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## Laser-assisted narrow gap arc welding of an 18MND5 steel thick plate

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### Abstract

Narrow gap arc welding is a common solution for the welding of thick structures. In this study, a defocused laser beam is used to pre-melt the narrow gap walls in front of an arc-welding bath. Such a welding configuration can be referred to a hybrid welding configuration. In the present work, a particular attention is given to evaluation of the interaction between an arc plasma and a defocused laser beam. High-speed imaging of the metal transfer through arc plasma is achieved thanks to a diode laser illumination system. Electrical arc parameters are logged, synchronously, in order to perform a correlation analysis and to make a diagnosis of the interaction level between laser beam and arc plasma.

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*Keywords:* Narrow-gap, GMAW, Laser, Welding, Hybrid, 18MnD5

### 1. Introduction

Hybrid welding process is a combination of a laser beam with an electrical arc plasma. The addition of a laser beam allows increasing productivity of arc welded steel structures. Arc welding process offers the possibility to produce a weld structure with alloying elements by means of a filler wire.

The aim of such a combination is to take advantage of the gap-bridging ability of Gas Metal Arc Welding (GMAW) and the productivity associated with high speed proper to laser beam welding (LBW). At the end of seventies, first tests have been carried out with this technology [1, 2]. Despite some encouraging results, hybrid laser-GMAW technology was not fully developed. Since 2000, a reliable technology has become available [3, 4, 5, 6]. Progress is linked to an increasing reliability of laser and arc power sources. In particular, an increase of available power for laser sources and a better regulation for electrical arc sources have been at the origin of the improvement.

The distance between the arc and the laser beam has a significant influence on the synergy between these heat

sources [7, 8, 9, 10]. Experiments carried out in works [11, 12, 13, 14] showed that a synergetic effect remains even under a condition of maximal distance between heat sources. Interaction between laser and arc exists down to a distance of 5 to 8 mm. The presence of a laser beam within the arc zone decreases the electrical conductivity of the arc, inducing undesirable effects such as arc instabilities, or can provoke an irregular metal drop transfer. According to [15], the distance between the laser beam and electric arc has to be sufficient in order to maintain a suitable current density distribution in the arc center to avoid irregularities during the metal transfer. According to [16, 17], it is also possible to get a negative effect due to sources closeness, *i.e.* the loss of volatile alloying elements. The authors of [18, 19, 20, 21, 22] observed a strong interaction with the plasma resulting in a weld-bead humping or periodic bath fall. Authors of [23, 24, 25, 26, 27] suggested that modification of the distance from 2 to 12 mm does not affect significantly the shape of the molten pool created during hybrid welding.

The advantages of hybrid welding essentially come from the synergy between the associated processes. Electrical arc

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and laser deposited energies promote a stable process [28, 29], and enhance the productivity and the quality of weld seams. Some tests carried out on a steel plate show that the use of a CO<sub>2</sub> laser source allows to stabilize the electric arc thanks to the interaction with a laser-induced plasma. It is possible to increase per 2 to 10 times the welding speed depending on the considered material thicknesses. Effect of the energy contribution of each process is the most studied point [30, 31]. In addition to productivity gains, this process is attractive because of lower strains and improved mechanical characteristics of the joint, absence of defects and optimal corrosion resistance.

In the present work, a narrow gap arc welding is proposed as a solution for the welding of very thick structures such as pipe junctions for nuclear industry. Two main issues have been encountered in such a condition: a lack of fusion of the walls and a limited filler metal deposition rate. To overcome both issues, a defocused continuous laser beam was used to pre-melt the wall in front of the arc welding bath. In this condition, a particular attention is given to the evaluation of interaction between the arc plasma and unfocused laser beam. In order to estimate the reciprocal influence, instrumentation methods have been used in order to evaluate this interaction. High-speed imaging of the metal transfer in arc plasma was performed using laser illumination system CAVITAR®. Electrical arc parameters have been logged, synchronously, in order to perform a correlation analysis and to make a diagnosis of the interaction level between the laser beam and the arc plasma in the case of welding of a thick sheet made of 18MND5 steel grade.

## 2. Experimental Procedures

### 2.1. Welding

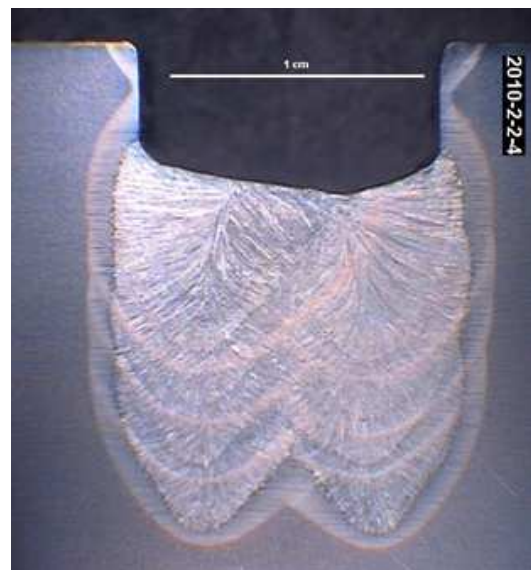
Hybrid laser-GMA equipment consisted of a Fronius hybrid welding torch and a Precitec optical head. GMA welding source was a Fronius Transpuls Synergic 5000 with a maximum intensity of 500 A. Laser source was a Trumpf Yb:YAG Trudisk 6002 with 6000 W maximal continuous power. The laser beam was injected into a fibre with a core diameter close to 200 µm. The laser head was comprised of two plano-convex lenses with 200 mm focal length. This optical set-up allowed focusing the laser beam in a 0.2 mm diameter spot.

The weld specimens in bainitic steel 18MND5 had the dimensions 300 mm × 90 mm × 90 mm and contained a tooled U-chamfer with dimensions 50 mm × 10 mm. The filler wire was UNION I MoNi from Thyssenkrupp with 1.2 mm diameter. The laser beam spot was placed in front of the gas metal arc and positively defocused with regard to the bottom part of the U-chamfer. The laser spot size was approximately 6 mm diameter and a melt pool was created due to interaction between the laser beam and the workpiece. The shielding gas was a mixture of Ar with 18 % CO<sub>2</sub> at a 20 L min<sup>-1</sup> flow rate. The main welding conditions are given in Table 1. The sample surface has been etched with a 3% Nital solution for a couple of seconds. A cross section metallographic observation is given in Fig. 1.

Table 1. Hybrid welding parameters.

Welding position	flat
GMA Welding mode	DCEP, pulsed
Stick-out distance	18 mm
Welding speed	0.7 – 1 m/min
Wire feed speed	12 m/min
Laser Power	1 - 6 kW

An apparatus has been especially designed in order to perform two weld passes, side by side, as presented in Fig.1. A series of 16 tests has been carried out in the frame of this work. A test consisted in producing 5 layers in a narrow gap, i.e. 10 weld passes. In order to estimate the influence of processing parameters such as welding speed and laser power, a 16 tests Design Of Experiment (DOE) has been carried out. Other parameters such as the distance from stick out end till narrow gap wall (L2), the distance from stick out end till laser axis (L3) and the distance from laser axis till gap centreline (L1) have been considered in order to take into account both tip holder tilt and the influence of distance from the laser axis.



The series of tests are presented in Table 2.

Fig. 1. Cross-section optical macrograph of a multi-pass weld consisting in 4 layers with 2 passes per layer. For each layer, the first pass has been made on the right hand-side of the narrow gap.

### 2.2. High-speed imaging

A Phantom V9.1 camera was used to record the welding experiments. The duration of single welding operation was less than 30 s, for a 300 mm length assembly. An illumination diode laser system CAVITAR® was used in order to enhance the visibility within the dazzle arc plasma. This system contains a pulsed diode laser with 500 W peak power [32]. The sensor exposure and the laser pulse were synchronized. The camera exposure time was set to 5 µs and the laser pulse width was limited to 4 µs. The high speed camera was placed at a distance of 0.5 m, with a normal view onto the wire.

Table 2. Design of experiment with 16 tests.

Test reference	Welding speed (m/min)	Laser power (kW)	L1 (mm)	L2 (mm)	L3 (mm)
A	0.8	6	4	2.6	3
B	0.7	6	5	1.6	4.5
C	0.9	6	3	3.6	1.5
D	1	6	2	4.6	0
E	0.8	4	5	3.6	0
F	0.7	4	4	4.6	1.5
G	0.9	4	2	2.6	4.5
H	1	4	3	1.6	3
I	0.8	2	2	1.6	1.5
J	0.7	2	3	2.6	0
K	0.9	2	5	4.6	3
L	1	2	4	3.6	4.5
M	0.8	1	3	4.6	4.5
N	0.7	1	2	3.6	3
O	0.9	1	4	1.6	0
P	1	1	5	2.6	1.5

The camera unit was mounted on a KUKA robot along with GMAW torch. A 105 mm focal length objective optics was combined with a 810 nm narrow band filter, chosen with regard to the laser diode wavelength. Focus of the camera was fixed and had 9.5 mm depth of field and 56 mm × 77 mm field of view. The synchronization at 60 frames per second (fps) was used in order to record the whole welding operation. The limitation of the frame rate was due to the lighting Cavitar system, whose laser is not cooled, so that it can work with a duty cycle of 0.03 % only to record a welding scene of duration more than 10 s. According to the chosen pulse length (5 μs), the 60 fps is the maximum rate reachable with the present system. For the metal transfer viewing, a rate >300 fps must be achieved to control GMAW due to droplet frequency detachment. Therefore, it is necessary to wait that Laser diode cool and, thus, total duration of high speed film cannot exceed 10 s.

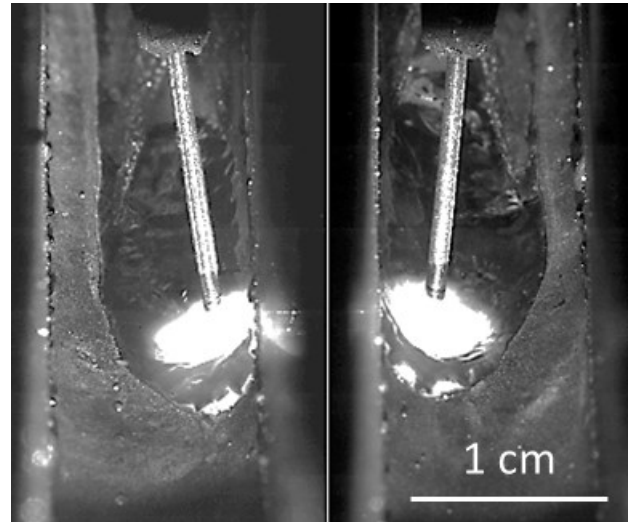


Fig. 2. Welding observations for both tip holder tilts.

An image processing algorithm was developed in MATLAB programming language. This algorithm aimed to compute the wire length and to detect path of the melt pool automatically. Details about the development of the program can be found in a previous publication [33].

### 2.3. Voltage and current acquisition

For the measurement of voltage, a differential probe has been used. The probe has been connected to the welding circuit. The positioning of the measurement was made to be as closest as possible to the arc. A connector was attached to the drive roller of the wire electrode, the other one was attached to the mass of the welding source. In order to measure the welding current, a Hall Effect amperometric clamp was used. The clamp was fixed to the mass cable. Acquisition of the voltage and current signals has been programmed on a FPGA Compaq RIO controller with the LabView software. The sampling frequency was set to 40k samples per second and per channel.

In addition to voltage and current signals, the control signal of the illumination system corresponding to exposure camera opening was acquired with the same controller in order to get a perfect synchronisation between signals and image acquisition. A 1 A/mV class was chosen for the amperometric clamp allowing an incertitude below 1.5 % and a 1/20 rate was chosen for the differential probe allowing and incertitude below 1.5%.

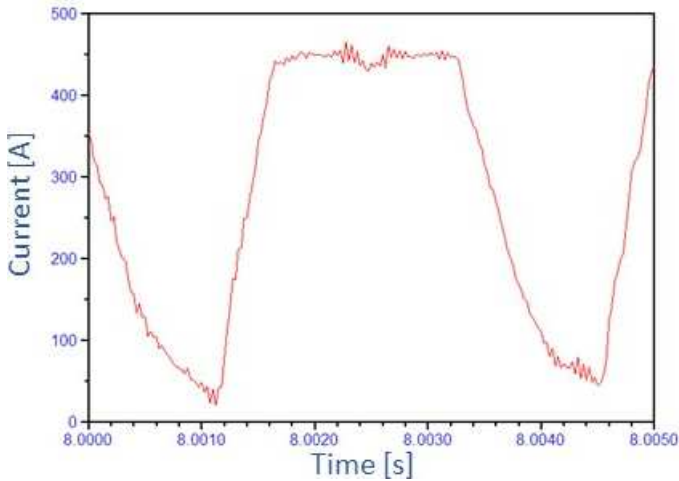


Fig. 3. Welding current recording during a short period.

### 3. Results and discussion

The voltage setting and/or desired welding current are not necessary achieved during the test. On one hand, different events may occur during the test, which may alter the voltage and/or welding current, e.g. a short-circuit, a premature deterioration of the nozzle, a blowing magnetic oscillation of the meniscus and a change in the metal transfer mode. Such an event tends to induce an inadequate control by the generator, i.e. setting it to reach an operating point that cannot be reached. On the other hand, knowledge of the welding current and voltage gives the possibility to estimate the power dissipated during the welding.

The combination of laser welding and arc welding causes a significant complexity with respect to a single source welding process. Therefore, the study of the process requires a large number of tests in order to evaluate the influence of each parameter. The "Design of experiment" (DOE) method has been used in order to establish an experimental strategy that minimizes the number of tests required for a given number of parameters to be studied. The five parameters selected to program a 16 tests experimental design (Table 2) were: laser power (kW), welding speed (m/min) and L1, L2, L3 stick-out positioning parameters (mm). For each parameter, four levels have been chosen. DOE analysis allowed to establish the parameters hierarchy considering their influence on the interaction level between laser beam and arc.

#### 3.1. Transfer mode

Fig.4 shows a metal transfer mode sequence. One image is recorded each 250  $\mu$ s. The whole sequence corresponds to one current pulsation period. The sequence shows that a liquid vein was established. This transfer mode can be identified as a streaming spray free flight transfer according to Scotti classification [34]. For this kind of transfer mode, electromagnetic forces operating in the arc plasma govern main effect. As observed in Fig. 4, electromagnetic force induces a stretching of the molten metal liquid vein from end of filler wire till the molten pool. The pulsed welding mode is usually reserved for a globular transfer mode in order to

facilitate the detachment of the drop and to avoid metal projection.

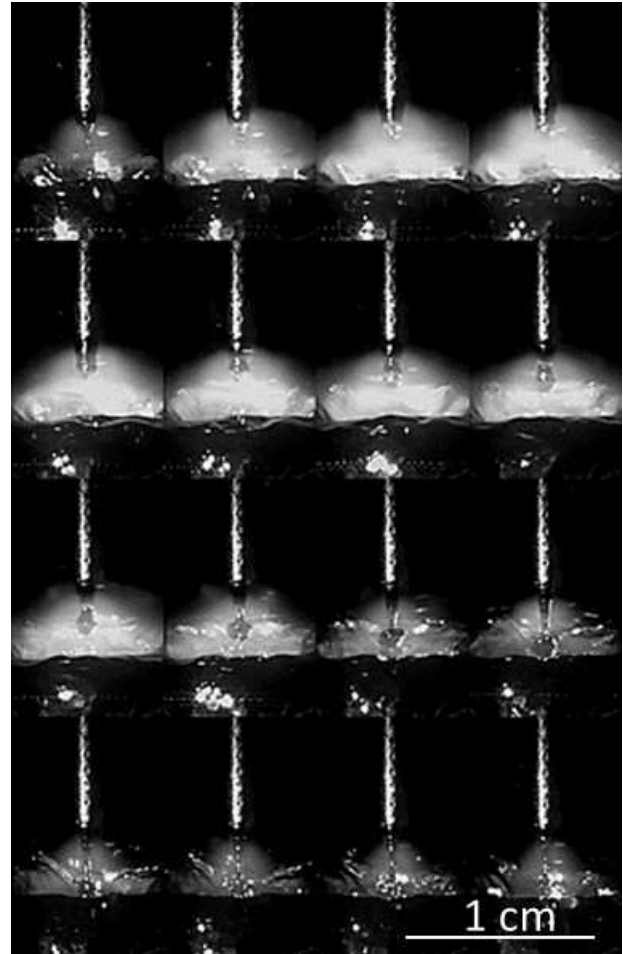


Fig. 4. The view of transfer mode during one current pulsation period (4 ms).

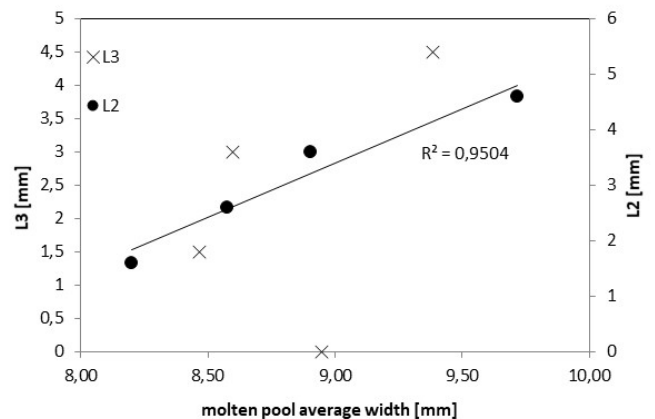


Fig. 5. Molten pool width as a function of L2 and L3 parameters.

The first image on Fig.4 corresponds to the moment when the welding current level is at its lowest point, i.e.  $I_{\text{background}} = 140$  A, a small liquid vein is still visible at the end of the wire. The next image is taken at an intensity value of 340 A ( $140 + 0.25 \cdot 800 = 340$ ), then in the third image, the current has reached its high value, i.e. 440 A. During next 7 images, the current is at its maximum value (440 A), a spherical drop is formed. From 10th image, the current begins to decline

towards  $I_{\text{background}}$ , the drop begins to fall and stretches a liquid vein. Due to the existence of a liquid metal vein, arc is guided through it and prevents from arcing higher up the gap wall.

### 3.2. Molten pool width

Fig.5 shows influence of positioning parameters L2, L3 on the measured width of the molten pool. According to DOE analysis, L1 parameter has no significant influence on the molten pool probably due to laser beam defocusing. Laser beam irradiates a large surface at the bottom of gap hence a 3 mm positioning variation has no significant influence on the molten pool dynamics. According to Fig. 5, L2 has a significant influence on the molten pool dynamics. L2 represents the distance between the stick out end and gap wall. Shorter L2 distance induces a smaller molten pool.

Fig. 6 shows influence of laser power and welding speed on the measured width of the molten pool. Laser power increase induces a larger molten pool as welding speed decrease induces a larger molten pool. These results were expected and, thus validated the DOE approach to assess laser-arc interaction.

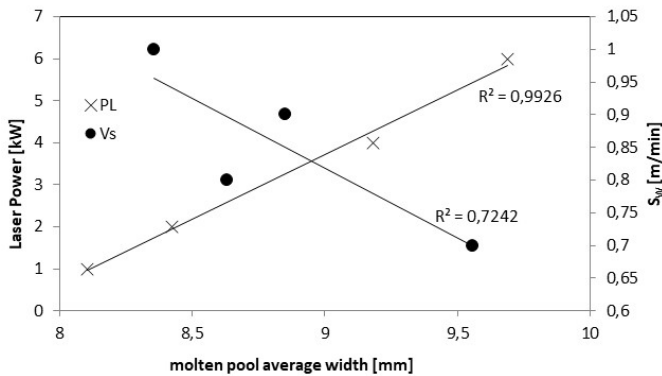


Fig. 6. Molten pool width as a function of laser power and welding speed parameters.

### 3.3. Arc height

Arc height is a key factor in GMA welding. Higher is the arc height, higher is the energy dissipated in the arc plasma. In process-stick-out-distance measurements show arc height variation during welding. A shorter stick-out induces a higher arc height.

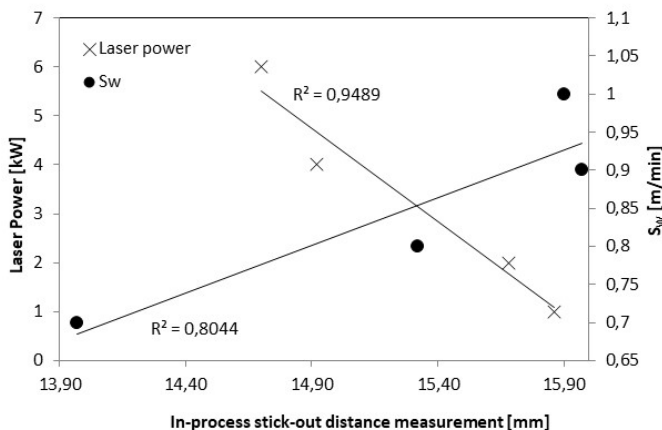


Fig. 7. In-process stick out distance in function of laser power and welding speed parameters.

Fig. 7 illustrates the arc-laser interaction due to a high correlation level between laser power and arc height. Laser power decrease induces stick-out increase and thus arc height decrease. Metal vaporization induced by laser-metal interaction enhances the arc plasma electrical conductivity due to ionization potential decrease. As the arc source generator operates in CV mode and in order to compensate the decrease of arc plasma electrical resistance, the arc source generator automatically increases the electrical current and voltage inducing arc height increase. Welding speed increase induces arc height decrease.

## 4. Conclusion

Laser-arc interaction in thick metal welding conditions has been evaluated for the filling of 18 MND5 narrow-gap plates.

High speed visualization of metal transfer mode in arc plasma allowed determining the nature of the metal transfer mode, *i.e.* a streaming spray free flight transfer mode..

Design of Experiments method has been applied to study the influence of parameters on the molten pool and arc plasma dynamics. Laser beam-leading arc affects the GMA penetration. This observation can be explained by the significant influence of the Laser power level on arc height. For the maximal Laser power level, the arc height increase more than one millimeter. This increase induces a slight limitation of the GMA molten pool penetration. A way to overcome this issue is to reduce the welding speed from 1 to 0.7 m/min.

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