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Procedia CIRP 12 (2013) 151 – 156

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8th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Arc leading versus laser leading in the hybrid welding of aluminium alloy using a fiber laser

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Abstract

Hybrid welding technology can be defined as the combination of a laser heat source with a secondary welding source. In this paper a new generation of high power fiber laser was used and it was coupled with a TIG arc source. Two separate sets of experimental trials were performed. It included testing process parameters such as laser power, welding speed and arc current. Microstructure, microhardness and weld appearance were analyzed. A comparison was performed between laser leading and arc leading configuration. The experimental results showed that the laser leading configuration produces a better penetration and sounder weld. The overall investigation gave the clear input that the laser leading configuration is more convenient with respect to the arc leading one. The obtained results worth a larger investigation for a statistical prove of the here presented results.

Selection and peer review under responsibility of Professor Roberto Teti

Keywords: hybrid welding; fiber laser; leading configuration.

1. Introduction

Hybrid laser arc welding (HLAW) is a process that combines conventional arc welding, either gas metal arc welding (GMAW) or gas tungsten arc welding (GTAW), and laser beam welding (LBW) such that the combined heat sources interact at the same time on a single weld pool having a synergistic effect. Advantages of hybrid process over arc welding and laser welding include higher welding stability, higher melting efficiency and lower power input under the same penetration [1].

There are many process variables associated with hybrid laser arc welding, and it is important to understand how they affect the welding process. In hybrid laser arc welding, the arc power controls the weld width and the bridging ability, and the laser power controls the penetration [2].

The used laser source has been either the carbon dioxide (CO_2) or the neodymium-doped yttrium aluminium garnet (Nd:YAG), whose wavelengths are 10.6 and 1.06 μm, respectively. Wavelength is an important parameter that needs to be considered because affects the choices of the other welding parameters.

Those lasers can operate both in the continuous and pulsed mode. The CO_2 laser has high power output, high efficiency, proven reliability and safety. It is more efficient in the conversion of electrical power to laser radiation than Nd:YAG laser. However the reflectivity of most metals is much higher at the CO_2 wavelength than the Nd:YAG wavelength. Nd:YAG has a higher welding efficiency if compared with CO_2 laser. Highly reflective materials such as aluminium, copper and gold are more difficult than steel to weld with an Nd:YAG and even more difficult with the CO_2 laser [3].

A few years ago the major competitors in the power laser market were CO_2 and Nd:YAG. The latter entered the fields dominated by the CO_2 laser thanks to the recent development of high output power, the improvement of beam quality and the possibility of glass fiber delivery.

The recent commercialization of high-power fiber laser has modified the market competition between lasers. [4]

Fiber laser has high energetic efficiency, compact design, good beam quality, the possibility to deliver several kilowatts of power, and an extended lifetime [5].

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Selection and peer review under responsibility of Professor Roberto Teti
doi:10.1016/j.procir.2013.09.027

Nd:YAG and fiber lasers have close wavelength around 1 μm, while CO_2 has a wavelength that is very poorly absorbed by a wide range of materials [6]. For each specific material there is a wavelength which has the maximum absorption of laser energy. Due to the shorter wavelength of fiber pumped laser the metals absorb more energy. Moreover the operating costs of fiber laser equipments are lower than those of the CO_2 and Nd:YAG lasers, which is due to the higher electrical efficiency and reduced need for replacing electronic components. Fiber laser has been receiving higher attention due to its capability to produce narrow and deep penetration welds at high-welding speeds [7].

Ever new applications are investigated for fiber laser with a particular attention to the dissimilar joint [8].

A last generation fiber laser was also coupled to a friction stir welding machine for aluminium welding, which showed the potentiality of laser assisted friction stir welding in terms of quality and productivity [9].

Hybrid arc-laser welding founds on the interaction between a laser source and an arc source. It is well known that synergetic effects between the arc plasma and the laser radiation occur during welding, which produces an increase in welding performance [10].

About the hybrid laser welding of aluminium it is noteworthy the investigations on aluminium-magnesium (Al-Mg) whose metallurgy, mechanical and technological properties were investigated for arc-CO_2 laser welding [11, 12] and using statistical tool [13].

Laser–arc hybrid welding requires that several parameters be adjusted in order for high quality welds to be obtained. In order to increase the knowledge about the hybrid welding process, many researchers studied the potentialities and advantages of the process [14-15]. Weld penetration was improved as well as the bridging ability. The welding speed compared to the individual processes of laser and arc welding was faster.

In this paper, a high power fiber Laser–TIG arc hybrid welding process was tested for making aluminium alloy joint. The laser source was used in programmed waveform mode for both the arc leading and the laser leading configuration.

The effects of some welding parameters, such as the laser power, the arc current and the welding speed were investigated. Eventually a comparison between the performance of the arc leading and laser leading configurations was performed.

2. Experimental setup

The material studied was the AA5754-H111 magnesium aluminium alloy. These alloys are the highest strength non-heat treatable aluminium alloys and they are optimal and extensively used for structural applications. The alloy was in annealed condition.

Butt welds were produced. The sizes of the weld were 3 mm thickness, 250 mm length and 40 mm. The heat source was an Ytterbium Laser System (IPG YLS-4000) combined with a direct current TIG generator (SELCO GENESIS 504 PSR). The laser, whose wavelength was 1070.6 nm, was focused by a lens with a focal distance of 250 mm.

The laser source was transmitted via a 200 μm diameter fiber, a beam parameter product of 6.3 mm*mrad and a laser spot of 0.4 mm on the surface of the workpiece. The laser was focused on the upper surface of the workpiece using a programmed emission mode. During welding the workpiece was fixed by four vertical clamps on a plane support. The hybrid laser-arc welding station had five axes and was controlled by CNC programming unit.

In this work, the authors used two different setups for the leader heat source: an arc leading setup (AL) and a laser leading setup (LL). The TIG torch was tilted to an angle θ with respect to the workpiece surface, as shown in figure 1.

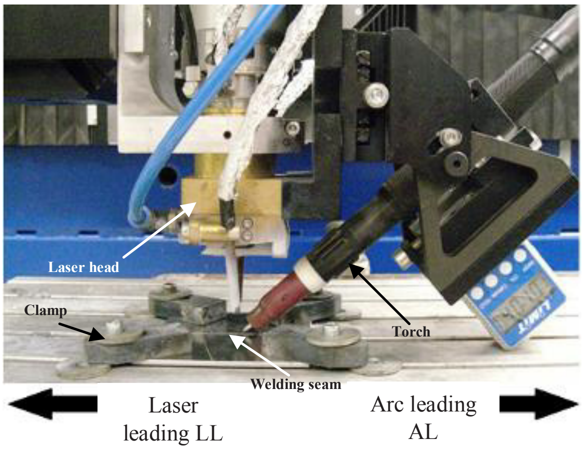

Fig. 1. Welding area with the two different welding configurations (LL and AL).

After welding the transverse cross section of each sample was etched by hydrofluoric solution in water to highlight the bead shape and size. They were observed, measured and photographed by an optical microscope. The Vickers microhardness was measured using HV 0.05 kg and a load time of 15s.

In order to compare the two different leading setups all the trials were repeated for each configuration using the same welding parameters. The TIG torch angle was 50°. The protection gas was 100% Ar, supplied from the coaxial nozzle of the TIG torch and from two nozzles on the laser head. The total air equivalent flow was 400nl/h. The distance between the arc source and the laser source was 3 mm. The distance between the tip of the TIG torch and the surface to be welded was 6 mm. The TIG generator was used in "Fast Pulse" mode, i.e. with a high frequency of 500 Hz. In order to reduce the oxide formation on the aluminium surface during welding, the workpiece was brushed with a steel brush before the welding process and thereafter cleaned with alcohol. Every test was performed with a programmed mode of power laser source, which followed a square intermittent pattern. The programmed emission of the laser power was useful for reducing the reflection problem. In arc leading setup, in order to avoid this problem, many preliminary tests were made with a rotation of the hybrid welding head of about 20°. The hybrid welding head was positioned in vertical and symmetric position. In table 1 the main welding parameters are shown.

Table 1. Welding parameters.

Sample No.	Laser Power (W)	Welding speed (m/min)	Arc current (A)	Arc Voltage (V)
1 and 6	3000	3	200	25
2 and 7	3000	3,5	50	23,5
3 and 8	3000	4,5	75	19,5
4 and 9	3000	4,5	100	21,5
5 and10	3500	4,5	75	39

3. Results for the arc-leading configuration

Figure 2 presents the surface and cross section morphologies of weld.

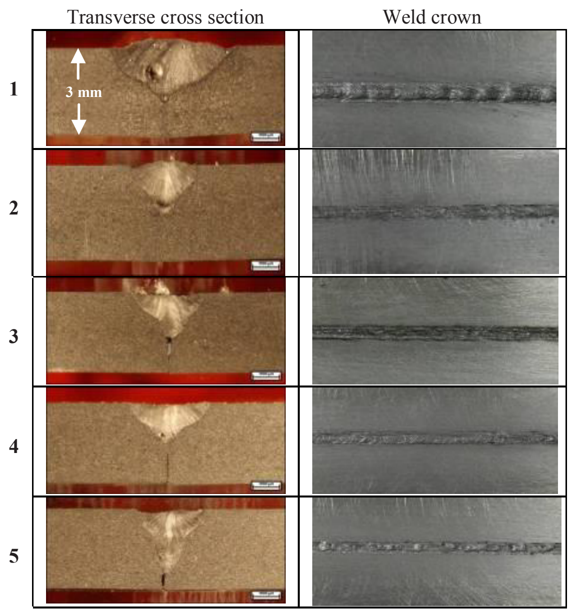

Fig. 2. Transverse cross section and crown appearance for arc-leading configuration.

The weld were obtained using the process parameters in table 1. The hybrid welds have the typical "wine-cup" shape with a wide upper zone and narrow lower zone. The former is more like the weld shape of arc welding and the latter is more like that of the laser welding.

This classification does not mean the upper zone is in relationship only with the arc and the lower zone is only with the laser source. In fact, the laser energy is absorbed in the whole thickness on the contrary the arc energy mainly acts in the upper zone.

It is evident that during arc leading welding the weld upper zone is acted by arc and laser energy, which forms the wide cup zone whereas the underneath of the weld is mainly acted by laser energy and form the narrow laser zone. Moreover a high arc current implies a reduction of laser penetration and an increasing of the width of the upper zone, as shown in samples 1 compared with samples 3 and 4. Table 2 contains the values for the crown and penetration values.

Table 2. Dimensions of the transverse cross section.

Sample No	Crown (mm)	Penetration (mm)
1	4.7	1,8
2	2.7	1,6
3	2.9	1,7
4	4.0	1,8
5	3.7	2,4

All the samples present localized porosity that is strictly related to a number of conditions, which regarded the material and the operating technique. Several authors reported the same weld defects. In particular porosity in aluminium laser welding was imputed to the high Magnesium content that favours gas occlusions and non-stable key-holes [16-17].

Some researchers studied the connection between the shielding gas and the pore formation on laser-arc magnesium alloys joints. They found that a favourable weld without porosity can be obtained by appending lateral shielding gas for laser beam. Too much heat input and a dirty base material could be possible causes of porosity [18].The high frequency of 500Hz of the TIG heat input could be an important obstacle to the emission of gases. A high TIG frequency could agitate the molten pool at a rate that allows typically trapped gases or impurities to escape. So a turbulent flow in the weld pool can be linked to the porosity formation [19].

The surface preparation reduces the hydrogen sources responsible for micro porosity generation, and produces a noticeable suppression of porosity [20].

4. Results for the laser-leading configuration

Figure 5 shows the pictures of the welds obtained with the laser leading configuration. The results depend on the arc current, the laser power and the welding speed.

It can be observed that the global heat input is strictly related to the three parameters. Observing sample 8 and 9, a reduction of TIG amperage caused an increase in the weld penetration. This phenomenon is related to the support function exerted by the arc source.

A growth of the arc current implied a larger crown but decreased the synergic effect. Nevertheless this phenomena is much less evident in the LL configuration rather than in the AL configuration.

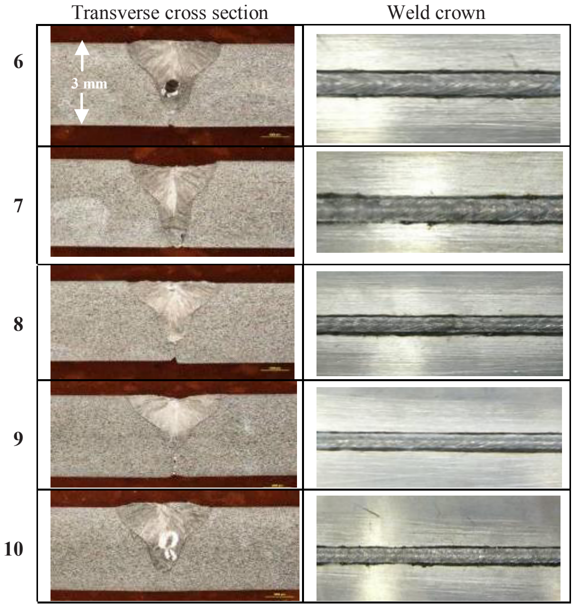

Fig. 3. Transverse cross section and crown appearance for laser-leading configuration.

Sample 6 is characterized by a wormhole defect. Wormhole pores are normally not observed in aluminium welds and are strictly related to bad process parameters. In subsequent trials, reducing the TIG amperage and increasing the welding speed, there were any more wormholes.

Table 3. Dimensions of the transverse cross section.

Sample No	Crown (mm)	Penetration (mm)
6	3.4	2.4
7	3.2	3.0
8	3.6	2.3
9	3.6	1.9
10	3.4	0.7

Table 3 contains the values for the crown and penetration values.

5. Discussion

5.1. Weld shape and porosity

In figure 4 the welds with AL and LL configurations are shown.

The laser-TIG configuration limits the synergy between the sources. In particular the laser penetration had a significant difference from that of the arc leading configuration, see sample 2 (AL) and sample 7 (LL).

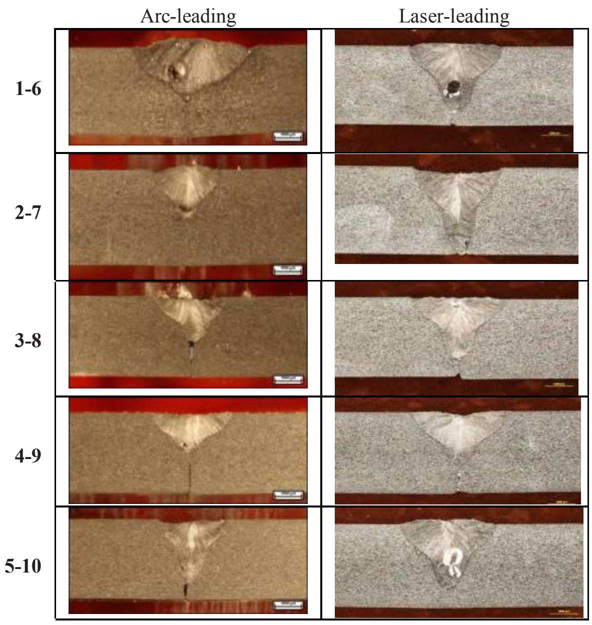

Fig. 4. Comparison at-a-glance between transverse cross sections.

The difference in penetration tended to decrease for samples 5 and 10, which was obtained using a higher laser power. This implies that the request for the maximum penetration using the TIG-laser technology needs a higher laser power.

The weld crown was almost constant, which means that the current parameter had the same effect for both configurations.

For both laser leading and arc leading configurations the “wine-cup” shape of hybrid weld appeared neat, which proves the overwhelming effect of arc over laser at bridging capability.

It is noticeable that the higher the welding speed the stronger is the heat input reduction, which is much more important for the leading arc. Therefore the arc leading configuration seems to be less suitable for high speed.

Some welding defects are present in both configurations, although to a lesser extent for the leading laser configuration. An incomplete penetration is a common defect and could be related to a loss in laser power. In fact, loss in laser power or changes in the power distribution are usually the causes for incomplete penetration and could be related to a contamination of optical surfaces, that can cause changes in laser power density at the work. Samples 3 and 7 had incomplete penetration. The explanation can be that small deviation in joint alignment can cause the laser beam to miss the weld joint and result in an incomplete fusion defect. Moreover, samples 7 through 10 do not show porosity. The greatest source of porosity in aluminium alloy welds is atmospheric contamination of the shielding gas. Hydrogen, formed by the reaction of water vapour with molten aluminium, may be responsible.

Porosity may be also linked to the high arc current, i.e. 200 A, or the high current frequency. Also the keyhole stability was found to play a major role in porosity formation [21]. In order to reduce these defect further experiments may be performed using a helium-argon-mixture shielding gas, which is recommended to reduce porosity, and a lower arc current and frequency.

5.2. Weld efficiency

In figures 5 and 6 3D plots of the penetration against the heat inputs of the laser and the arc source is shown fro AL and LL.

The values are in millimetres. Penetration is plotted as a function of heat input for each heat source of the hybrid system, or rather the relationship between welding speed v and thermal power of the laser source Pl or the thermal power of the arc source Ptig.

The surface is built basing on the values of the welding process parameters listed in Table 1.

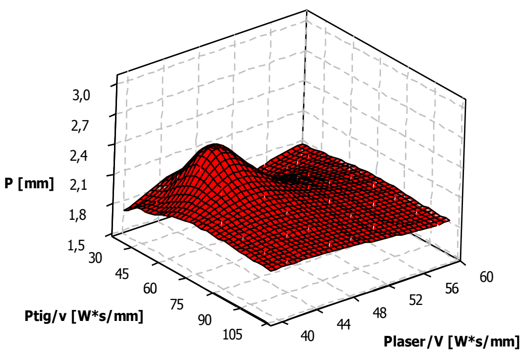

Fig. 5. Penetration against arc and laser heat input for AL.

So the comparison between the penetration between the LL configuration and the AL configuration is more effective. The LL configuration allows reaching higher values of penetration than the AL one. The maximum value of penetration for AL is about 2.37 mm versus 3 mm, which is the full penetration, for LL.

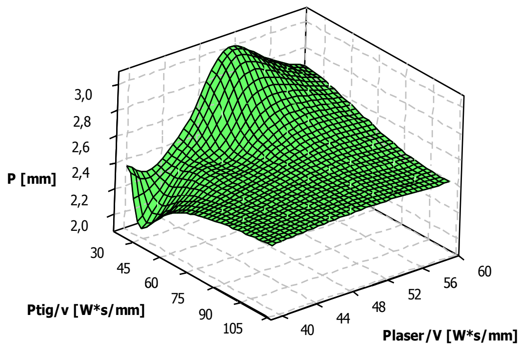

Fig. 6. Penetration against arc and laser heat input for LL.

It follows that the LL configuration allows a better use of synergetic effects resulting from the union of the sources. The global efficiency of the process itself is enhanced using this configuration. This result is valid for the window of process parameters used in this trial.

Penetration shows a peak for lower arc power and laser middle levels of power in the LL configuration.

5.3. Microhardness

In Figures 7 and 8 the Vickers microhardness profiles of samples 7 and 8 are shown. The fused zone (FZ) was 3 mm wide for both samples.

Their heat affected zone (HAZ) width was less then 1 mm, which was due to the high cooling rate due the high welding speed respect to the standard welding speed in TIG welding, which are one third of the here used velocity. The HAZ experienced one or more cycles of heating and cooling so the properties may be radically different from those of the unaffected parent metal.

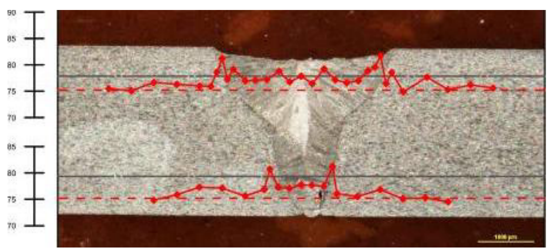

Fig. 7. Microhardness for sample 7.

In this case the aluminium was welded in the annealed condition so the properties of the HAZ match those of the parent metal. The slight elevation of the microhardness in the HAZ was due to a grain size refinement, which was due to the rapid cooling rate.

The microhardness elevation was more significant in the low zone of the weld where the laser produced more rapid cooling rate then in the upper zone where the TIG mitigated it.

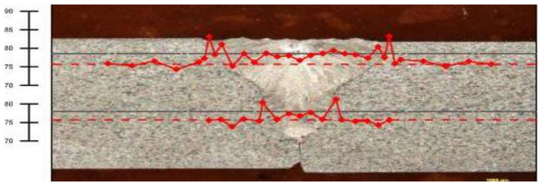

Fig. 8. Microhardness for sample 8.

The plot of microhardness for sample 5, figure 9, showed an irregular shape of the fused zone as a results of some turbulence in the melting pool due to the AL configuration. Moreover the micro hardness plot of hybrid weld shows a larger extent of the HAZ with respect to the samples welded with LL configuration.

Beside the solid solution zone, where alloy elements are dispersed and cooled to retain solid solution, a large partially annealed over-aged zone can be observed. In the latter zone the heat causes precipitation and/or coalescence of particles of the solution constituents. As a result the microhardness was equal or less of that of the base material. For the microhardness of the lower line the sharp fall was due to the incomplete fusion, which was close to the indentation spots.Nevertheless the LL configuration allowed obtaining a uniform distribution of micro hardness, a narrower HAZ, a big reduction of weld defects and a better quality of welded joints.

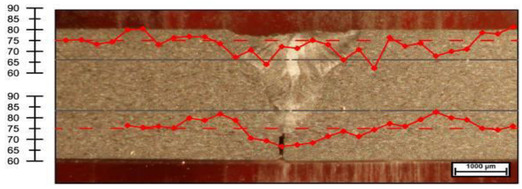

Fig. 9. Microhardness for sample 5.

6. Discussion

A preliminary study of weldability of annealed AA5754 aluminium alloy using hybrid laser welding was achieved. A last generation fiber laser was coupled to a standard TIG torch. Two different heat source configurations, arc leading and laser leading, were used for butt joint fabrication. The following conclusions were derived from the above experimental trials.

- For the Arc leading a lower penetration requires speed slowdown for deeper penetration. The interaction between the heat sources appears weak and instable. Micrographs and microhardness show an increased presence of defects and a wider HAZ.
- Laser leading produces joints with a better weld shape and more efficiency. Low arc current allows obtaining a narrower bead, a more stable melting pool and the reduction of welding defects.
- Laser-TIG hybrid welding is an effective process for AA5754, suitable for welding aluminium in industrial applications. The authors will be address further investigation to prove the here obtained results on a statistical ground.

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