PRELIMINARY EVALUATIONS ON LASER – TANDEM GMAW

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ABSTRACT

Recently there has been considerable research and development activity in the use of lasers for welding operations, turning this process into an important tool for a variety of applications. Although it is possible to use lasers as a unique source of heat to promote union of materials, the combination of the beam provided by a laser system with an arc welding process has been studied widely and applied in the so-called hybrid welding systems. Generally, the final result of such a combination is an increase in the weld penetration depth, width and welding travel speed. Despite these advantages, there are many issues still requiring further research and development concerning the use of hybrid welding using laser and arc welding, including a more comprehensive understanding of the various welding phenomena involved and the exploitation of new combinations. This paper describes an approach for hybrid welding combining a laser with tandem GMAW, in particular placing the laser beam between the tandem GMAW wires. This hybrid process variation is described and some basic aspects regarding its performance are discussed. The laser beam was found to have a positive effect on the appearance of the weld beads produced and best results are obtained if the laser is located halfway between the leading and trailing wires. A 10 mm inter-wire distance was found to be the most appropriate of the separation distances tried. The hybrid process approach was able to increase the welding travel speed or penetration depth significantly in comparison with tandem GMAW (operating in pulsed mode).

IIW-Thesaurus keywords: Combined processes; GMA welding; Laser welding; Tandem welding.

1 Introduction

Systems have been described for hybrid welding combining laser with Gas Tunsten Arc Welding [1], with Plasma Arc Welding [2, 3], with Gas Metal Arc Welding [4, 5] and even with Submerged Arc Welding [6]. Regardless of the arc welding process chosen, the general result is an increase in the effectiveness of the welding process. It is well-known that LBW (laser beam welding) provides high power density, deep penetration, high welding speed, low distortion and high precision. However, because the small focused laser beam spot, LBW exhibits poor gap bridging ability and increased precision in joint preparation is an essential requirement. On the other hand, arc welding processes produce wider weld beads, delivering good bridging ability of joint gaps and improved tolerance to joint preparation. The combination of LBW and arc welding tends to enhance the advantages and compensate for the limitations found in each process. Generally the result is an increase in the weld penetration depth, width and welding travel speed.

A number of studies on hybrid welding employing a laser and single wire GMAW process have been published, most of them using CO_2 or Nd:YAG lasers. Qin *et al.* [7], for instance, studied hybrid Nd:YAG laser – pulsed GMA welding and found that the laser energy influences the weld penetration, that the weld width depends on the arc process and that the hybrid process increases the welding speed and improves the weld appearance at low arc currents. Cho and Farson [8] showed that the use of a laser beam in front of the GMAW weld pool prevents the formation of weld bead humping. Kim *et al.* [4] found that the heat input delivered to the plate is dependent on the nature of the leading heat source (laser or GMAW) and also on the joint condition used in the hybrid setup. Kim *et al.* [4] also mention that the synergistic effects of the two heat sources are maximized when the laser beam is located between the arc centre and the impact point of the molten droplets within the weld puddle. Tusek and Suban [6] claim that the main advantage of the use of both heat sources is the more efficient use of the energy supplied. They also state that the synergic action of the laser beam and welding arc, when current intensities are low, affects ionisation, reduces arc resistance, and increases the number of carriers of electric current. The hybrid process has even become an option for use in pipeline girth welding applications, where the demand for high speed welding is always present [9]. Besides being largely used in combination with pulsed GMAW, Mulima *et al.* [5] undertook preliminary trials using a diode laser combined with GMAW in a controlled dip transfer mode and showed that, in this case, by adding the laser beam in front of the GMAW wire, the welding travel speed could be significantly increased and deep penetration achieved. A process using a laser and two GMAW arcs has also been developed [10]. This processes, named HyDRA (Hybrid welding with Double Rapid Arc), has been able to bridge gaps of more than 2 mm in the roots of V-prepared joints without any weld pool support and in one pass for a thickness of 5 mm. In this process all the three welding heat sources act in one zone and the geometrical arrangement of the individual

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components is of vital importance. Staufer [11] mentions another hybrid approach for laser and tandem GMAW. In this version a tandem GMAW torch trails the laser beam. It has been claimed that this process is able to increase not only the welding speed, but also the ability to bridge root gaps when compared to the conventional laser hybrid – single GMAW.

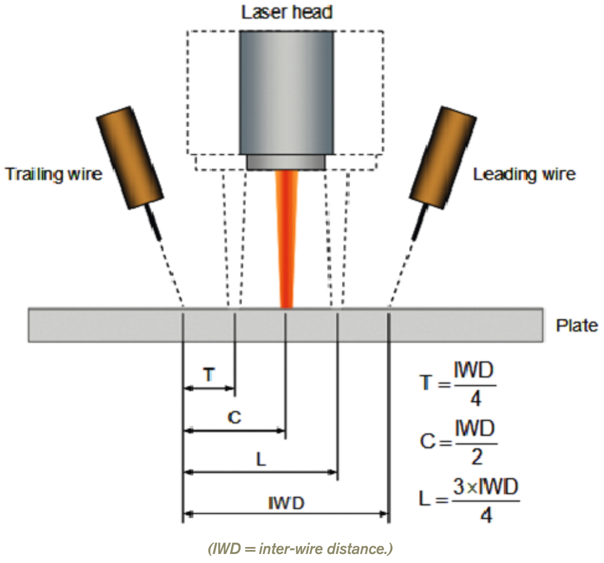
In recent years tandem GMAW (especially in pulsed mode) has been widely applied in production due to developments of digital welding power sources and advances in control of this process [12-15]. In pulsed tandem GMAW the waveform control technique ideally produces one droplet per pulse of current, which results in a stable welding process and less spatter at high travel speeds. It is believed that a combination of this arc welding process with LBW should be investigated further since it may potentially improve weld quality, provide even higher welding speeds and increase penetration. The current paper describes an approach to hybrid welding combining LBW with tandem GMAW, in this case placing the laser beam between the tandem GMAW wires. Details of this hybrid process variation are described and some basic aspects regarding its performance are discussed.

2 Experimental procedure

2.1 Equipment set-up

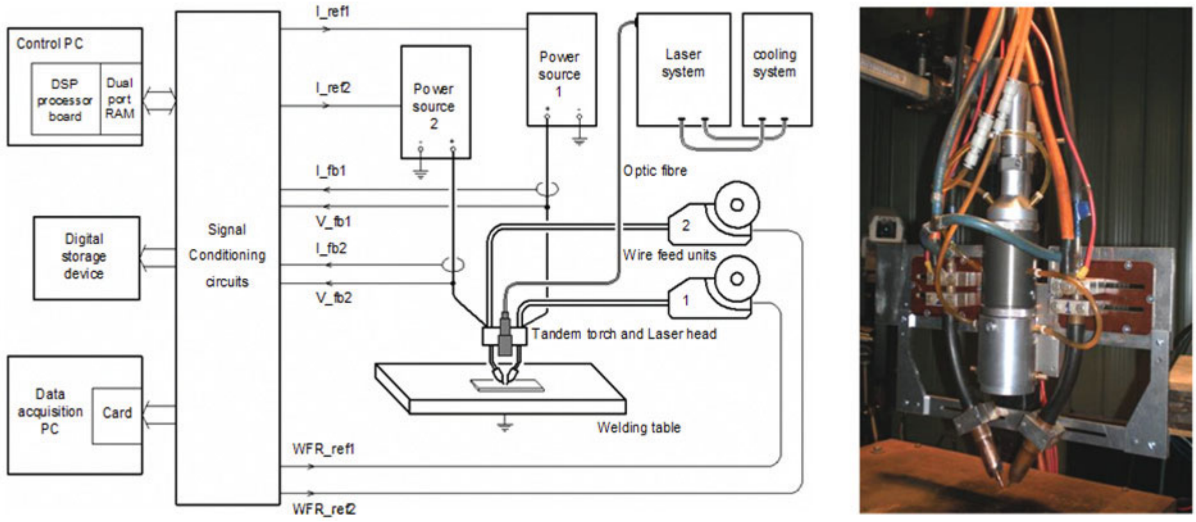
In order to evaluate the chosen variation of hybrid welding using LBW and tandem GMAW, a test rig was designed to provide a mounting for the components of a tandem GMAW torch whilst providing accommodation for a 3 kW diode laser head between the two GMAW heads. In this approach, the laser head is placed between the wires, and its beam can be used perpendicular to the workpiece, meaning that the laser can deliver its energy with maximum efficiency. Figure 1 shows the test facility and the hybrid welding head.

As the use of a laser beam between the wires in a tandem torch is a new approach for hybrid welding, some basic evaluation of the process was needed to determine the effect of the position of the laser beam in relation to the wires, whether the laser beam allows increased inter-wire distances (IWD) to be used, and the effect on weld bead profile caused by the addition of the laser beam between the wires. In order to evaluate the first two aspects, tests were carried out varying the position of the laser beam between the wires whilst varying the inter-wire distance for two levels of laser beam power (1 and 2 kW). As illustrated in Figure 2, three relative positions for the laser beam were used for each of the inter-wire distances tested (5, 10 and 15 mm) and for each beam power level. After these tests, an evaluation of the effect of adding the laser beam to the tandem GMAW process on the weld bead profile was performed. Bead on plate welding on 2 mm plain carbon steel sheets without backing was used throughout the tests. The laser beam focus point was always placed on the upper surface of the sheets.



(IWD = inter-wire distance.)

Figure 2 – Position of laser beam in relation to the wires



a) Test facility diagram for the laser – tandem GMAW approach used

b) Image of the hybrid welding head

Figure 1

The tandem GMAW process was operated in the pulsed transfer mode, as in an attempt to obtain stable metal transfer at low mean currents. A condition previously derived for the optimized low mean current condition was set up (0.1 ms of delay between the current pulses in an 'almost-in-phase' synchronization providing one droplet per pulse and no arc interruptions) [15]. For each laser beam power level, two weld beads were produced; one to provide an opportunity to capture high-speed images synchronized with transient electrical data and one to provide longer transient electrical data acquisition time and to verify the repeatability of the process. For the cases in which the laser beam was set at the higher level of power, conditions using out-of-phase pulsed welding were also tried (10 ms of delay between the current pulses, delivering the pulse of current in the trailing wire when the leading wire was in the middle of its base current time). Weld beads were also produced using only the tandem GMAW process as a benchmark. Table 1 shows the electrical parameters used in the pulsed control program developed for tandem GMAW [15] whilst Table 2 shows the physical welding parameters. Figure 3 shows the angles for the wires in the tandem torch. Due to the requirement to accommodate the bulky laser head between the wires, the angles used were larger than usual for a conventional (non-hybrid) tandem torch.

Table 1 – Welding parameters selected for GMAW

Welding parameter	Value
Ipulse1 = Ipulse2 [A]	350
Tpulse1 = Tpulse2 [ms]	2
Ibase1 = Ibase2 [A]	50
Tbase1 = Tbase2 [ms]	18
Ramp_up1 = Ramp_up2 [A/ms]	2 000
Ramp_down1 = Ramp_down2 [A/ms]	2 000
Tailout1 = Tailout2 [dimensionless]	45
WFR1 = WFR2 [m/min]	3.8
Delay [ms]	0.1
Arc voltage control (wire 1 and 2)	ON

Table 2 – Additional welding parameters utilized

Welding parameter	Value
CTWD* (both wires) [mm]	18
Welding travel speed [m/min]	1.63
Shielding gas [98 % Ar + 1.5 % O_2] [l/min]	35
Diameter of wires [AWS ER 70S-6] [mm]	1.2
Inter-wire angle [°]	68

** The CTWD parameter was considered as the vertical distance measured from the contact tip to the workpiece.*

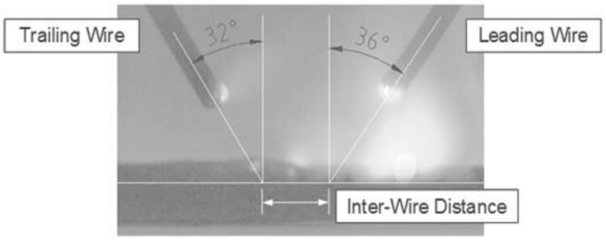


Figure 3 – Angle measured between the electrodes and inter-wire distance parameter

2.2 Weld bead characteristics

In order to assess the characteristics of the weld bead profile (Figure 4) produced by utilizing the laser – tandem GMAW process, tests were carried out using an inter-wire distance of 10 mm and the GMAW conditions shown in Tables 1 and 2 ('almost-in-phase' current pulses). The welding travel speed and laser beam position in relation to GMAW wires were varied. For each one of the conditions (bead produced) three cross-sections were taken from the plate and suitable sample preparation was carried out (each section was polished, etched with Nital 5 % and image analysis software was used to measure the weld bead geometrical parameters).

3 Results and discussion

3.1 Influence of inter-wire distance

The first laser – tandem GMAW conditions tested used an inter-wire distance of only 5 mm. Figure 5 shows a sequence of images synchronized with electrical transient data produced when using a 2 kW laser beam and 'almost-in-phase' current pulses, while Figure 6 shows the same data for a 2 kW laser beam and out-of-phase current pulses. The data in Figures 5 and 6 are generally representative of the hybrid process operating with an inter-wire distance of 5 mm.

In the case of 'almost-in-phase' pulses the trailing wire had a tendency to be attracted by the leading arc but no arc interruptions were observed since the small delay between the current pulses was effective in avoiding such interruptions, as described by Reis *et al.* [15]. An interesting observation was made regarding the metal transfer. The droplets were significantly deflected from the wire axis and, as a consequence, two situations occurred; the droplets hit the plate out of the weld pool region (especially the droplets from the trailing wire) or they merged close to or directly underneath the laser beam forming a large droplet. In the first case the weld bead appearance deteriorated since some of the droplets were not deposited into the weld pool, remaining beside the weld bead and were easily identified for their large-spatter shape

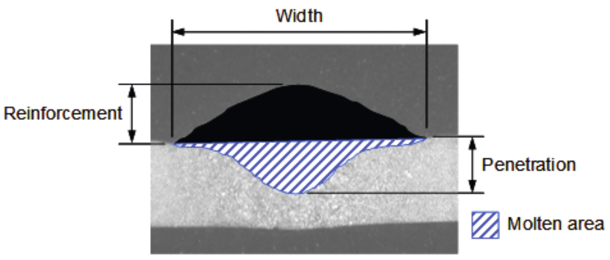
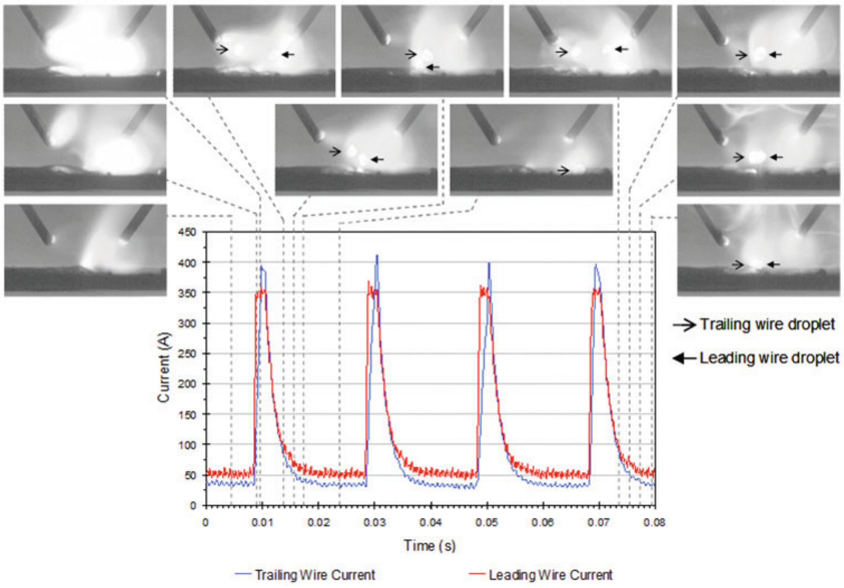
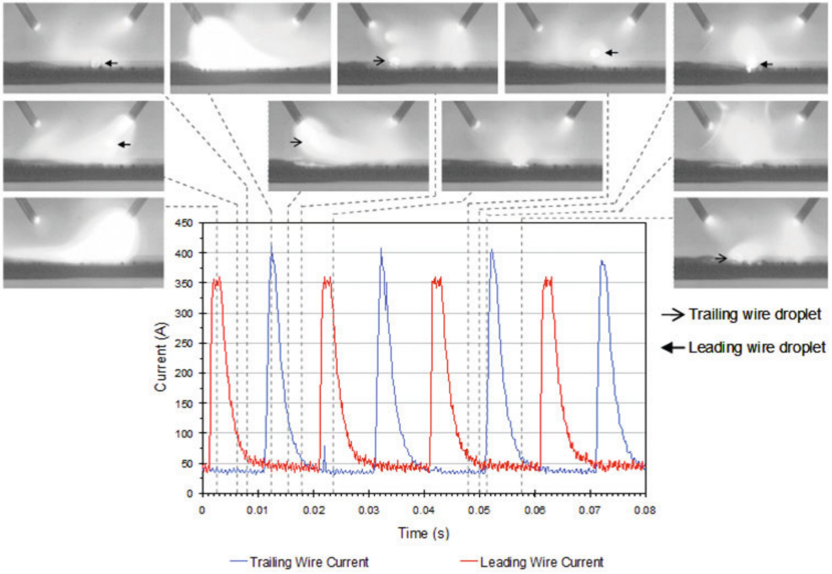


Figure 4 – Weld bead geometrical parameters measured for evaluation of the laser – tandem GMAW process



(Laser beam power = 2 kW and inter-wire distance = 5 mm.)

Figure 5 – Images synchronized with electrical transient data for laser – tandem GMAW using 'almost-in-phase' current pulses

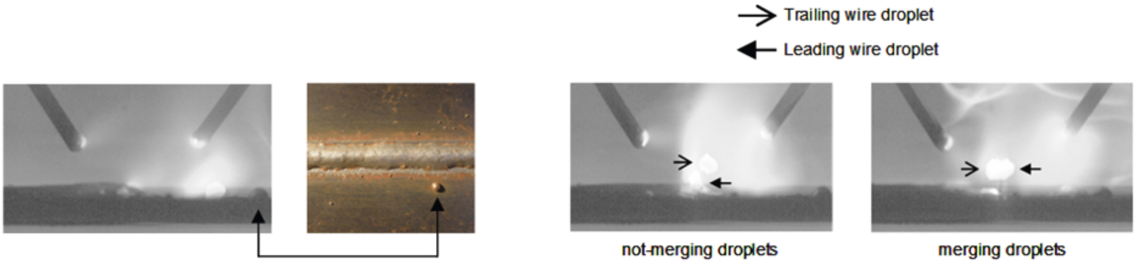


(Laser beam power = 2 kW and inter-wire distance = 5 mm.)

Figure 6 – Images synchronized with electrical transient data for laser – tandem GMAW using out-of-phase current pulses

[Figure 7 a)]. In the case of droplets merging under the laser beam, part of the energy provided by the laser is lost since the beam causes partial evaporation of the droplet producing high levels of fume [Figure 7 b)].

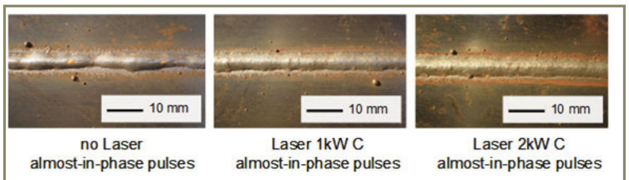
In the case of out-of-phase current pulses, arc interruptions were verified in the trailing wire for all the conditions regardless of whether the laser beam was added to the tandem GMAW process or not. Despite these undesirable



a) Droplet missing the weld pool

b) Increase in fume generation, when merging droplets are partially evaporated by the laser beam

Figure 7



no Laser almost-in-phase pulses

Laser 1kW C almost-in-phase pulses

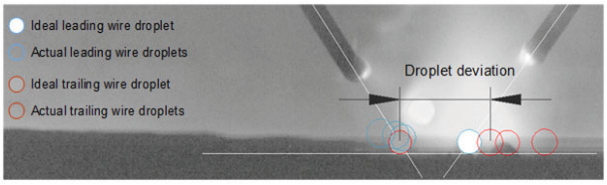
Laser 2kW C almost-in-phase pulses

Figure 8 – General appearance of weld beads produced with laser – tandem GMAW using an inter-wire distance of 5 mm

occurrences, some observations could still be made. The droplets were not deviated as much as in the 'almost-in-phase' case and they always hit the weld pool without merging. As they were detached from the respective wires at different times, they reached the region underneath the laser beam at different times. However, the droplets still hit the plate very close to or under the laser beam, in which case they were partially evaporated generating more fumes and probably reducing the process efficiency.

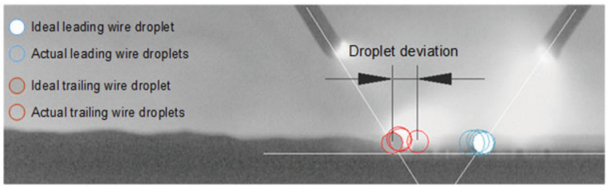
Regardless of welding with 'almost-in-phase' or out-of-phase current pulses for the GMAW process, the laser beam seemed to have a positive effect on weld bead appearance. The travel speed used was too high for the case of welding without the laser beam, but as the laser power was increased the bead appearance was improved (Figure 8).

Despite avoiding arc interruptions, having high current levels in both arcs when the droplets are detached, causes much more (undesired) 'attraction' by the opposite arc than when using out-of-phase pulses. With out-of-phase current pulses the droplets tended to follow the axial projection of the respective wire towards the weld pool. In order to determine the magnitude of these deviations, some measurements were carried out with the laser beam placed halfway between the wires (position C – centralized), as shown in Figures 9 and 10. Figure 11 collates the results of droplet deviation measurement for an inter-wire distance of 5 mm. The deviation of the droplets coming from the trailing arc tended to be larger, confirming that the trailing arc is deflected more than the leading arc. It is worth mentioning that the disturbances in the tandem GMAW arcs, including large deviation of droplets, are likely to be related to the low mean current level used. Motta *et al.* [16] and Scotti *et al.* [12] present results for tandem GMAW with out-of-phase pulsing technique at high current levels and such disturbances were not observed.



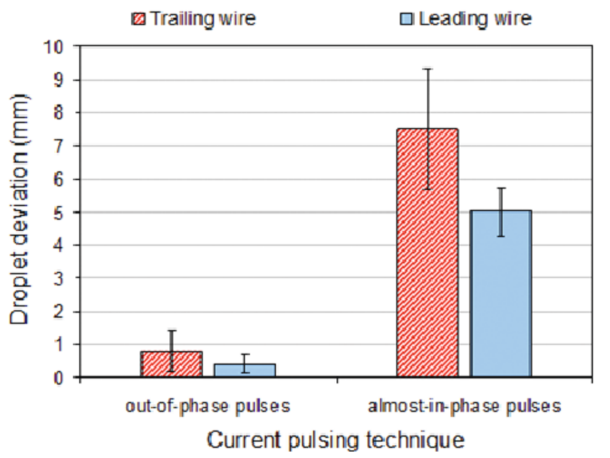
(Inter-wire distance = 5 mm and laser beam power = 2 kW at position C.)

Figure 9 – Droplet deviation for 'almost-in-phase' current pulses



(Inter-wire distance = 5 mm and laser beam power = 2 kW at position C.)

Figure 10 – Droplet deviation for out-of-phase current pulses



(Inter-wire distance = 5 mm and laser beam power = 2 kW at position C.)

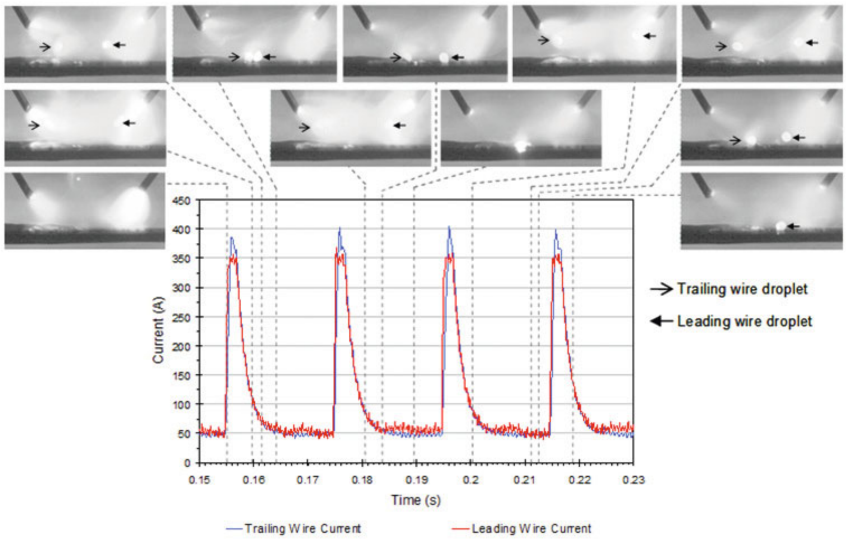
Figure 11 – Droplet deviation in the leading and trailing arcs for different pulsing techniques

In order to continue the evaluation of the laser – tandem GMAW process, the inter-wire distance was increased to 10 mm. Figure 12 shows a sequence of images synchronized with electrical transient data for the case of a 2 kW laser beam and 'almost-in-phase' current pulses and Figure 13 with out-of-phase current pulses. These figures are generally representative of the process operating with an inter-wire distance of 10 mm.

As was observed for the case of an inter-wire distance of 5 mm, the use of 'almost-in-phase' pulses caused a small tendency for droplets from the trailing wire to be attracted towards the leading arc, but no arc interruptions were observed. As expected, the droplets were not deflected as much as when using only 5 mm between the wires. The droplets were more consistently deposited in the weld pool region right next to the laser beam without crossing their paths or merging, which is the likely reason for the good visual appearance of the weld beads produced (Figure 14). The droplets from the leading wire were deposited close to the leading edge of the weld pool, indicating that the inter-wire distance value may be close to the acceptable limit for the welding travel speed used (or the travel speed may be close to the acceptable limit for the inter-wire distance used).

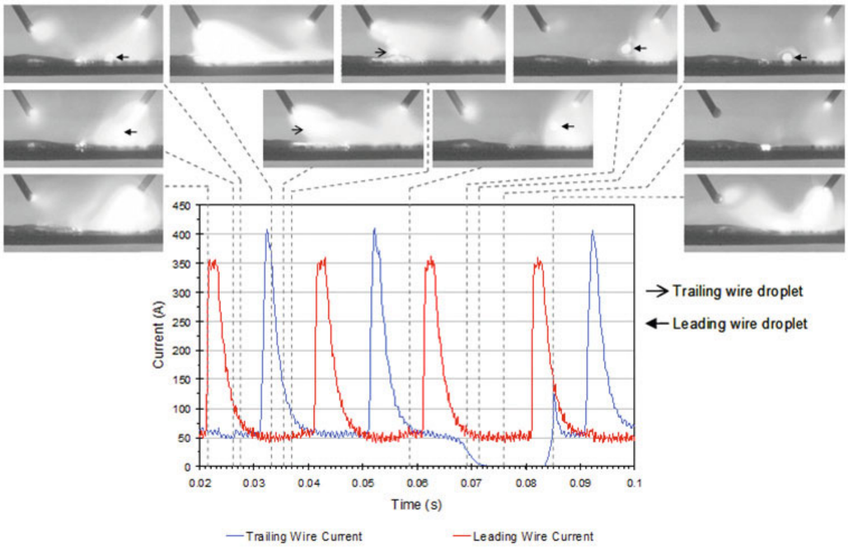
The effect of the laser beam on weld bead quality followed the same trend that was observed for an inter-wire distance of 5 mm. That is, the laser beam has a positive effect on weld bead appearance and the higher the laser beam power the better (Figure 14).

The deviation of the droplets was verified following the same procedure used for an inter-wire distance of 5 mm



(Laser beam power = 2 kW and inter-wire distance = 10 mm.)

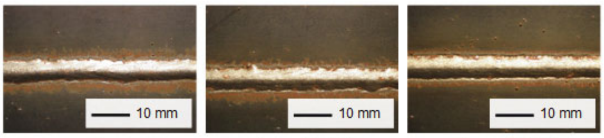
Figure 12 – Images synchronized with electrical transient data for laser – tandem GMAW using 'almost-in-phase' current pulses



(Laser beam power = 2 kW and inter-wire distance = 10 mm.)

Figure 13 – Images synchronized with electrical transient data for laser – tandem GMAW using out-of-phase current pulses

and the results are collated in Figure 15. As the inter-wire distance was increased, the deviation of the droplets when using 'almost-in-phase' pulses tended to decrease, with the droplets originating from the trailing arc being slightly more deviated. The droplet deviation for the out-of-phase case did not change in comparison to the case of an inter-wire distance of 5 mm with the same pulsing technique. The decrease in droplet deviation for the 'almost-in-phase'

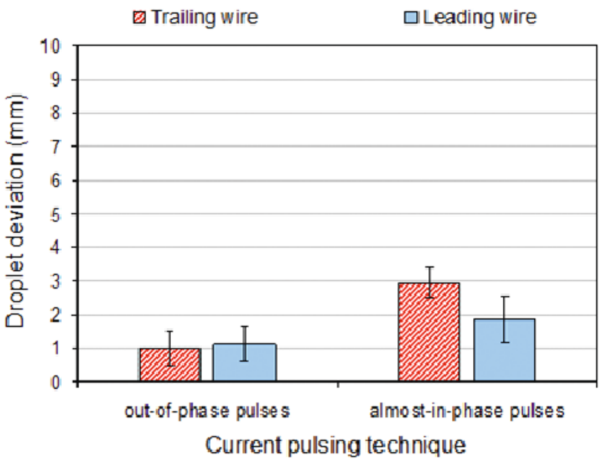


no Laser
almost-in-phase pulses

Laser 1kW C
almost-in-phase pulses

Laser 2kW C
almost-in-phase pulses

Figure 14 – General appearance of weld beads produced with laser – tandem pulsed GMAW using an inter-wire distance of 10 mm



(Inter-wire distance = 10 mm and laser beam power = 2 kW at position C.)

Figure 15 – Deviation in the leading and trailing arcs for different pulsing techniques

case was expected since the magnetic force acting in the arcs (and consequently on the droplets) decreases as the distance between the electrodes is increased.

The inter-wire distance was further increased to 15 mm. As previously observed in experiments using low levels of current for pulsed tandem GMA welding [15], the use of 15 mm for the inter-wire distance caused interruptions in the trailing arc for both out-of-phase and 'almost-in-phase' pulsing techniques. Nevertheless, some observations regarding the effect of such inter-wire distance could still be made. The droplets from the leading wire tended to be deposited too far ahead of the weld pool leading edge, forming a concentration of molten metal on the plate before being absorbed by the weld pool (Figure 16). This phenomenon took place on a cyclical basis. It appears that 15 mm is outside of the inter-wire distance range suitable for the welding travel speed used (1.63 m/min). In addition, the frequent interruptions of the trailing arc caused significant deterioration of weld bead appearance. Without the laser beam, lack of molten metal and porosity were commonly produced defects. However, the defects were minimized by adding the laser beam. For an inter-wire distance of 15 mm the droplets originating from both leading and trailing wire had small and similar deviations towards the opposite arc for both 'almost-in-phase' and out-of-phase cases. The deviation values were comparable to those found for all of the out-of-phase cases assessed so far.

3.2 Influence of welding travel speed

Figure 17 shows the influence of the welding travel speed on the weld bead penetration. The travel speed range for each condition was chosen in order to assure a good visual appearance of the beads produced (regular shape and no burn-through on 2 mm steel sheet). It is worth mentioning that, in the case of the condition with laser beam at 2 kW, the travel speed could be probably further increased, but the existing welding table system could not produce a higher travel speed. This limitation also made it impossible to use a higher laser beam power (up to 3 kW was available), which could probably increase the travel speed even further. Nevertheless, it is very clear that adding the laser beam to the tandem GMAW process allows a substantial increase in the welding travel speed level while producing the same weld bead penetration. From the data shown in Figure 17, a penetration of 1 mm is possible by using the GMAW process on its own at around 1 050 mm/min. The same penetration is achieved at around 1 400 mm/min by adding a laser beam of 1 kW. By extrapolation, 1 mm penetration is likely to be achieved at around 1 900 mm/min by using a laser beam power of 2 kW.

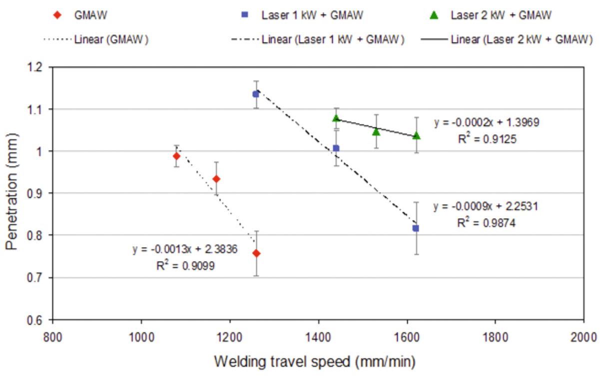
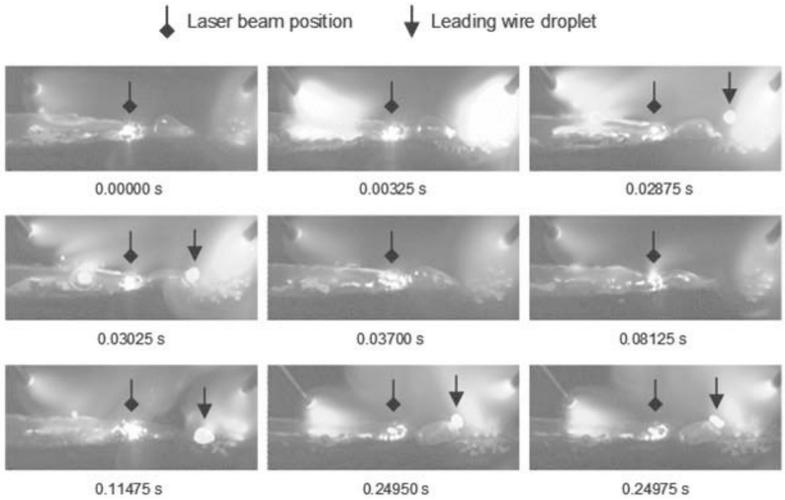


Figure 17 – Influence of welding travel speed on weld bead penetration for tandem GMAW and laser – tandem GMAW at 2 levels of laser beam power (laser beam at position C)

A similar effect took place in relation to the width of the weld beads. Figure 18 shows how the additional heat input from the laser helps to achieve the same width at higher welding travel speeds. This is likely to be due to the increase in the 'wettability' of the deposited metal on the base metal as a consequence of the extra heat provided by the laser beam.

The effect on the weld bead reinforcement was as expected. As the weld width tended to increase by



('Almost-in-phase' pulses, laser beam power = 2 kW and inter-wire distance = 15 mm.)

Figure 16 – Sequence of images showing tendency for accumulation of molten metal originated from the leading wire close to the leading edge of the weld pool

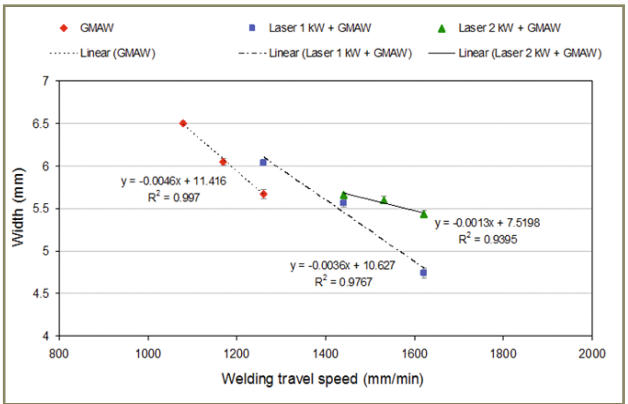


Figure 18 – Influence of welding travel speed on weld bead width for tandem GMAW and laser – tandem GMAW at 2 levels of laser beam power (laser beam at position C)

adding the laser beam to the process, the reinforcement decreased, since the wire feed rate was kept constant throughout the tests.

Figure 19 shows the influence of the welding travel speed on the base metal molten area. The result indicates that by combining the tandem GMAW process with the laser process it might be possible to keep the weld profile required for a specific joint design at higher travel speeds than those possible using only tandem GMAW.

3.3 Influence of laser beam position

According to the experimental data collated in Figure 20, the position of the laser beam does not seem to affect the width or reinforcement of the weld bead. However, the penetration depth is significantly increased, around by 50 %, if the beam is placed centrally between the wires. Figure 21 shows the influence of the laser beam position on the base metal molten area. Such influence was a direct consequence of the penetration depth changes. The molten area with the laser beam centralized between the wires was around 50 % higher than in the other positions. The laser beam applied in the central position not only favoured beads with good appearance (previous results), but also with high penetration depth and base metal molten area.

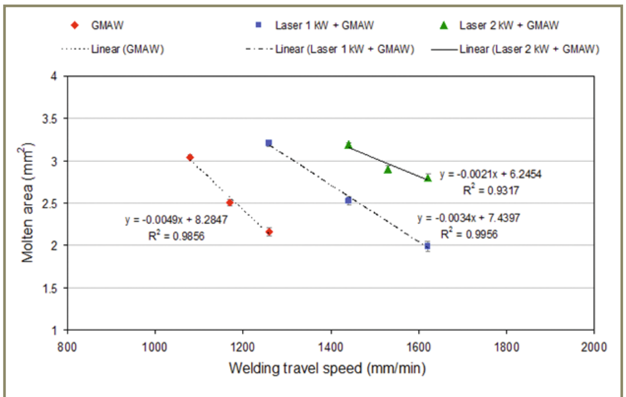
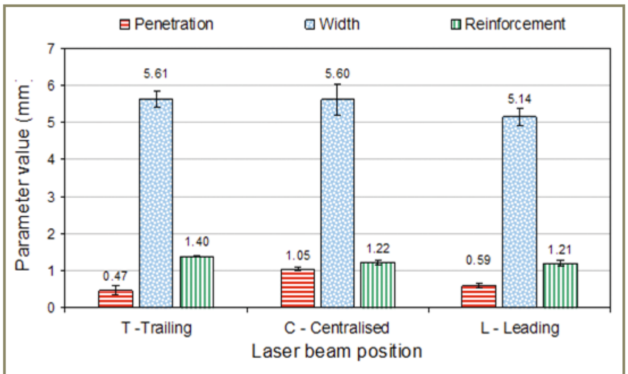
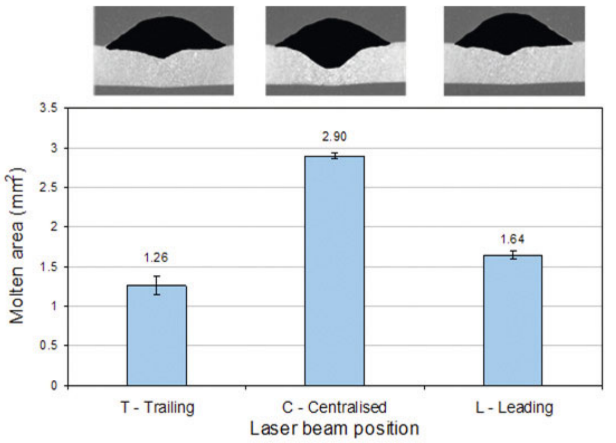


Figure 19 – Influence of welding travel speed on base metal molten area for tandem GMAW and laser – tandem GMAW at 2 levels of laser beam power (laser beam at position C)



(Laser beam power = 2 kW and welding travel speed = 1 530 mm/min.)

Figure 20 – Influence of laser beam position on weld bead penetration, width and reinforcement for laser – tandem GMAW



(Laser beam power = 2 kW and welding travel speed = 1 530 mm/min.)

Figure 21 – Influence of laser beam position on base metal molten area for laser – tandem GMAW

4 Conclusions

Based on the experimental assessment of hybrid welding combining laser beam welding and pulsed tandem GMAW, the following conclusions can be made:

1. Regardless of whether 'almost-in-phase' or out-of-phase current pulses are used for the tandem GMAW part of the hybrid process, the laser beam has a positive effect on the appearance of the weld beads produced (the higher the laser beam power the better);
2. Initial trials indicate that the laser beam produces best results if located half way between the leading and trailing wire, and an inter-wire distance of 10 mm produces the best welding results under the conditions used;
3. The application of the laser beam between the wires does not reduce the occurrence of arc interruptions if the out-of-phase current pulsing technique is used for the tandem GMAW part of the hybrid welding process; and
4. The hybrid process is able to significantly increase the welding travel speed or penetration depth in bead on plate tests in comparison to tandem GMAW (pulsed mode).

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