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High speed videography of gap bridging with beam oscillation and wire feeding during the laser welding of stainless steel and aluminum alloys

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Abstract

Laser beam welding is known for its quality and speed. Given its susceptibility to gaps, the technology is applied in the industrial field with hard automation and dedicated fixtures rather than small-batch production. The latter cannot always guarantee the strict conditions on the fit-up of joints, especially with complex geometries. Gap-bridging techniques may be exploited to overcome these inaccuracies. The present work investigates the simultaneous use of low frequency circular beam oscillation and wire feeding as means to produce a continuous weld seam in presence of a constant gap. Lap joint welding of 2 mm-thick AISI301LN and butt joint welding of 3 mm-thick AW6005A-T6 alloy were investigated with gaps up to 1 mm. Optical inspection and metallographic analyses were used to verify the gap-bridging capability as well as the resulting seam quality. High-speed imaging at 10kHz provided an insight in the dynamics of gap-bridging mechanisms.

Keywords: laser welding; high-speed imaging; beam oscillation; wire-feeding; gap-bridging

1. Introduction

Laser beam welding with high brilliance fiber lasers is an industrially established joining technology that allows to reach high penetration with limited thermal input (Garavaglia et al, 2020). Such advantages have been widely exploited in highly demanding sectors such as aerospace, oil & gas and automotive. The decreasing cost of laser sources will make laser systems more available in the future for less demanding applications, as well as for the realisation of products with higher variability and smaller batch size. However, not all these applications inherently respect the geometrical tolerances required by the laser welding process.

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In particular, laser welding is very sensitive to the presence of gap so that the accuracy required in the relative positioning of the workpieces is in the order of the laser waist diameter (de Graaf et al., 2010). Positioning errors might be caused by inaccuracies of previous manufacturing steps as well as be generated during welding process by thermal distortions. A typical solution is the use of dedicated fixtures and jigs: the high rigidity and the specific design of these systems provide the required accuracy and avoids the formation of gaps. Nevertheless, this approach is costly and only possible in cases where dedicated solutions are economically sustainable, such as for large-batch production.

Wire feeding as well as wobbling can be valid solutions to reduce the sensitivity of the process to the gap formation. In literature, oscillation welding of stainless steel and aluminum alloys with the aid of filler-wire has been discussed in several works. Sun and Kuo, 1999 showed that a 1 mm gap could be bridged in butt welding of 2 mm thick AISI304 stainless steel sheets with the use of filler-wire but highlighted the criticality in laser-wire relative positioning. Goebel et al., 2007 relaxed the constraint by oscillating the laser beam on a transversal line perpendicular to weld direction. This way wire was deployed more easily to create a bridge of molten material in a 2 mm-wide groove. Thiel et al., 2012 discovered that beam oscillation is more efficient as a joining technique than laser defocusing, both in terms of weld bead area and penetration. Similar results were obtained by Li et al., 2021 who also reduced pore formation and obtained a grain refinement thanks to the stirring action of circularly oscillating beams. Aalderink et al., 2010 compared different joining techniques for the butt welding of AA5182 and determined single-spot laser welding with filler-wire to be the most promising solution for gap-bridging. Schultz et al., 2014 bridged a 3.14 mm gap in a butt joint on a 1 mm thick aluminum alloy sheet with use of wire and linear oscillation. Martukanitz et al., 2005 indicated that circular wobbling can increase weld depth and reduce porosity during the welding of aluminum alloys. Wang et al., 2016 found out that wobbling triggers a mixing motion responsible for grain refinement. Besides, the soundest welds could be obtained with a circular trajectory for the spot.

While these works show fundamental benefits of the oscillating beam on gap bridging, the process dynamics require further attention for a better comprehension. From this perspective, the use of experimental methods combined with simple analytical tools and high-speed imaging can be a viable approach. Accordingly, this work explores the weldability of a 2 mm-thick AISI301LN sheet in lap and 3 mm-thick AW6005A-T6 sheet in butt joint configuration, that cover two of the welding configurations most widely requested by industry. Laser weldability is benchmarked using both oscillating and fixed beams as well as a filler wire. High-speed imaging is employed to show the weld pool formation and provide an insight in its dynamics and the increased melting efficiency observed with wobbling.

2. Materials and methods

2.1. Experimental setup

The welding tests were performed with the prototypal robotic welding cell by BLM Group - Adige. It features an IPG YLS 6000 C(T) fiber laser source with maximum power 6kW, equipped with a 100 µm delivery fiber. The laser is coupled to a wobbler head (IPG Photonics D50) with 300 mm focal and 200 mm collimation lens for a resulting theoretical Rayleigh length of 1.5 mm and a focused spot diameter of 150 µm. The wobbler head is equipped with two galvanometric mirrors able to oscillate the beam with a maximum amplitude of 3 mm. An ABB IRB4600 anthropomorphic robot is present for laser head displacement and a 2-degrees of freedom positioner ABB-IRBPA250 provides workpiece manipulation. The wire-feeding is handled by an Abicor-Binzel MFS v3 system which features two motors in a push-push configuration and has a maximum wire speed of 20 m/min. The wire was fed in the weld pool from a leading position, inclined at 30° above workpiece surface. The gas nozzle for argon shielding was mounted in trailing configuration. The setup is shown in Figure 1.

The welded materials were 2 mm-thick stainless steel (AISI301LN) and 3 mm-thick aluminum alloy (AW6005A-T6) sheets. The oxide layer of aluminum sheet was removed with a brush right before welding. The wire used in the welding was LNM 304LSi (Lincoln Electric) and AW5356 (MTL), respectively, both 1.2 mm in diameter.

The high-speed camera utilized for this research is a Photron FASTCAM Mini AX200. The framerate was fixed at 10kHz, with an exposure time of 0.5 µs, whilst the spatial resolution was approximately 16 µm/px. A region of interest of 896x512px was adopted for a total field of view of 14.33 mm x 8.19 mm. The camera triggered a high intensity, low coherence laser illuminator by Cavitar, model Cavilux HF. The illuminator has an emission power of 280W at a wavelength of 640+/-10 nm. The high-speed camera was equipped with a corresponding passband filter. Videos were recorded in two different off-axis positions of the camera. In the first one, the camera was at an angle of approximately 30° with respect to the weld surface and 45° with respect to weld direction (Figure 1a-b). In the second one, the camera was perpendicular to weld direction and parallel to surface (Figure 1c). The second configuration provided a side view of the pool inside the gap and was utilized only during lap joint welding with 1 mm gap. In all cases, the camera pointed at the joint at 50 mm distance from weld start to capture images of the steady-state weld pool.

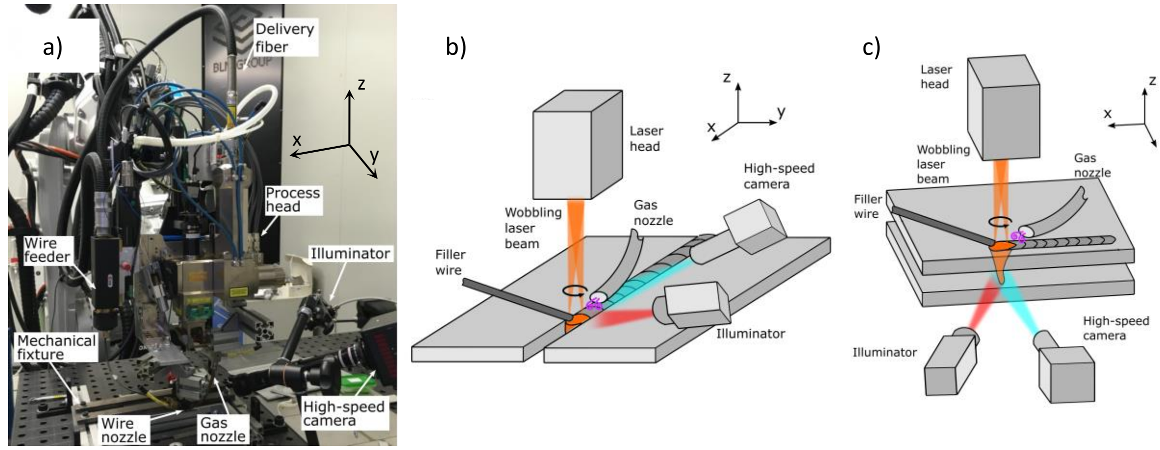


Fig. 1. Laser welding and high-speed imaging experimental setup: a) physical set-up and schematization of high-speed camera view b) from above and c) from side.

2.2. Experimental design

The study aimed at investigating the gap-bridging capability of simultaneous wire feeding and beam oscillation for the laser welding of stainless-steel lap joints and aluminum alloy butt joints. To evaluate the single contribution of each technique as well as their combined effect, each of the two material-joint combinations was welded both in conditions of ideal fit-up (0 mm gap) and in the presence of a constant 1 mm gap, with and without use of wire and wobbling, for a total of 16 conditions. Prior tests explored these conditions and were able to produce welds with a consistent level of quality for almost all cases. The parameter searches are not reported in detail here and only the best welds are proposed as they are considered representative and used hereafter for benchmarking purposes. The process parameters investigated in these tests were laser power, weld speed and focal position for autogenous, fixed-spot welding. The wire speed is an additional parameter when filler wire is used. Circular wobbling adds two more parameters, namely wobbling frequency and amplitude. A circular wobbling pattern was chosen as expected to be more effective in stirring the weld pool, this way increasing its degassing capability and homogeneity (Wang et al., 2016).

Shielding gas pressure was instead fixed at 3 bar and flow rate at 20 l/min. The fit-up condition was granted by a mechanical fixturing system, consisting of two steel brackets bolted at their ends to a rigid welding table and running parallel to weld trajectory. The two metal sheets were either overlapped (for lap welding) or juxtaposed (butt welding) and placed underneath the brackets where, by tightening of four bolts, they were pressed in position to get a solid and motionless fixturing. To reproduce the presence of gap, separators with calibrated thickness were introduced in between the two sheets and outside of laser trajectory before tightening of fixture. All weld tracks were linear and 150 mm long.

Table 1. Fixed and variable parameters of the experimental campaign

Fixed parameters	
Shield gas	Argon
Shield gas flow rate	20 l/min
Shield gas pressure	3 bar
Variable parameters	
Material, joint type and thickness	AISI301LN, lap joint, 2 mm – AW6005A-T6 butt joint 3mm
Joint gap	0mm – 1mm
Spot position	Fixed – circular oscillation
Filler	None – wire
Laser power	Determined for each configuration
Weld speed	Determined for each configuration
Wire feed rate	Determined for each configuration
Defocus	Determined for each configuration
Wobbling frequency & amplitude	Determined for each configuration

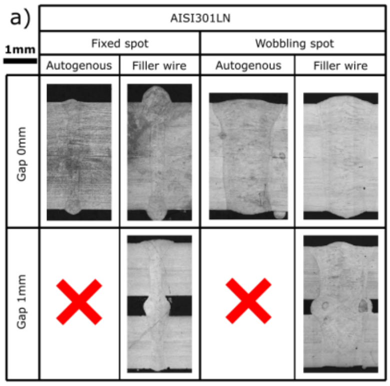
2.3. Material characterization

To characterize each welding condition, cross-sections of the beads were observed. These were obtained by cutting specimens perpendicularly to weld direction at a minimum distance of 50 mm from start point. Cross-sections were subsequently hot-mounted, polished and chemically etched to reveal grain boundaries. A 1:1:1 solution of distilled water, HCl and HNO_3 was used to etch stainless steel whilst Keller's reagent was employed for the Al alloy. The etched samples were subsequently imaged with a Mitutoyo QV202-PRO5F and cross-sections were analyzed with ImageJ software to extract the weld bead area (A_{bead}).

3. Results

3.1. Assessment of the process feasibility via metallographic analysis

The weld sections and the parameters for AISI301LN lap joints are shown in Figure 2. It can be observed that, for the 0 mm gap case, the fixed laser beam produces the elongated bead typical of keyhole regime. The addition of a moderate quantity of wire (1.2 m/min, 40 % of weld speed) causes a growth in head and root but does not modify the bulk of the weld. In the absence of gap, the autogenous welding is adequate. The introduction of a 1 mm gap, on the other hand, causes autogenous welding to fail and a 2 m/min wire feed rate (66 % of weld speed) is needed for bridging the gap. The high aspect ratio of the bead is retained indicating that keyhole is still present. The central gap acts as an outlet for molten material that flows laterally and away from laser in that point. The use of wobbling enlarges the bead and this is expected to have a positive influence on resistance to traction of welded joints. In turn, the increase in molten material, performed at same laser power, requires weld speed to be halved (1.5 m/min). The vertical sides of the bead are maintained with wobbling, indicating that keyhole is still present. It can be noted that the autogenous welding of 1 mm gap with wobbling is unsuccessful and a consistent wire quantity is instead needed to bridge it (1.5 m/min, 100 % of weld speed). In conclusion, in the case of lap welding of AISI301LN, wobbling has a desirable widening effect on the bead but requires higher powers or lower speeds and cannot cope with significant gaps in autogenous welding. Wire-feeding instead finds its use in the presence of gaps but is not meaningful for ideal fit-up in welding of steel lap joints. The combination of the two techniques produces the best results in terms of resistant section and gap-bridging.

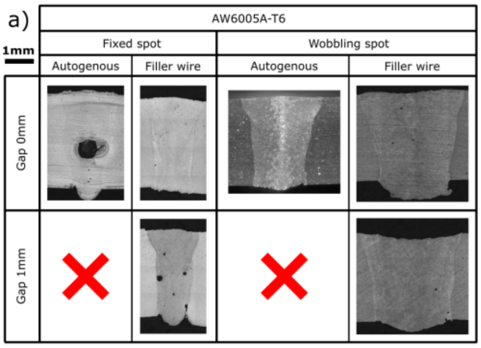


b)

Gap [mm]	Spot	Filler	Weld speed [m/min]	Laser power [kW]	Defocus [mm]	Wire speed [m/min]	Wobbling amplitude [mm]	Wobbling frequency [Hz]
0	Fixed	None	3	4	-2	0	0	0
0	Fixed	Wire	3	4.25	-2	1.2	0	0
0	Wobbling	None	1.5	4	-4	0	1.5	35
0	Wobbling	Wire	1.5	4.5	-4	0.3	1.5	35
1	Fixed	None	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1	Fixed	Wire	3	4.75	-2	2	0	0
1	Wobbling	None	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1	Wobbling	Wire	1.5	4.5	-3	1.5	1.5	35

Fig. 2. AISI301LN welds: a) sections of samples; b) process parameters Red crosses and ‘n.a.’ refer to failed combinations

The weld sections and process parameters for AW6005A-T6 butt joints are instead shown in Figure 3. The 0 mm gap autogenous fixed-spot weld shows a significant gas porosity. The issue of gas inclusion was present throughout the experiments with fixed spot. The weld root is elongated as an effect of the high fluidity of aluminum that tends to drip out of the joint more than steel. The bead is also wider because of the higher thermal conductivity of aluminum that tends to better distribute the heat (Table 2). The addition of wire reduced the pore formation in the fixed-spot 0 mm gap welds. On the other hand, a 1 mm gap causes autogenous laser welding with fixed spot to fail: the gap is 6 times larger than the focused spot diameter. The use of filler-wire in this case recreates a sort of laser brazing condition, where wire is hit and molten by the laser and the base material remains outside of the beam, heated by conduction mainly. The resulting weld quality is not sufficient: undercuts are formed, penetration is incomplete, and pores are also an issue. The introduction of wobbling increases widths and gap-bridging capability is boosted. This happens at the expenses of higher laser powers. The 0 mm gap autogenous case shows no pore thanks to the stirring and degassing action of circular wobbling. Moreover, the edges are almost vertical, and the weld quality is overall high. The best results for 0 mm gap with wire feeding and wobbling are instead produced with a quite high wire rate of 2.2 m/min (110 % of weld speed) and a 2mm wobble amplitude. This relatively high need for wire probably comes from the high fluidity of the molten pool that tends to collapse under the effect of its own weight, as testified by the excessive reinforcement at weld root. From this perspective, the net effect of wire-feeding seems less positive. In all cases, the molten pool is better sustained with a higher defocus that corresponds to a smaller laser spot on the bottom surface of workpiece, therefore a narrower drain for molten material. The introduction of a 1 mm gap makes autogenous welding fail even if the laser beam is wobbled with an amplitude wider than gap (1.8 mm vs 1 mm). Too much material is lacking, and gap cannot be bridged. In fact, a very high wire feed rate is required for bridging with wobbling, i.e. 5.3 m/min (265 % of weld speed). The resulting bead appears sagged but to an acceptable degree. It can be concluded that the welding of AW6005A-T6 benefits from the degassing effect of circular wobbling. Wobbling is also an effective means for quality gap-bridging but requires the simultaneous addition of external wire. On the other hand, filler wire cannot cope with very large gaps alone. In all cases, a higher rate of wire is needed for AW6005A-T6 welding in butt joint.



b)

Gap [mm]	Spot	Filler	Weld speed [m/min]	Laser power [kW]	Defocus [mm]	Wire speed [m/min]	Wobbling amplitude [mm]	Wobbling frequency [Hz]
0	Fixed	None	3	2.5	-2	0	0	0
0	Fixed	Wire	3	3	-2	1	0	0
0	Wobbling	None	3	3.5	-2	0	1.2	100
0	Wobbling	Wire	2	3.5	-4	2.2	2	40
1	Fixed	None	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1	Fixed	Wire	3	4	-4	8	0	0
1	Wobbling	None	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1	Wobbling	Wire	2	4	-5	5.3	1.8	30

Fig. 3. AW6005A-T6 welds: a) sections of samples; b) process parameters. Red crosses and ‘n.a.’ refer to failed combinations

3.2. Comprehension of the gap bridging dynamics by high-speed imaging

High-speed videos were taken to understand the behavior of the weld pool in the case of simultaneous use of filler wire and laser wobbling. The two material-joint combinations of this study were filmed both in absence and presence of 1 mm gap. Figures 4, 5 and 6 show some images acquired during the welding of stainless steel. Figures 7 and 8 show the high-speed images during the welding of the aluminum alloy. Firstly, in all the investigated conditions, the oscillating beam generates a large and continuous weld pool rather than a small pool moving with the spot. As visible in Figure 4a, the material fused by subsequent wobbling tracks merges together to create a single pool as wide as the wobble trajectory. When the wobbling frequency and amplitude are correctly selected, an apparent heat source that is much larger than the laser beam can be achieved so that molten material quantity can be controlled by wobbling amplitude. Secondly, the wobbling frequency strongly influences laser-wire interaction. In fact, the ratio of wire speed and wobbling frequency determines the amount of wire fed in a full laser revolution period: a small amount of wire will be completely molten whereas a higher one will result in a solid chunk of wire being chopped off (Figure 8b). This has also an impact on the interaction between parent and wire material. In fact, a stable flow of molten material from wire to workpiece was observed to rely on the surface tension of the liquid phase. In the stainless-steel, 0-mm gap case, a bridge of molten material is created (Figure 4c) and broken (Figure 4d) in a stable way thanks to the presence of a droplet of liquid material at the wire tip. This was observed to assist correct material deployment, as also described by Yu et al., 2013. In this case, the wire tip remains molten because of its very low consumption that allows a better heat storage (Figure 4e).

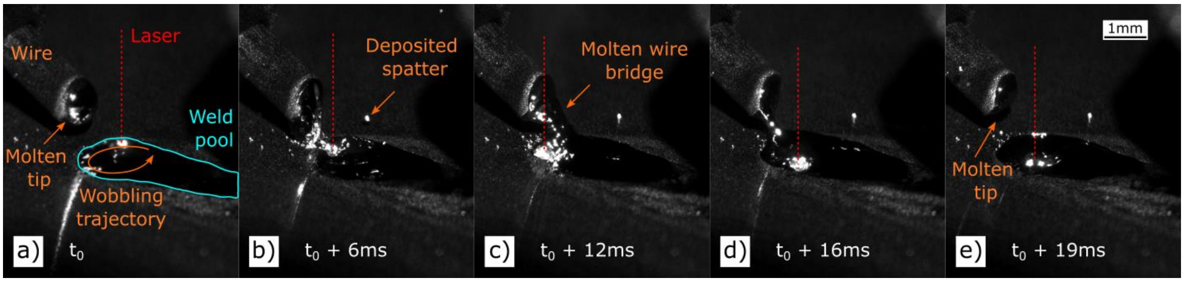


Fig. 4. High-speed images of AISI301LN welding with 0 mm gap: a) extended weld pool has dimension of wobbling diameter and wire tip is liquid; b) when laser gets close to wire, first spatters are generated then c) a bridge of molten material is established after passage of laser; d) detachment of bridge is not turbulent and e) wire tip remains wet until next laser passage

On the opposite, the higher wire-rate of 1 mm-gap makes wire material replacement high and the tip is in this case always solid at beginning of every wire-laser interaction (Figure 5a). It is observed that in this case no stable molten material bridge is formed and as a result of the lack of surface tension a significant part of molten wire is ejected vertically by vapors when the laser forms the keyhole (figure 5d), in accordance with Kaplan et al., 2015. A more careful tuning of wire speed in dependence of wobbling frequency could affect the wetting of wire tip and recreate the correct conditions over a wider range of cases.

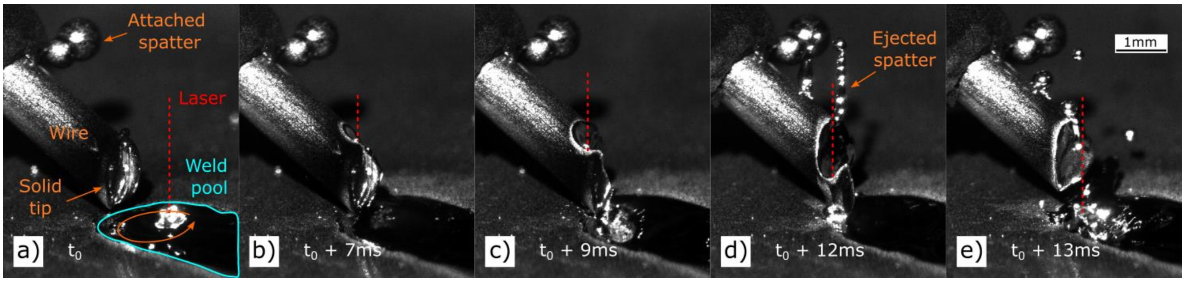


Fig. 5. High-speed images of AISI301LN welding with 1 mm gap: a) wire tip is solid; b) when laser melts the wire, this does not bind to the pool; c) flow is irregular as a result; d) towards the end of wire cut, a significant part of molten wire is ejected by keyhole vapors and e) the wire cut-off produces some spatter as well

The side view of lap joint (Figure 6) provides an insight of how the laser progresses during lap welding. It first pierces through the upper sheet (Figure 6a) then fuses wire material and pushes it in the gap (Figure 6b-c) as seen in the bead section of Figure 2a. At this point some minor losses of material might occur from lower surface (Figure 6d) but this does not affect the stability of the pool.

The tested aluminum alloy shows generally a better capability to create a bridge of fused material. Moreover, bridge is maintained throughout laser wobbling trajectory even when it is not heating the wire. Aluminum also features a higher fluidity, and stronger pool vibrations are observable (Figure 8c-e), mostly excited by the passage of laser from wire to pool (Figure 7d, 8c). These vibrations might induce turbulences and also rare explosions (Figure 7e).

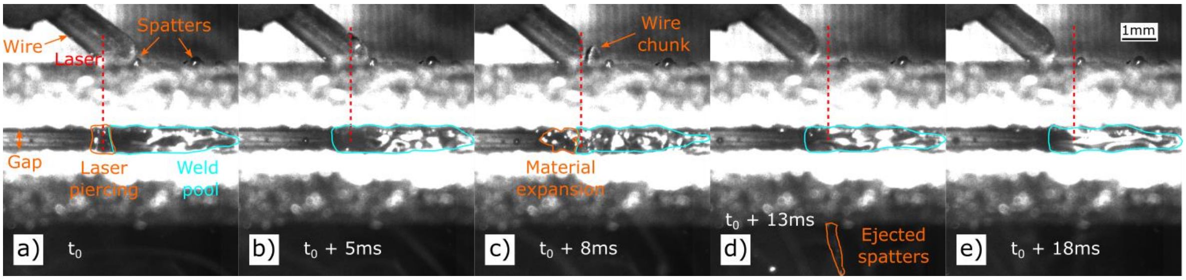


Fig. 6. High-speed images of AISI30LN welding with 1 mm gap – side view. a) in its most advanced position, the laser pierces through the upper sheet b) then encounters the wire and reduces penetration; c) when wire is completely molten, a rush of material expands in the gap; d) subsequently, when laser gets to rear position, a jet of material is blown out of lower surface; e) pool stabilizes

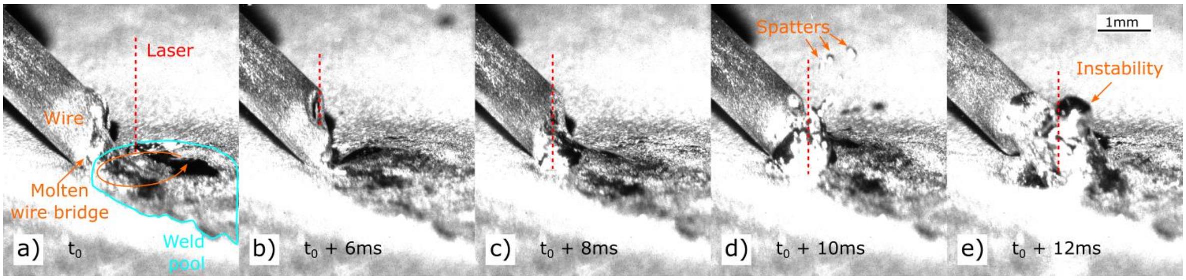


Fig. 7. High-speed images of AW6005A-T6 welding with 0 mm gap. a) before laser melts wire, a bridge of molten material already binds it to the pool; the pool is as large as wobbling trajectory; b-c) wire gets molten by laser; d) when laser gets back in the pool an instability arises, causing spatters initially and e) a significant quantity of material to be blown up.

This behavior might be due to the high power step that the pool experiences at this point. In fact, wire takes away a significant part of the radiation, both because of its high reflectivity at solid state and because of the energy it requires for melting. When the full laser power is conveyed to pool and keyhole is formed back, absorption goes almost to a unitary value and this impulse causes a surge in vapors that inflate pool. The produced waves look different from those experienced by Schweier et al., 2016, caused instead by the keyhole closing at changes of direction of the laser. Given the cyclical nature of the issue, the stability of the system might be increased with a power control within wobble circles, where power could be increased at wire melting and reduced at pool entrance.

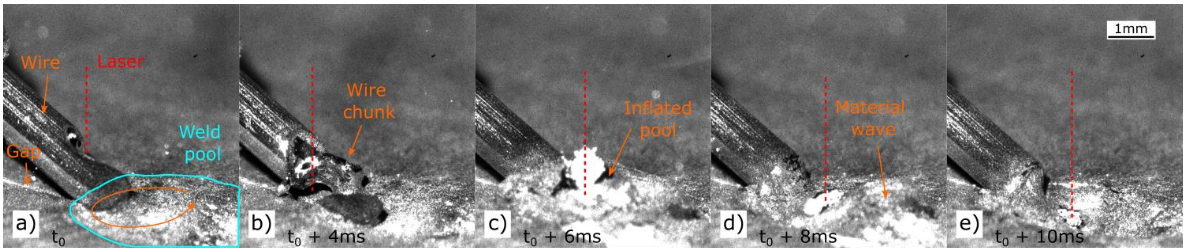


Fig. 8. High-speed images of AW6005A-T6 welding with 1 mm gap. a) Laser starts to melt wire until b) a chunk of solid material is cut off and sinks in the pool; c) the pool gets inflated by the return of the laser and this generates a wave of molten material towards the tail of the pool d); e) after wave front has drifted, a throat momentarily remains in the pool that is then filled by recoil pressure

3.3. Effect of wire-feeding and beam oscillation on melting efficiency

Finally, a melting efficiency parameter is introduced for the comparison of the different weld conditions. Considering the result of high-speed imaging that the wobbling spot produces a continuous, enlarged weld pool, a model inspired to the lumped heat capacity model of Steen (Steen and Mazumder, 2010) was introduced. The melting efficiency η is estimated for a virtual extended laser beam as:

$$\eta = \frac{v \cdot A_{bead} \cdot \rho \left(c_p \cdot (T_m - T_0) + L_f\right)}{P} \tag{1}$$

where P is laser power, c_p is the heat capacity, $T_m$is the melting temperature, T_0 is the starting temperature, L_m is the latent heat of fusion, v is the weld speed and ρ is the material density. The area of the molten material A_{bead} is measured from cross-sections. The thermo-physical properties of the studied materials are reported in Table 2. A high value of η indicates a better melting capacity of the process. The comparison of its value amongst different conditions (especially concerning fixed and wobbled spots) can be beneficial to understand the role of the energetic coupling and weld pool stability in gap filling capacity.

Table 2. Thermal properties of AISI301LN (Davis, 1994) and AW6005A-T6 (Davis, 1993)

	Heat capacity (c_p) [J/kg/K]	Melting temperature (T_m) [°C]	Latent heat of fusion (L_f) [J/g]	Density (ρ) [g/cm^3]	Thermal conductivity (k) [W/m/K]
AISI301LN	480	1430	280	7.8	15
AW6005A-T6	900	650	410	2.7	190

Figure 9 shows the melting efficiency of the different techniques on the two materials, where a lower efficiency means that a smaller quantity of melt is produced with the same energy. From this perspective, it can be noted that laser wobbling clearly increases the melting efficiency for stainless steel in all cases. Moreover, the melting efficiency of stainless steel is unaffected by the presence of gap, indicating a low loss of material. This phenomenon is probably due both to higher viscosity of molten steel and to the geometry of lap joint, less prone to dripping than the open butt joint. Aluminum shows a smaller yet notable improvement with the use of wobbling. This slighter effect might be due to the higher thermal conductivity that makes the energy distribution of beam-shaping less felt. It is anyway very sensitive to gap, that causes almost a net 10 %

decrease in efficiency. Wire feeding does not change the efficiency, testifying for the fact that laser reflection is not an issue at this angle of wire nozzle, as observed in Salminen, 2010.

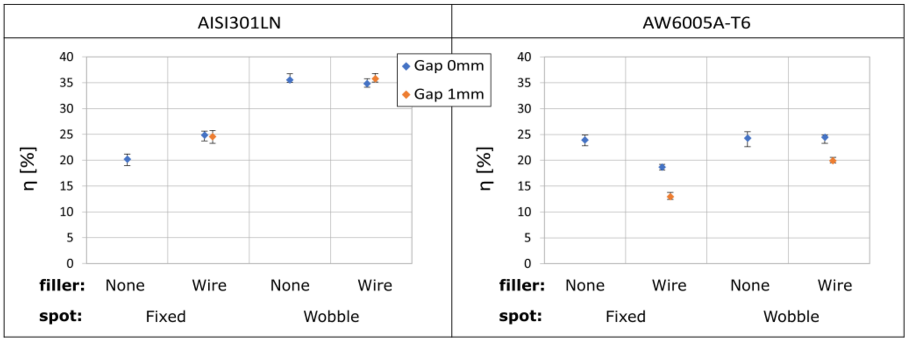


Fig. 9. Melting efficiency of laser welding techniques; error bars represent maximum and minimum values of bead area measurements

4. Conclusions

In conclusion, filler-wire was determined to be crucial for high gaps both in AISI301LN lap joints and AW6005A-T6 alloys butt joints, where very large gaps up to 1 mm could be welded with the use of simultaneous circular wobbling. Wobbling was observed to promote wire melting and mixing while also reducing pores. The analysis of metallographic samples shows that circular laser wobbling at low frequencies can tailor the dimension of the bead to the needs of the joint if the conditions for an apparent large heat source is achieved. This leads to a greater control. The study of volumetric energy inputs shows that these techniques can increase the melting efficiency of laser welding thanks to the enlarged weld pool. Finally, the observation of high-speed videos confirms that the low frequency laser wobbling creates a weld pool whose dimensions are directly related to the diameter of wobble trajectory; additionally, filler-wire positioning was shown to be key for a stable welding. The simultaneous use of wire and wobbling is an effective means of relaxing the stringent requirements on joint preparation of laser beam welding and still grants satisfactory results in terms of welded beads thanks to an enhanced gap-bridging capability. It would be therefore interesting to fully exploit the flexibility provided by the two techniques with a control system for wobbling and filler-wire parameters. Future efforts will concentrate on the study of an algorithm for gap recognition and the implementation of *ad-hoc* strategies for the real-time bridging of varying gaps.

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