Lasers in Manufacturing Conference 2013

Guidelines in the choice of parameters for hybrid laser arc welding with fiber lasers.

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Abstract

Laser arc hybrid welding has been a promising technology for three decades and laser welding in combination with gas metal arc welding (GMAW) has shown that it is an extremely promising technique. On the other hand the process is often considered complicated and difficult to set up correctly. An important factor in setting up the hybrid welding process is an understanding of the GMAW process. It is especially important to understand how the wire feed rate and the arc voltage (the two main parameters) affect the process. In this paper the authors show that laser hybrid welding with a 1 μm laser is similar to ordinary GMAW, and several guidelines are therefore inherited by the laser hybrid process.

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Selection and/or peer-review under responsibility of the German Scientific Laser Society (WLT e.V.)

Keywords: Hybrid, GMAW, fiber laser, high speed imaging

1. Motivation / State of the Art

The possibility of combining laser welding with arc welding was first proposed by Steen in 1980. Reviews of more recent laser hybrid welding research have been authored by; Bagger and Olsen, 2005, Mahrle and Beyer, 2006, Ribic et al., 2009 and Kah, 2012. One of the most successful Hybrid Laser-Arc Welding (HLAW) processes involves a laser combined with gas metal arc welding (GMAW). There are several reasons to why HLAW is sometimes preferred to either the laser or the arc in isolation:

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The addition of filler material increases weld reinforcement and reduces undercut. The welding speed can be increased significantly compared to ordinary arc welding. Due to the stabilizing effect of the laser.

Filler material of different alloys can be added to the fusion zone. Lower heat input than arc welding of the same penetration (particularly beneficial when welding high strength steel). Stridh, 2007

The heat input is higher than laser welding of the same penetration and gives slower cooling rates which are beneficial in some materials. Westin and Fellman, 2010

Compared to arc welding less filler material is used due to the penetration capability of the laser. Joint preparation tolerances are relaxed compared to autogenous laser welding. Engstrom et al., 2001

Given these benefits one would expect a large number of industries to be using laser hybrid welding, but compared to laser welding the use of laser hybrid welding is fairly limited. One reason for this could be the large amount of process parameters involved. All the parameters from the laser welding and the arc welding must be adjusted simultaneously, and new combination parameters such as laser-arc separation must be chosen carefully in order to achieve an effective process.

Depending on the joint being welded and what benefit is being sought, there are several ways to set up the HLAW process. The first question is the level of laser power needed to achieve the required penetration/welding speed. The penetration depth of the HLAW process is determined by the power and power density of the laser beam together with the welding speed and is similar to that achieved by autogenous laser welding. The laser has a stabilizing effect on the arc at any power and can therefore be used to increase the ‘arc alone’ welding speed even at low powers. If a high power laser is used the welding speed and the welding depth can be increased compared to an arc weld, or a multi pass joint can be completed in a single pass.

A correctly adjusted process is essential to achieve good weld quality; therefore it is important to understand the basics of the process parameters to be able to adjust them correctly. This paper will discuss parameter selection in laser-GMA hybrid welding with multi kW fiber laser in a practical manner to help avoid common mistakes.

2. GMAW metal transfer mode

A first guideline is to choose a proper metal transfer mode for the GMAW process. In GMAW there are different ways for the metal to pass from the wire towards the melt pool. The two major types are short circuit transfer and spray transfer. These are both based on a controllable constant voltage power source. In these transfer modes there are only two process parameters to set on the power source; the wire feed rate and the arc voltage. The length of the arc is controlled by the applied voltage, and is essentially independent of the wire feed rate as seen in Fig 1. In a short (low voltage) arc the molten metal will, from time to time, make an electrical short circuit between the melt pool and the wire. A higher voltage produces a longer arc where no short circuits are created and the metal is transferred in a spray of molten metal from the wire towards the melt pool.
A higher wire feed requires more power to melt the wire and a constant voltage power source will automatically increase the current to keep the set arc voltage. This means that the welding current is almost linearly dependent of wire feed rate as seen in Fig 2. Changing the arc voltage will also change the welding current as the arc can be seen as a sort of resistance following Ohm’s law. But the biggest effect of a change in voltage is the arc length - which will affect the bead shape.

One important parameter in GMAW is the distance from the contact nozzle to the work piece. This will affect the wire stick out (tip-to-work distance minus arc length) that has an influence on the welding current. Increasing stick out will increase the resistance in the wire and the total resistance, this lowers the weld current. By changing the wire stick out a manual welder can control the heat input during welding to prevent burn through and lack of fusion. In laser hybrid welding the torch is fixed to the laser optics and the wire stick out is held as constant as possible during welding. The general recommendations for GMAW are to use a tip-to-work distance of 10-15mm for short arc welding and 15-25mm for spray arc depending on wire diameter and welding current.

The arc length and welding current are the factors that decide how the metal is transferred from the wire to the melt pool. In short circuit transfer a lower voltage (<24V) creates a short arc length and from time to time the molten metal makes a complete electrical short circuit. When this happens the power source increases the current until the short circuit is burned off. This is repeated several hundred times per second and produces a
fine spatter. At higher voltage the metal is transferred from the wire in a spray mode that is almost spatter free. If a low wire feed rate is used in combination with a high voltage a large droplet is built up on the wire tip and a globular transfer mode is achieved. This globular transfer mode is considered unstable and can produce large spatter droplets and is therefore avoided if possible.

The property of the shielding gas is also very important for the arc behavior. Argon is often used as an inert gas protecting the welding process from the oxygen and nitrogen in the surrounding atmosphere. Additions of \( \text{O}_2 \) or \( \text{CO}_2 \) to the Argon can stabilize the arc and promote good fusion between the weld pool and base material in GMAW of steel. As \( \text{CO}_2 \) gas is cheaper than \( \text{Ar} \) there is a possible cost saving in using higher \( \text{CO}_2 \) contents but with high \( \text{CO}_2 \) content the current (wire feed rate) required for spray transfer will increase and with a \( \text{CO}_2 \) content above 20% a true spray arc can usually not be maintained. A high \( \text{CO}_2 \) content in the shielding gas will also increase the fume formation during welding, Pires et al., 2007.

To reduce the spatter a pulsed arc or other surface tension controlled metal transfer modes can be used. Miller Electric’s Regulated Metal Deposition (RMD), Lincon Electric’s Surface Tention Transfer (STT) and Fronius Cold Metal Transfer (CMT) are different manufacturer’s versions of low spatter computer controlled transfer modes. These state-of-the-art technologies are capable of high quality welds, but are unable to surpass the deposition rates and cleanliness of welds made with argon based shielding gas and spray transfer, according to Soderstrom and Mendez, 2008. These new metal transfer modes can have benefits over short arc transfer when low feeding rate is desired, but are harder to adjust and can be unstable in hybrid welding.

Manufactures of welding equipment often supply standard settings for different wire and gas combinations to ease the weld set up. This is essentially a look up table, setting the voltage to a given value depending on the wire feed rate. As seen in Fig 3 there is a rather abrupt change in voltage in the transition zone between short arc and spray arc. If the equipment is operated in this region the arc can be very unstable, and better results may be achieved if manual control is used.

![Fig. 3. Synergy line from power source manufacturer (ESAB) for low alloy Fe wire.](image)

In some cases, such as welding aluminum or stainless steel, a pulsed arc metal transfer can be beneficial. In the pulsed arc a low voltage/current is used to melt the wire and a short high voltage/current pulse pinches off a droplet with a strong electromagnetic force. The low background current gives a low heat input weld, comparable to a short circuit arc at the same wire feed. But the high peak voltage produces a long stable arc...
that can create spatter free welds. The pulsed arc has benefits; it has reduced spatter and has a cooler melt pool than spray arc, making it possible to weld thin gauge material. However in the pulsed arc there are several interlinked parameters such as peak current, pulse time and frequency that make the process difficult to adjust.

3. Laser hybrid

As mentioned in section 1 the HLAW process has existed for three decades. Using the relatively new 1µm disk/fiber lasers the laser hybrid process is somewhat simplified compared to the combination GMAW and CO₂ lasers. Laser light guidance can be accomplice with an optical fiber which allows robot welding with more agility than gantry systems. The shorter wavelength also has less influence on the electrical arc and almost no plasma formation. This means that the shielding gas can be chosen according to the recommendations for pure GMAW, whilst a CO₂ laser requires shielding gas with a helium content of at least 30% according to Tani et al., 2007. A 1µm laser can be used without helium in the shielding gas, as reported by Le Guen et al., 2011 where a standard GMAW gas without helium was used. So the guideline in the choice of parameters for hybrid laser arc welding with fiber lasers is to simply select a shielding gas suitable for the GMAW process.

The next guideline concerns the torch angle and this was investigated experimentally for the preparation of this paper. A 15kW fiber laser (IPG YLR-15000) was used in combination with a standard GMAW power source (ESAB LUD-450). For geometrical considerations the GMAW torch needed to be inclined at a 25 degree angle to the laser beam (or more). Additional parameters can be found in Table 1. In laser welding the laser beam is usually aligned perpendicular to the welded surface although with fiber lasers a small angle can be used to reduce the risk of back reflections. The fiber laser manufacturer IPG recommends a 7 degree tilt from perpendicular for the laser and if this angle was used the GMA-torch would 18 degrees from vertical.

Table 1. Experimental parameters

| Parameter                  | Value                                |
|----------------------------|--------------------------------------|
| Base material              | Duplex stainless steel 2205          |
| Plate thickness            | 8mm                                  |
| Joint type                 | Square but joint (shear cut)         |
| Filler material            | 22.8.3L                              |
| Wire diameter              | 1mm                                  |
| Welding speed              | 1.8m/min                             |
| Wire feed rate             | 15m/min                              |
| Background current         | 84A                                  |
| Peak current               | 340A                                 |
| Pulse frequency            | 216Hz                                |
| Pulse time                 | 1.7ms                                |
| Arc voltage                | 35V                                  |
| Wire stick out             | 16mm                                 |
| Shielding gas              | 68%Ar, 2% CO₂, 30%He, 0.03%NO (Mison 2He) |
| Arc-laser separation       | 5.5mm (arc leading)                  |
| Laser power                | 6kW                                  |
| Focus position             | 3mm below top surface                |

Compared to the general recommendations for GMAW this is a larger torch angle than recommended; in the PA position (welding two flat horizontal sheets together) the torch should be held close to perpendicular. To achieve this for our experimental set up the laser was inclined at 25 degrees. This arrangement gives a clear reduction of spatter and a more stable arc. Fig 4 shows the spatter reduction achieved by changing the torch angle from 72 degrees pulling to 90 degrees (perpendicular) during hybrid welding of duplex stainless
steel 2205. With a vertical torch the arc becomes more symmetrical and spatter created is more often captured by the melt pool.

Fig. 4. Spatter reduction by using a vertical torch. (a) torch pulling, 18 degrees from vertical (b) vertical torch

In the case of a varying gap size there is a need to regulate the amount of filler material added to the weld. There are two ways this can be done; either the wire feed or the welding speed can be changed. If a pulsed arc is used then a change in wire feed rate also requires changes in the other parameters. An easier approach is to keep the GMAW parameters constant and adjust the welding speed to acquire the desired fill rate. When the welding speed is changed the laser power needs to be altered to attain the same penetration depth, but usually there is a rather simple relationship between welding speed, laser power and penetration depth. At higher welding speeds the penetration depth is linearly correlated to the laser power. In Fig 2 this principle is demonstrated by a practical example. The welding parameters are listed in Table 1. To increase the filling of the joint the welding speed was lowered by 22% (1.8m/min to 1.4m/min) and this was accompanied by a reduction in the laser power by 22% from 6kW to 4.66kW.

Fig. 5. Cross section of weld a) 0mm gap b) 0.5mm gap 22% lower welding speed.

Hybrid welding with 10,6 µm CO₂ laser requires a high helium content in the weld gas to avoid plasma generation in the weld zone because the plasma absorbs the laser beam. High speed video observation has revealed that a 1µm laser wavelength (Nd:YAG-, Disk-, Fiber-laser) does not affect the electrical arc as much as a 10.6µm CO₂ laser therefore standard Ar/CO₂ gas mixes can be used. For this reason the standard GMAW parameters can often be used in the hybrid process without major adjustments. Fig 6 and Fig 7 show the effect of adding 3kW laser power to a standard spray arc. In a bead on plate experiment on low alloy carbon steel, a 1.2mm Mn4Ni2CrMo wire was fed at 9m/min with an arc voltage of 27.5-33V, (creating a typical spray arc using a 2% CO₂ gas mix). The welding speed in this case was 1m/min. With the addition of a 3kW fiber laser
the arc appears slightly shorter in the high speed video and there is some disturbance of the shielding gas (not visible in still images). This disturbance is caused by the ejected vapor exiting the laser keyhole, affecting the shielding gas properties slightly, both by adding metal vapor and by mixing with oxygen from the surrounding air. This disturbance lowers the welding current by 4-7% during hybrid welding compared to pure GMAW.

![Fig. 6. Welding current as a function of applied voltage for 9m/min wirefeed 1.2mm Mn4Ni2CrMo wire](image)

In spite of these small changes to the arc welding process, the effect of the laser beam is clear; the weld is wider (due to changes in the fluid flow caused by flow around the laser evaporated keyhole) and deeper. In Fig 7 the weld appearance for 31V with and without laser is shown. The focused energy from the laser increased the penetration by 75% in this case, but the total heat input was only increased by 33%.

![Fig 7 Comparison of pure GMAW (upper) and Hybrid (lower) with same GMAW settings, (Top view, High speed image of arc and cross section for each case)](image)

4. Discussion and Conclusions

Laser-GMA welding has a potential to increase productivity compared to arc welding with less strict joint preparation than autogenous laser welding. Using a fiber guided 1μm wavelength laser the process can be implemented by a welding robot into existing production lines. With the aid of a laser the penetration or/and welding speed can be increased. There is also a potential cost saving in the reduced use of filler material.

The following guidelines will help in setting up the hybrid welding process;
Given that a 1μm laser has only a minor effect on the GMAW process, a general guideline to the choice of parameters is to follow the existing recommendations for regular GMAW.

A 1μm laser (fiber/disk/Nd:YAG) is not sensitive to the shielding gas composition, the GMAW process on the other hand is sensitive to the shielding gas mix. Therefore the choice of shielding gas should be based on the recommendations for the GMAW.

If high metal deposition is desired a spray arc should be utilized. This requires high argon content in the shielding gas, a high wire feed rate and a high arc voltage.

If low heat input is required a short arc can be used but this will produce spatter that can be a problem on some products.

Pulsed arcs can produce high quality welds with low spatter, but it is more difficult to adjust the parameters, and slightly incorrect parameters produce very poor quality welds.

Using a torch angle similar to the recommendations for pure GMAW (<15degree) will give a more stable arc and minimal spatter. This requires an inclined laser beam of slightly higher laser power to reach a given penetration depth.

When the laser is used to produce a deep penetration weld the laser power is the easiest parameter to change. At relatively high welding speed there is also a linear connection between laser power and penetration depth (keeping other parameters constant). This make it relatively easy to adjust the laser power to the desired penetration depth.

The guidelines can be summarized as:

- Chose a suitable transfer mode for the GMAW.
- Chose shielding gas according to the GMAW.
- Use the standard (perpendicular) torch angle.
- Adjust welding depth by changing laser power.

Acknowledgements

The authors acknowledge funding by the EU-Interreg IVA North project PROLAS, no.304-58-11

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