is essential to improve the gap bridgeability. A low power laser preheats the base plate that helps spread the molten material at the cost of filling the gap. An increase in laser power increases the throat thickness and improves the gap bridgeability in a lap-fillet joint. In one way, the lower leg length is the manifestation of increased throat thickness due to the material passing by the gap. In one of the first of its type, the investigation explains the ability to close the gap based on process parameters. The mechanism of the gap bridgeability is deduced based on the material flow in the lap-fillet weld pool.

Keywords Laser-arc hybrid · Lap-fillet joint · Gap bridgeability · Material flow · Joint strength

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Introduction

Laser-arc hybrid welding (LAHW) is highly beneficial for the conditions where laser or arc welding presents practical limitations. The laser, because of its small spot diameter, increases the power density, but it requires accurate joint alignment. In contrast, arc welding may bridge a larger gap, but its power density is limited. The amalgamation of the two processes (Fig. 1) overcomes the mutual limitations and offers additional advantages like preheating or post-heating either of the welding sources. The benefits of hybrid welding to improve the penetration and gravity filling of larger weld deviations in butt welds are well documented.

The LAHW is studied to bridge the gap in different configurations of weld joints, namely butt, lap-fillet, and overlap (Fig. 2). The gap bridgeability in butt configuration is reported more often than in the lap configuration. The gravitational force and arc force help gap filling in the butt configuration (Fig. 2a). The molten metal flux is directed to the bottom of the weld pool, which heats the weld root [1]. In the lap-fillet configuration, filling predominantly depends on the capillary action (Fig. 2b, making it difficult to bridge the gap. The gap acts as a vent hole in the overlapping pattern (Fig. 2c) to reduce the porosity [2].

In the butt configuration, when the GMAW torch follows the arc, the molten droplets move towards the joint edges, thereby filling the gap; however, the optimal parameters that work for GMAW more often are not optimal for the LAHW [3]. A seam tracking sensor and adaptive control of welding parameters can bridge a gap greater than 1 mm [4]. However, larger gaps can result in insufficient melting in the lower part of the weld, as the laser does not succeed to reach there [5]. The capability of bridging the gap could be enhanced by irradiating the GMAW wire directly with a laser beam. With about 10% energy absorption from the laser beam, the wire could bridge the 2 mm gap in thin sheet metal butt welding [6]. Deviation tolerances in hybrid laser-arc thick plate welding could be improved by additional methods such as the electromagnetic welding pool backing system [7]. The studies on the effect of the gap in the lap-fillet configuration

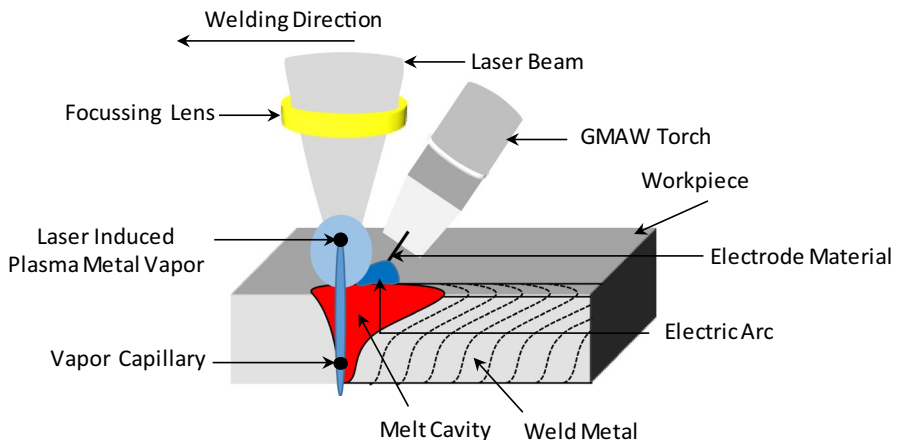


Fig. 1 Laser-arc hybrid welding

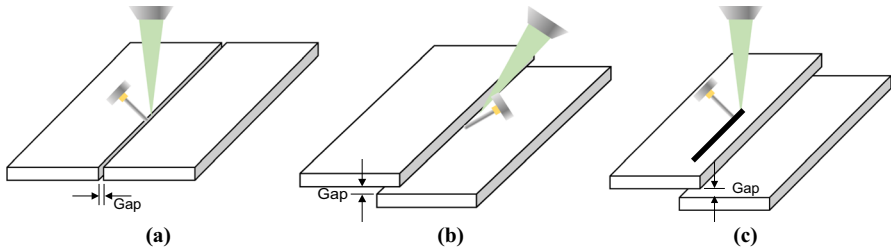


Fig. 2 Laser-arc hybrid welding with a gap in (a) butt, (b) lap-fillet, and (c) overlap configuration

are reported for hot-wire laser welding [8] and laser welding [9, 10]. The gaps considered in the laser welding studies have been very narrow, such as 0.2 mm and 35 μm , providing a vent hole for reducing porosity rather than gap bridgeability.

The ability to fill the gap in fillet condition for a typical lap-fillet weld, as shown in Fig. 2b, is still an open question, barring very few preliminary investigations [11, 12]. The gap bridgeability is influenced by the interaction between the laser beam and the arc process. The laser stabilizes the welding arc. The molten material could flow into the gap because the capillary action to fill the gap needs further investigation. The throat thickness is the main feature that governs the strength of the weld joint. However, the gap between the plates—designed or due to misalignment—alters the throat thickness and affects the strength. The process of LAHW can achieve deeper penetration [13], whereas the leg length of LAHW is smaller than the standard arc welding. The weld bead formation in the laser-arc hybrid lap-fillet joint is complex because of the bead asymmetry coupled with an increased number of controlling parameters because of the hybridization of two processes [14]. A systematic study is essential to exploit the best of the laser-arc hybrid process's capabilities, especially with the gap between the lap-fillet configuration plates. The gap bridgeability is directly connected with the performance of welded joints; for example, the fatigue damage evolution and lifetime prediction of welded joints are studied in the previous research [15]. Process parameters-weld bead geometry and strength correlations have been studied for different high power density processes such as electron beam [16] and laser beam [17] welding. Such a study for laser-arc hybrid in lap-fillet configuration with the gap between the plates is not revealed in the literature. In this investigation, experimental research is designed wherein the gap along with the arc and laser welding parameters is investigated to assert their impact on the joint strength, material flow, and the associated mechanism of the failure. The investigation aims to divulge the dynamics of the gap-filling mechanism of laser-arc hybrid arc welding, thereby establishing bridgeability as a controllable function of the process parameters.

Materials and Method

A test program is designed to perform lap-fillet joints over a wide range of process parameters, namely welding current, laser power, welding speed, and welding voltage, along with gap and no gap conditions. Steel sheet of type JSC780 (The

Table 1 Chemical Composition

Steel	C	Si	Mn	P	S	Ni	Cr	Cu	Ti	Mo	Fe
JSC780	0.12	0.25	1.01	0.013	0.003	0.03	0.68	-	-	0.24	Rest
MG-60	0.04	0.82	1.95	0.013	0.010	-	-	0.25	0.20	0.35	Rest

Japan Iron and Steel Federation Standards) and size 2.0 mm × 100 mm × 200 mm was welded with welding wire type MG-60 (Kobelco) of diameter 1.2 mm. The chemical compositions of the base plate and welding wire are given in Table 1.

The laser beam and metal active gas (MAG) arc arrangement is shown in Fig. 3. The joint type was a lap-fillet with an overlapping space of 5 mm. The torch angle θ_1 was 60, while the laser-arc distance L was 3 mm. MAG welding machine Digital inverter control type (DP500; DAIHEN) was used. The wire extension was 15 mm. The shielding gas was Ar-20% CO₂ supplied at 25 L/min. The laser fibre diameter was 0.3 mm with focusing optical $fc = 200/ff = 300$ mm. The torch angle θ_2 was 65°. The welded plates were cut for the examination of the macrostructure.

Five welding parameters, namely, welding speed, wire feed speed, welding current, voltage, and laser power, varied along with the gap between the plates (0–1.2 mm), as shown in Table 2. A total of 27 experiments was conducted. The experimental condition No. 4 was repeated three times to examine the process consistency. The weld bead was cross-sectioned and geometric attributes, namely, Reinforcement height (h), penetration at the top plate ($d1$), penetration at the bottom plate ($d2$), leg-length at the top plate ($L2$), leg-length at the bottom plate ($L1$), and throat thickness (t), as shown in Fig. 4a, were obtained. The macrographs were analyzed for the material flow, as shown in Fig. 4b. The tensile shear test was performed following JIS 2241 standard. Figure 5a shows the sampled position of the tensile shear specimen. The fracture location was noted and analyzed for the mode of failure. Figure 5b shows the typical failures in the weld metal (a few) and HAZ. Some of the samples also failed in the base metal. The joint strength, i.e., nominal stress, was calculated using the base plate cross-section area.

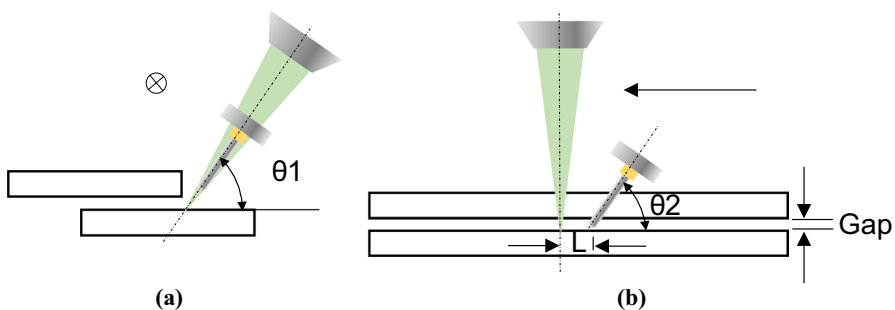
**Fig. 3** Laser-arc hybrid welding in lap fillet configuration (a) side view (b) front view

Table 2 Results of laser-arc hybrid welding

No	Experimental conditions					Results							
	MAG		Laser			Weld geometry features (all dimensions in mm)							
	Welding speed (m/min)	Wire feed speed (m/min)	Current (A)	Voltage (V)	Power (KW)	Gap (mm)	H*	d1	d2	L1	L2	t	Joint strength (Mpa)
1	1	6.7	200	21.2	1.5	0	1.3	2.9	2.3	6.9	2.2	2.6	828
2	1	6.7	200	21.2	1.5	0.7	1	2.7	1.8	7.1	2.4	2.8	832
3	1	6.7	200	21.2	1.5	1.2	-0.4	4.4	2.8	5.8	3.2	0.3	835
4(1)	1.5	6.7	200	21.2	1.5	0	0.9	2.2	1.1	5.7	1.9	2.2	829
4(2)	1.5	6.7	200	21.2	1.5	0	1.1	2.2	1	5.4	2	2.2	825
4(3)	1.5	6.7	200	21.2	1.5	0	1	2.1	1.3	5.8	2	2.3	829
5	1.5	6.7	200	21.2	1.5	0.7	0.7	2.1	1.1	5.6	2.6	2.1	847
6	1.5	6.7	200	21.2	1.5	1.2	-0.5	2.1	2.1	3.8	2.8	1.2	382
7	2	6.7	200	21.2	1.5	0	0.8	1.6	0.9	4.6	1.9	2	826
8	2	6.7	200	21.2	1.5	0.7	0.3	1	1.2	3.7	2.6	1.3	650
9	2	6.7	200	21.2	1.5	1.2	-0.3	2.4	1.4	3.8	2.9	1.2	473
10	2	5	150	19.7	1.5	0	0.9	1.4	0.9	4.1	1.5	1.7	800
11	2	5	150	19.7	1.5	0.7	0.5	1.1	0.9	4	2.5	1.1	649
12	2	5	150	19.7	1.5	1.2	0.8	1.5	1.2	4.6	2.1	0.8	534
13	2	8.6	250	23.2	1.5	0	0.9	2	1.7	3.7	2	2.2	848
14	2	8.6	250	23.2	1.5	0.7	0.2	2.3	1.6	4.4	2.6	1.7	780
15	2	8.6	250	23.2	1.5	1.2	0.9	2.4	1.6	3.6	2.7	1.4	576
16	1.5	6.7	200	19.1	1.5	0	0.8	1.8	1.2	5	1.9	2	840
17	1.5	6.7	200	19.1	1.5	0.7	0.3	1.8	1.5	4.2	2.6	1.8	828
18	1.5	6.7	200	19.1	1.5	1.2	0.4	1.9	1.2	3.1	2	1.3	622
19	1.5	6.7	200	23.1	1.5	0	0.9	2.3	1.2	6.2	1.9	2.3	838

Table 2 (continued)

No	Experimental conditions				Results									
	MAG	Welding speed (m/min)	Wire feed speed (m/min)	Current (A)	Voltage (V)	Power (KW)	Gap (mm)	Weld geometry features (all dimensions in mm)				Joint strength (Mpa)		
								H*	d1	d2	L1	L2	t	
20	1.5	6.7	200	200	23.1	1.5	0.7	0.4	2	1.2	5.7	2.8	2.1	838
21	1.5	6.7	200	200	23.1	1.5	1.2	-0.4	3	1.6	4.6	2.8	1	847
22	1.5	6.7	200	200	21.2	1	0	1.1	2.2	1.2	5.6	2.1	2.3	830
23	1.5	6.7	200	200	21.2	1	0.7	0.5	1.9	1.1	5.5	2.6	2.2	848
24	1.5	6.7	200	200	21.2	1	1.2	-0.6	1.9	1.3	2.9	2.6	1.2	610
25	1.5	6.7	200	200	21.2	2	0	1	2.2	1.3	5.7	2	2.2	838
26	1.5	6.7	200	200	21.2	2	0.7	0.5	1.9	1.4	5.5	2.5	2.1	845
27	1.5	6.7	200	200	21.2	2	1.2	0.4	2.5	2.5	2.9	2.5	2.2	313

* In the case of a concave fillet bead, the value is negative

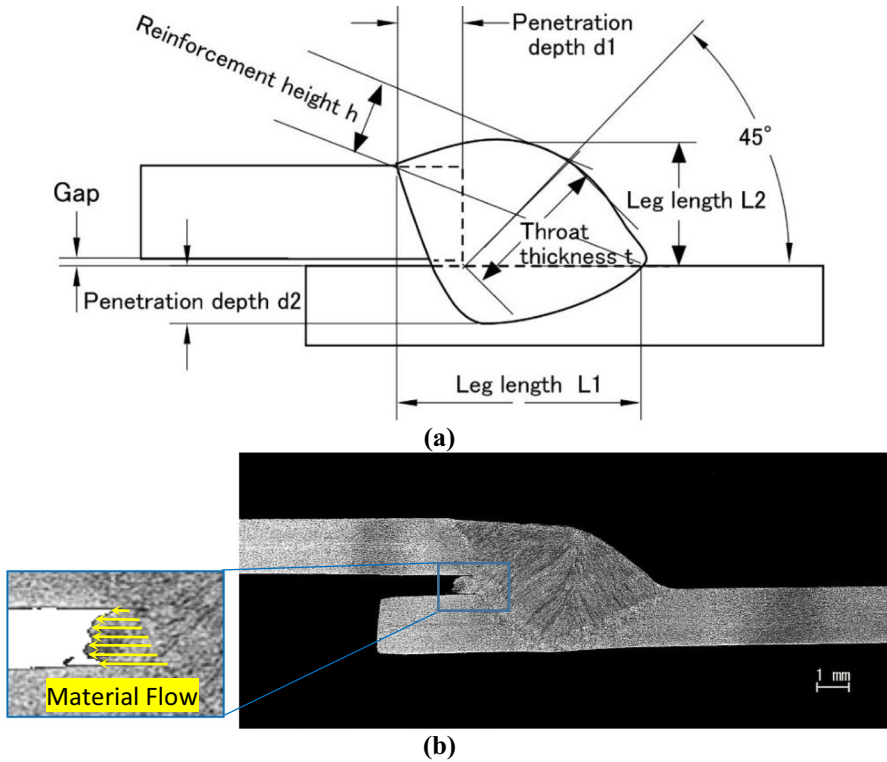


Fig. 4 **a** Laser-arc hybrid weld bead geometry and **b** material flow in the gap

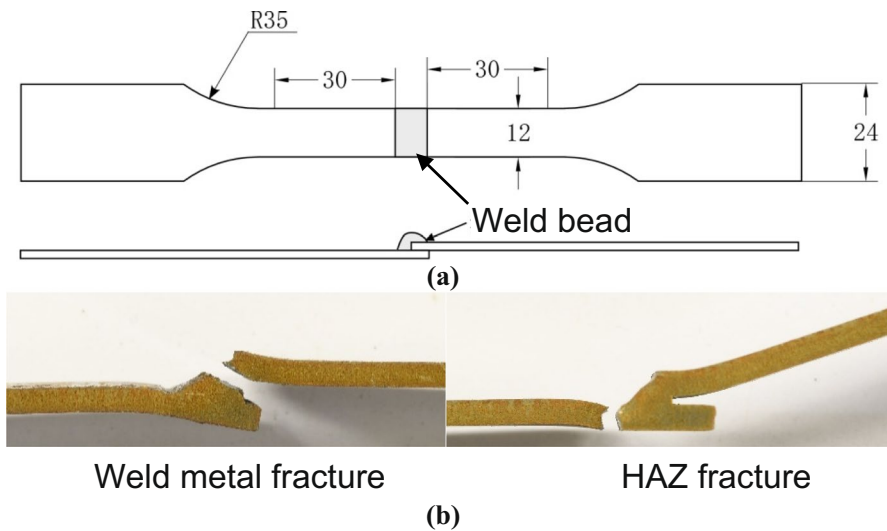


Fig. 5 **a** Lap shear test specimen **b** fractured specimens

Results and Discussion

Weld Bead Geometry in Laser-Arc Hybrid

The laser-arc hybrid welding process is relatively consistent in terms of process parameter effect on the weld bead's shape and size. As the welding was conducted on a fully automated system, the shapes of the beads were expected to be repeatable. To ensure the same, one sample was checked for repeatability. Figure 6 shows the cross-sections of three welds obtained with the same welding process parameters and zero gap. The process (vis-a-vis weld geometry) is remarkably stable. Therefore, variation in weld bead geometry is a reliable indicator of changing process conditions.

The introduction of a gap in between the plates alters the weld bead geometry of the lap-fillet joint. As illustrated in Fig. 7, typical weld bead shapes are the results of the interactive effect of the welding parameters and gap. With the appropriate selection of the process conditions, the molten material could fill the gap and serve the purpose of reinforcement (Fig. 7a). At low speed and a wide gap, the material could flow through the gap and make a large bump at the root of the weld, as shown in Fig. 7b. This is the over-reinforcement condition wherein the bead is aesthetically poor from the top and bottom, but the effective throat thickness (T) increases, increasing the joint strength. With a wide gap and moderate to higher welding speed, the top surface depresses (concave), and the throat narrows. Such a bead is under-reinforced (Fig. 7c) that leads to a weak joint. Despite sufficient reinforcement, higher speed or higher welding current creates an undercut (Fig. 7d), leading to failure at the base plate. On the other side, a low value of current and high speed may lead to underfilling (Fig. 7e), i.e., thinning the joint at the top plate. Such joint may subject to a little reduction in strength.

Weld Geometry and Process Parameters Correlation

The prominent weld bead features, bottom leg-length (L_1) and throat thickness (t), are analyzed in terms of the effect of welding process parameters, as shown in Fig. 8. The weld gap of 0 and 0.7 mm produce almost identical bottom leg length and throat thickness. The gap of 1.2 mm reduces the leg length and the throat thickness, significantly impacting joint strength. The slow welding speed (1 m/min) and a wider gap reduce the throat thickness but produce a larger leg length. The material is pushed into the gap and accumulates in the back of the weld in the lower

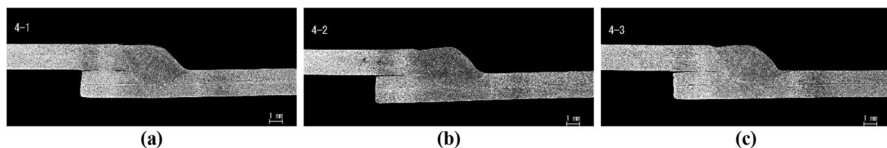


Fig. 6 Repeatability of bead geometry in laser-arc hybrid weld **a** sample 4–1, **b** sample 4–2, and **c** sample 4–3

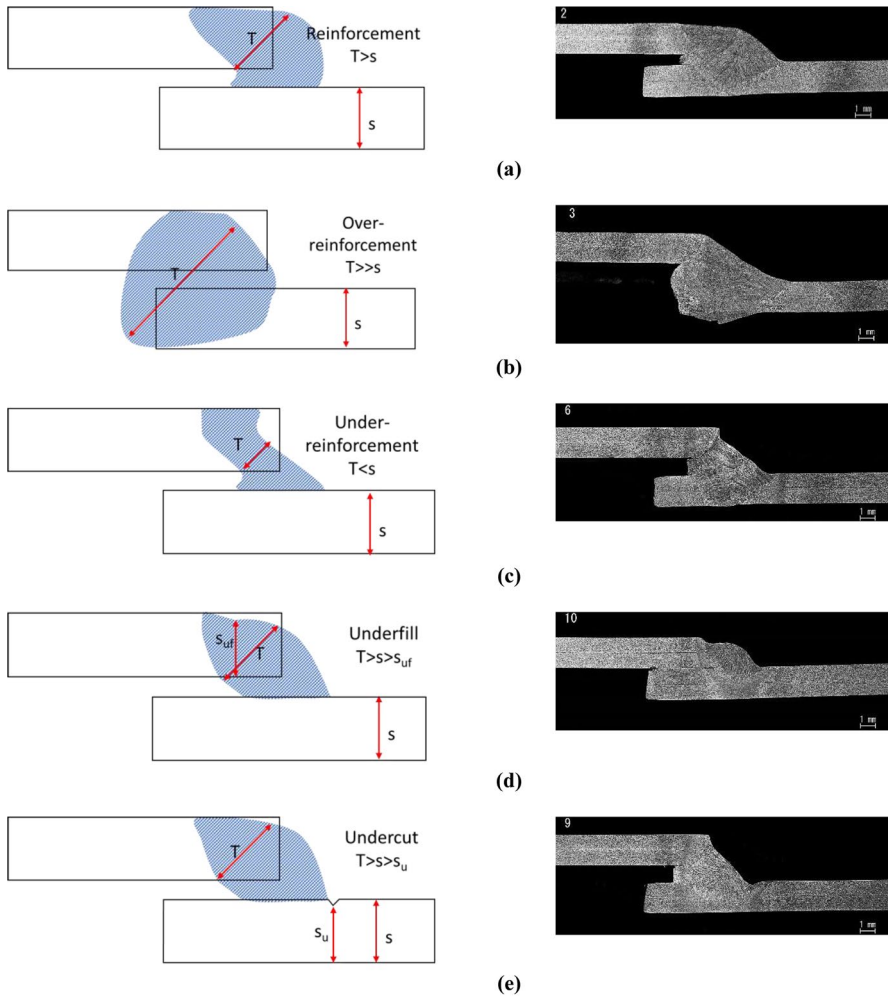


Fig. 7 Typical weld bead geometries in laser-arc hybrid lap fillet joint with the gap **a** reinforcement, **b** over-reinforcement, **c** under-reinforcement, **d** underfill, and **e** undercut; s -plate thickness, T -effective throat thickness, s_{uf} – thickness of the underfilled section, s_u – thickness of undercut section

fillet area (Fig. 7b); thus, the effective throat thickness (T) increases and up to an extent prevents the loss of strength. Among the welding parameters, the welding speed (Fig. 8a and b) and arc current (Fig. 8c and d) significantly impact the bottom leg length and the throat thickness.

An increase in welding speed causes a reduction in throat thickness and leg length (Fig. 8a and b, respectively) because of the decrease in welding heat per unit weld length. The increase in current increase the throat thickness due to an increase in the deposition rate (Fig. 8c), but a slight reduction in the leg length is observed with the current increase (Fig. 8d). The arc concentrates at a higher current and attains deeper penetration vis-a-vis increased throat thickness at the leg length loss (L_1).

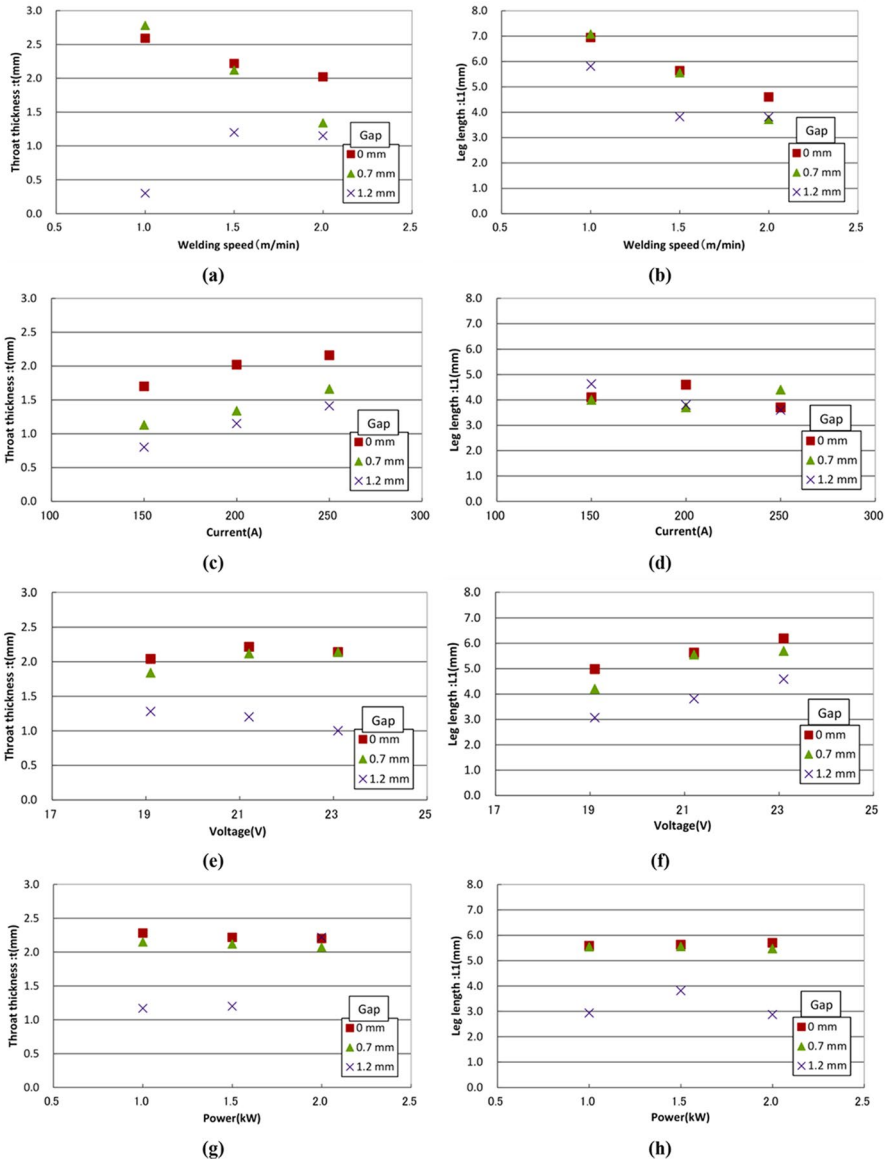


Fig. 8 Effect of welding speed (a, b), welding current (c, d), voltage (e, f), and laser power (g, h) on throat thickness and leg length at the bottom plate, respectively

A slight increase in the leg length is observed with the voltage increase (Fig. 8f) because of the arc spreading at a higher voltage.

The laser plays a role in altering the bead geometry. At low to moderate power (1 to 1.5 kW), the laser primarily preheats the base plate that helps spread molten metal, i.e., increase in leg length without increasing the throat thickness (Fig. 8g).

Further increase in laser power increases the penetration, i.e., throat thickness (Fig. 8h).

Gap-Process-Geometry-Strength Correlation

The weld bead geometry is the determining factor for joint strength. The weld bead is expressed in terms of geometrical attributes like penetration, weld width, and reinforcement height [18] or the total shape is predicted through mathematical [19] or analytical [20] models. The lap-fillet joint is complicated in shape and thus requires several attributes to define the geometry. The relation in between these attributes, namely, reinforcement height (h), penetration at the top plate (d_1), penetration at the bottom plate (d_2), leg-length at the top plate (L_2), leg-length at the bottom plate (L_1), and throat thickness (t) and the joint strength, especially for the weld that is produced with a gap is not available in the existing literature. Analysis of the results, as shown in Fig. 9, provides a record of the relative significance of the weld attributes on their impacts on the weld strength. Among the weld attributes, as investigated, the leg length at the bottom plate (Fig. 9d) and throat thickness (Fig. 9f) are the two that have a direct impact on joint strength. The remaining attributes and strength have a kind of inconsistent relation (Fig. 9a, b, c, and e). The collective effect of the leg-length at the bottom plate and throat thickness reflects in

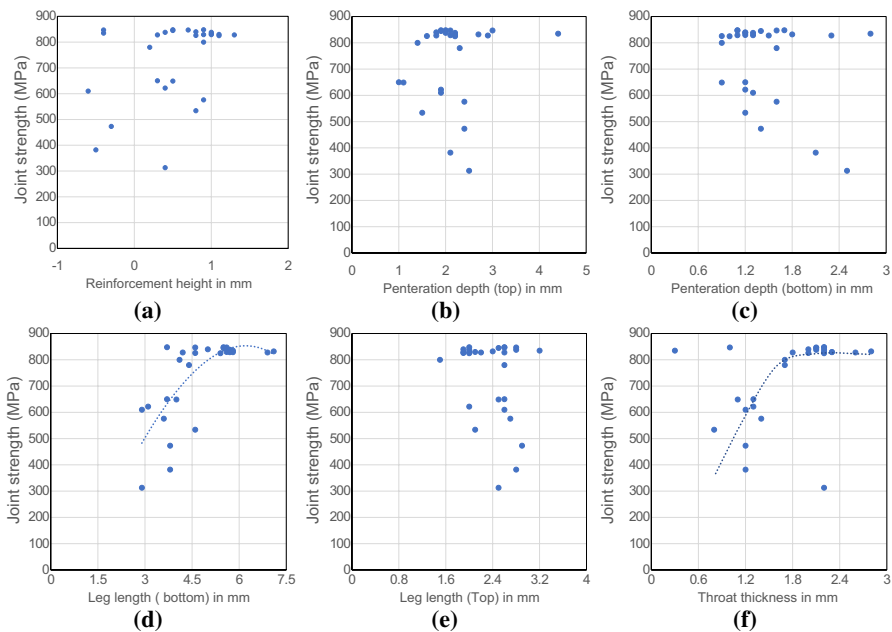


Fig. 9 Joint-strength geometry correlation – **a** reinforcement height, **b** penetration depth (top), **c** penetration depth (bottom), **d** leg length (bottom), **e** leg length (top), **f** throat thickness

the effective throat thickness (T), which is different from the throat thickness (t) that is used to design the fillet weld in normal condition (i.e., without and with a gap).

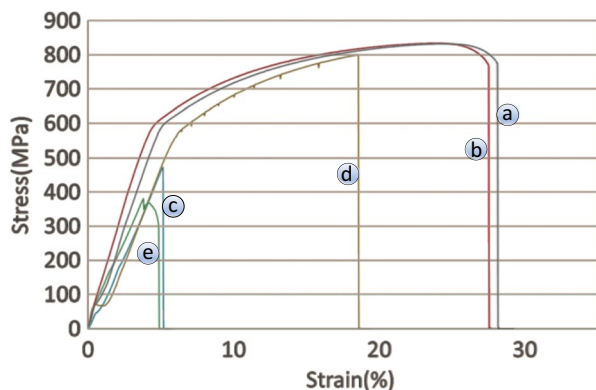
The weld bead shape and joint strength are directly related, as shown in the stress–strain diagrams for typical bead shapes in Fig. 10. The reinforced and over-reinforced beads show (a and b, respectively) maximum strength. The weld with an underfilling (d) typically breaks from the weld metal and offers a dip in strength. The weld with under-reinforcement and undercut, c and e, respectively, exhibit minimum strength.

The collective effect of the welding process parameters results in either straightening or weakening of the joint. The material may flow through the wider gap, or the welding parameters may cause undercut and underfill that weakens the joint. Favourable parameters (e.g., moderate welding speed, higher current, and higher laser power) reinforce the joint. Exceptionally low speed over-reinforces the weld that leads to the poor appearance of the weld.

Gap Bridgeability

The weld samples were subject to uni-axial strength to study the gap bridgeability. Figure 11 explains process parameters' effect on gap bridgeability through the joint strength contour plots as a function of gap and welding parameters. The samples with good bridgeability fractured from the base plate and attained 820 MPa or above. Figure 11a shows that lower welding speed can fill even the wider gap and attain maximum strength. With the increase in the welding speed, the strength decreases significantly. The higher speed in the range of 2 m/min attains maximum strength with zero gap condition that indicates poor bridgeability at higher speeds. A moderate to higher current is required to fill the gap and attain strength (Fig. 11b). A moderate bridgeability (<0.75 mm) can be achieved even at a high current. The advantage of increasing the amount of molten metal with the current increase is lost when the material is pushed in the larger gaps (>0.75 mm). The voltage helps fill the gap as the arc spreads more at a higher voltage (Fig. 11c). The laser power has a limited impact on gap bridgeability, but the increase in power helps increase the throat thickness and smoothens the weld surface, resulting in increased strength.

Fig. 10 Stress–strain diagrams for different weld bead shapes **a** reinforcement, **b** over-reinforcement, **c** under-reinforcement, **d** underfill, and **e** undercut



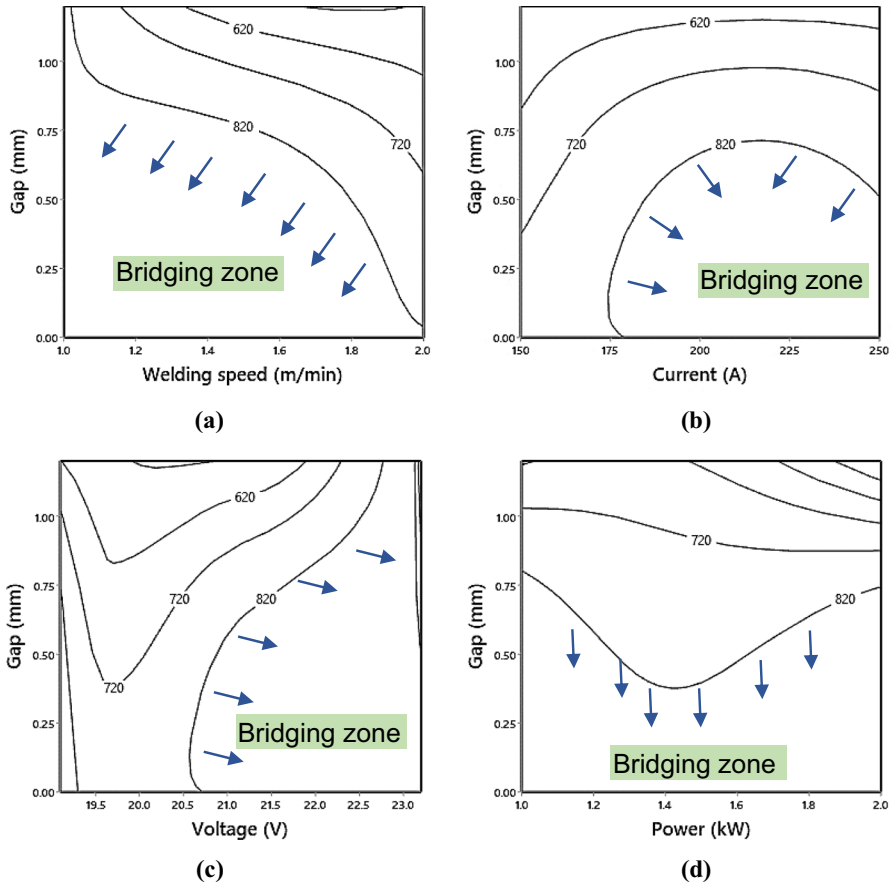


Fig. 11 Influence of **a** welding speed, **b** current, **c**, voltage and **d** laser power on gap bridgeability

This advantage is limited to a moderate gap (<0.75 mm). The spreading of the weld bead (increases in leg length) occurs without any significant throat thickness change when the laser operates in a low to moderate power range. The laser starts to play an active role at higher power and increases the throat thickness because of increased penetration. Consequently, the gap bridgeability improves at higher power (2 kW), as shown in Fig. 11d.

Mechanism of Gap Bridgeability

The gap between the plate influences the material flow in the weld pool. The molten metal flow is analyzed at three planes (Fig. 12a), which are coplanar to the arc, the plane in front of the arc where the arc will reach after s seconds and the plane in the rear of the arc where the arc passed τ seconds before. The flow pattern in laser-arc hybrid welding without the gap is simulated by Gao et al. [21]. A typical

flow pattern is shown in Fig. 12b. The plane before the arc, without gap condition, receives molten material flow from the arc, which spreads on the top of the top plate because of the surface tension and towards the bottom plate due to gravity. After τ seconds of the arc passing through the plane, the molten metal droplet impinges at the root, as shown by blue arrows in Fig. 12b and c. As a result, the flow of molten metal towards the top and the bottom plate further strengthens. The droplet impingement effect reduces in the plane, which was passed by the arc before s seconds. Here a vortex flow is observed. The fluid at the top surface flows down due to gravity and Marangoni shear stress. This molten metal hits the bottom of the weld and bounce toward the weld root making a vortex.

When a gap is introduced, the top plate's top surface moves far from the arc core. The molten metal in the plane in front of the arc flows towards the top and bottom surface, but the increased distance makes it difficult for the molten metal to reach the

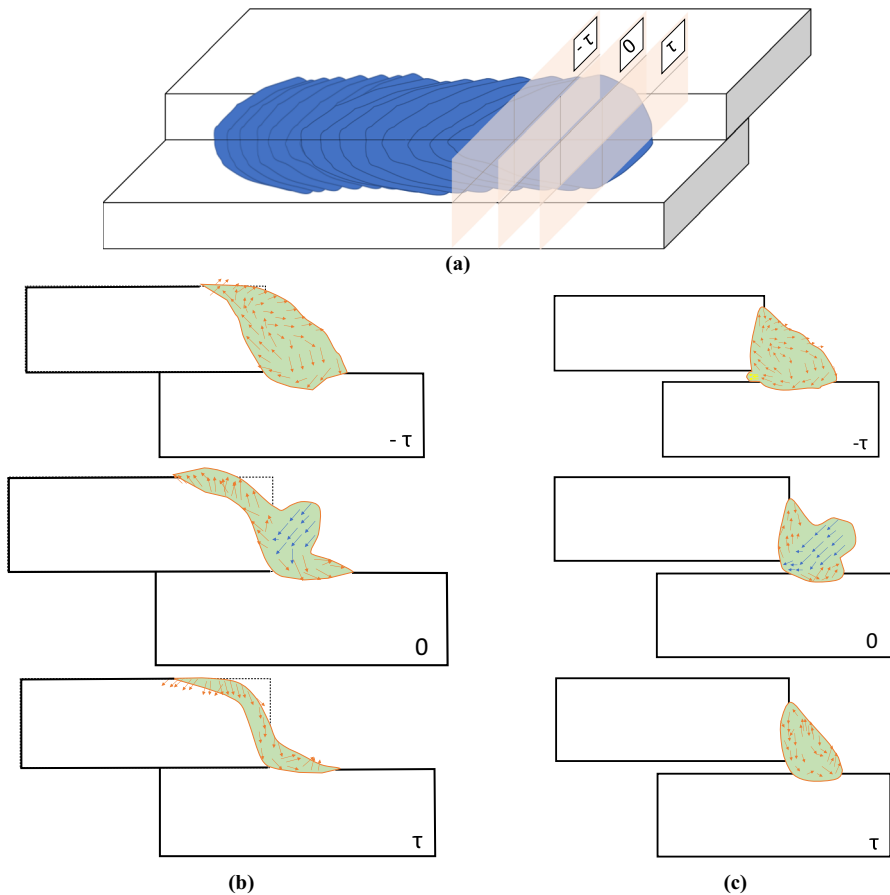


Fig. 12 a Reference planes for analysis of molten metal flow in (b) without gap and (c) with the gap conditions

top surface (Fig. 12c). When the arc impinges, the molten material spreads towards the top and bottom plate and the gap. After passing the arc, the retarding metal moving towards the root and enters the weld gap. When the gap is narrow, the capillary action helps the molten metal flow in the gap and plugging it. Still, a wider gap does not support capillary action. The separation between the molten metal and plate surface occurs, particularly when the welding current is low or the welding speed is high. The effect of the gap on material flow is visible in Fig. 13. With identical welding conditions, but the different gap, the weld with a narrow gap experience the flow of material (Fig. 13a) while wider gap (Fig. 13b) results in the separation of molten material from the plate surfaces. Besides, a separation between the molten metal and base plate is also observed. As a result, the weld with a wider gap (Fig. 13b) broke at 576 MPa compared to the weld at a narrow gap (Fig. 13a) fractured at 748 MPa.

The investigation brings out new findings on the capabilities of laser-arc hybrid welding. The industries involved in thin sheet welding will be benefitted from the outcomes of the investigations. As a next step, the process parameters may be optimized to accommodate uncertainty in plate fit-up and reduce the rejection rates on the incoming base material and outgoing welds. Moreover, the effect of the gap on weld corrosion and the need for plugging the rear side gap also merits investigation.

Conclusions

1. In contrast to the conventional understanding, the ability to fill the gap (bridgeability) in the lap-fillet laser-arc hybrid joint is a dynamic attribute that can be optimized by selecting the process parameters.

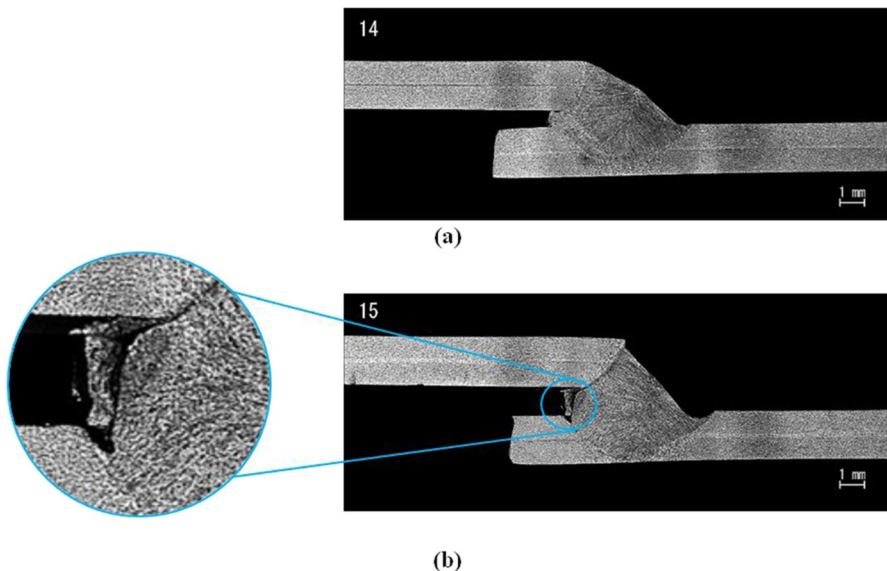


Fig. 13 Effect of the gap on material flow

2. High welding current and low welding speed are the prominent factors that affect the weld bead geometry, though with a possibility of obtaining aesthetically poor but sufficiently strong weld at low speed. Low welding speed and high voltage help fill the gap up to 1 mm for the chosen material and wire combination.
3. The throat thickness and the leg length at the bottom plate directly impact the weld strength as they define the effective throat thickness. The gap with appropriate welding parameters allows for flowing the material in the gap, thereby increasing the effective throat thickness. The laser in front of the arc preheats the baseplate and spreads the molten material, increasing the fillet leg length, which causes a slight dip in bridgeability. An increase in laser power more than a particular value increases the throat thickness that improves the bridgeability.
4. The gap-filling is a delayed phenomenon that starts during the arcing but continues after passing the arc. The molten material creates a vortex and flows back from the surface to the weld root after striking back to the weld bottom. With a moderate gap, the material remains in contact with the plates due to capillary action, but separates when the gap is quite wide.

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Data Availability All data generated or analysed during this study are included in this published article.

Declarations

Conflict of Interests The authors declare that there is no conflict of interest.

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