Parameter Influence in CO$_2$-laser/MIG Hybrid Welding

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Abstract

Hybrid welding, as the combination of laser beam and arc welding, is an innovative joining technology that has many advantages compared to the single processes. With the hybrid process joint gap can overbridges and hence additional and costly joint preparation can be avoided. Also the weld metal composition can be controlled by the filler wire. The laser/MIG hybrid welding process is up to 50% faster compared to autogenous laser welding. This paper presents results from an ongoing investigation into laser/MIG hybrid welding of 6 mm thick, high strength steels.

The results include welding parameters for a 6 kW CO$_2$-laser combined with conventional pulsed MIG/MAG equipment. The influences of the basic MIG parameters as the voltage, pulsing time and pulsing frequency on the welding result were investigated, where especially the geometry of the weld seams as well as undercut formation is considered. The influence of the welding result by adjusting the lateral position of laser beam and MIG arc was also examined as well as suitable parameter setup for different joint configurations like V- and butt joints. In the case of butt joint, the maximum bridgeable gap width was determined.

It was found that the MIG power has a major influence at the weld geometry. A high MIG power leads to increased undercut size and increased porosity. The variation of the lateral displacement of the MIG arc was shown to be tolerant. It can be stated that a variation of the lateral displacement of 1.5 mm gave still acceptable welding results. It was possible to weld butt joints with a gap of up to 2.0 mm and a maximum in welding speed was reached with a gap of 1.0 mm.

Keywords: laser welding, laser MIG hybrid welding, butt joints, fillet joints.

1 Introduction

High power laser beam welding is today an industrial joining process used in competition with conventional arc-welding processes. Both types of processes have their own characteristics, advantages and disadvantages. The main advantages of the laser welding process are low heat input and high welding speed, typically producing a narrow and deep weld seam, which minimizes thermal distortion. The narrow weld seam leads to a low gap bridging capability and requires an exact joint preparation and clamping.

The MIG welding processes gives a high heat input producing a wide and shallow weld at relatively low welding speeds. However, the arc welding processes are very efficient regarding the addition of filler material and therefore preferred when larger joint gaps are
present. Also the weld metal can be influenced metallurgical by the choice of the electrode type and composition.

In order to combine the advantages of the two processes the Laser Hybrid Welding process was developed by combining the laser beam welding and arc welding in one single process. This combination allows many advantages like a good gap bridging ability, high welding speed and improved process stability and the fundamentals of this process have been presented in a number of papers [1-6]. The positive synergy effect of the combination of laser and arc is because of the ignition resistance in the evaporated material is reduced and the arc can be ignited more easily. Therefore the stability of the arc is improved by the laser-induced plasma, which attracts the arc [7,13]. The attraction of the arc to the laser induced plasma is also shown in this work.

The number of applications of this new welding process in the industry is increasing. The hybrid welding is used today in the shipbuilding industry, the automotive industry and in the tank construction [7-12]. A disadvantage with the hybrid process is the great number of process parameters [14].

The aim of this project was to combine a CO2-laser and a MIG- source and evaluate the influence of essential MIG parameters on the welding result. Parameters investigated were pulsing time and frequency, the voltage and the wire stickout length and the lateral position of the MIG-torch. The optimal parameter setup was also determined for butt joints with a defined joint gap as well as the maximum gap possible to overbridge.

2 Experimental setup

2.1 Materials used

The material welded was a 6 mm thick high strength carbon steel Domex¹ 420 (DX420). The hot-rolled DX 420 is a high-strength cold forming steel with a minimum yield point of 420 N/mm². The excellent weldability of this material is based on the low content of carbon, sulphur and phosphorus, see Table 2.1. The few alloying elements of the steel reduce the danger of hot cracks in the weld seam or hydrogen embrittlement in the heat-affected zone. Typical applications for this coldforming steel are for example in truck building, bridge building or container frame structures. The filler wire in the MIG unit is a 1mm thick OK Autrod 12.51². This wire is recommended for the welding of Domex 420 from the manufacturer. It is a universally usable wire electrode for welding of general structural steels, grain-refined construction steels and shipbuilding steels. Table 2.1 give an overview of the chemical composition and Table 2.2 the mechanical properties of the Domex steel and the filler material.

Table 2.1: Chemical composition of base and filler material

<table>
<thead>
<tr>
<th>Material</th>
<th>C %</th>
<th>Si %</th>
<th>Mn %</th>
<th>P %</th>
<th>S %</th>
<th>N %</th>
<th>Cr %</th>
<th>Ni %</th>
<th>Cu %</th>
<th>Al %</th>
<th>Nb %</th>
<th>Ti %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domex 420</td>
<td>0.067</td>
<td>0.03</td>
<td>1.11</td>
<td>0.006</td>
<td>0.002</td>
<td>0.006</td>
<td>0.03</td>
<td>0.06</td>
<td>0.02</td>
<td>0.04</td>
<td>0.034</td>
<td>0.002</td>
</tr>
<tr>
<td>Autrod 12.51</td>
<td>0.08</td>
<td>1.5</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

¹ Domex is a registered trademark of SSAB Tunnplåt AB, Sweden
² OK Autrod is a registered trademark of ESAB AB, Sweden
Table 2.2 Mechanical properties of base and filler material

<table>
<thead>
<tr>
<th>Material</th>
<th>Min. yield point $R_{e,t}$ [N/mm$^2$]</th>
<th>Tensile strength $R_{m}$ [N/mm$^2$]</th>
<th>Break elongation $A_5$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domex 420</td>
<td>449</td>
<td>533</td>
<td>28</td>
</tr>
<tr>
<td>Autrod 12.51</td>
<td>470</td>
<td>560</td>
<td>26</td>
</tr>
</tbody>
</table>

The chemical composition of the materials and wire used are similar. Only the silicon content of the filler wire material is considerably higher. High silicon contents increase the viscosity of the molten metal through reduction of the surface tension.

2.2 Equipment used

The investigations for the CO$_2$-laser-MIG hybrid process were carried out with a Rofin Sinar RS6000 CO$_2$-laser with a maximum output power of 6 kW and a power at the workpiece of 5 kW. The focussing mirror of the CO$_2$ laser had a focal length of 275 mm and was protected against spatter by a horizontally mounted cross jet nozzle, see Figure 2.1. The MIG welding unit was an ESAB Aristo LUD 450W with a variable current of 15 - 450 A. The wire feed unit allows wire feed rates from 1.5 – 25 m/min. A standard MIG torch was mounted to the hybrid welding head in an inclination of 35°, see Figure 2.1

![Laser – MIG experimental set up](image)

Figure 2.1: Illustration of the Laser – MIG experimental set up

All the welds were done with the laser beam leading the arc as shown in Figure 2.1. The process gas, a mixture of argon, helium and CO$_2$, was supplied through the MIG torch nozzle.

2.3 Basic parameter study

In the first experiments the influence of different basic parameters on the welding result was investigated. All the welds were carried out as a 7° V-joint with milled edges, as shown in Figure 2.2a
First, the stickout length of the filler wire and the lateral position of the arc related to the laser were varied. The MIG torch was laterally moved out of the centre of the joint while the laser beam still remains in the joint as is shown in Figure 2.3a. Also the lateral position of both the arc and the laser together was changed, see Figure 2.3b.

The basic MIG parameter like arc voltage, pulsing time and pulsing frequency were changed and their influence on the welds was examined. Furthermore the settings of the optimal parameters for the best welding result were examined. Table 2.3 shows the variable parameters in the basic parameter study.

**Table 2.3: Variable parameters for the welding of V-joints in the basic parameter study**

<table>
<thead>
<tr>
<th>Geometric parameters</th>
<th>MIG parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral position of arc: 0...2 mm</td>
<td>Pulsing time: 2...3 ms</td>
</tr>
<tr>
<td>Lateral position of arc + laser: 0...1 mm</td>
<td>Pulsing frequency: 120...180 Hz</td>
</tr>
<tr>
<td></td>
<td>Voltage: 30...50 V</td>
</tr>
</tbody>
</table>
Also butt joints with milled joint edges according to Figure 2.2b, were welded using optimal welding parameters previously found. In the first experiments, welding was carried out without a gap between the plates. In further experiments a gap (g) was introduced and finally the maximum permissible gap width was determined as shown in Figure 2.2c.

## 3 Results

### 3.2 Influence of the pulsing time and pulsing frequency on V-joints

Since the MIG unit is used in pulsed mode, the pulsing time and pulsing frequency become additional variable parameters in the hybrid welding process. All the welds were done with a V-joint shown in Figure 2.2a. The current was periodically modulated between a low background current of 60A and the peak current of 332A, which were constant parameters that and not changed during the experiments. The pulsing time $\tau_H$ determines the duration of the peak current and with that the droplet size and the arc cone width. The pulsing frequency ($f$) influences the duration of the background current and therefore the average current $I_m$ and the overall heat input.

During the experiments, the investigations of the MIG pulsing time and pulsing frequency were carried out with all other parameters constant (stickout =21 mm, MIG voltage= 32 V) The results can be arranged in a diagonal symmetric matrix as shown in Figure 3.1. The pulsing time was varied from 2 to 3 ms, the pulsing frequency from 120 to 180 Hz. The pulse ratio $\varepsilon$ is introduced as the ratio between pulsing time ($\tau_P$) and the total time ($\tau$) of one duty cycle: $\varepsilon = \frac{\tau_P}{\tau}$

$$
\begin{array}{|c|c|c|}
\hline
\tau_P = 2 \text{ ms} & \tau_P = 2.5 \text{ ms} & \tau_P = 3 \text{ ms} \\
\hline
f = 120 \text{ Hz} & \tau = 8.3 \text{ ms} & \tau_P = 3.7 \text{ kW}; \varepsilon = 24\% \\
\hline
f = 150 \text{ Hz} & \tau = 6.7 \text{ ms} & \tau_P = 4.3 \text{ kW}; \varepsilon = 30\% \\
\hline
f = 180 \text{ Hz} & \tau = 5.6 \text{ ms} & \tau_P = 5.1 \text{ kW}; \varepsilon = 36\% \\
\hline
\end{array}
$$

$P_{MIG}$: MIG power.

Figure 3.1: Investigations of the pulsing time and frequency, $v_{weld} = 1.8 \text{ m/min}, U_{MIG} = 32 \text{ V}$
In this case the pulse ratio varies between 24 % and 54 %. With increasing pulse ratio the MIG power also increases. From Figure 3.2 it can be seen that the result matrix is symmetrical by the diagonal from the upper left to the lower right corner. This shows that the MIG power determines in the first place the geometry of the weld. The most favourable weld geometries can be found in the upper left corner of the result matrix i.e. low values of pulsing time, pulsing frequency and hence a low MIG power. Here the weld is characterized by a narrow HAZ, flat weld seam and a small undercut. With increasing values of pulsing time and pulsing frequency and hence increased MIG power the process becomes increasingly unstable, which leads to uneven weld seams with blowholes and a spatter.

3.2 Influence of the MIG voltage on V-joints

In additional experiments the influence of the adjustable MIG voltage on the welding result was examined by welding a V-joint shown in Figure 2.2a. The MIG voltage was varied from 30 to 50 V and the results are presented in Figure 3.2. As in the earlier cases also the MIG power was the decisive value that determines weld geometry and quality. Like in the earlier experiments, also the undercut and the width of the HAZ increase with increasing MIG power.

\[ \text{UMIG = 30 V, PMIG = 3.1 kW} \]
\[ \text{UMIG = 34 V, PMIG = 3.4 kW} \]
\[ \text{UMIG = 38 V, PMIG = 3.9 kW} \]
\[ \text{UMIG = 40 V, PMIG = 3.9 kW} \]
\[ \text{UMIG = 42 V, PMIG = 4.3 kW} \]
\[ \text{UMIG = 44 V, PMIG = 4.5 kW} \]
\[ \text{UMIG = 46 V, PMIG = 4.8 kW} \]
\[ \text{UMIG = 50 V, PMIG = 5.2 kW} \]

Figure 3.2: Micrographs of the weld seams with different MIG voltage, V-joint

\( v_{\text{weld}} = 1.8 \text{ m/min}, \; v_{\text{wire}} = 8 \text{ m/min}, \; \tau_p = 2 \text{ ms}, \; f = 120 \text{ Hz}, \; U_{\text{MIG}}=32 \text{ V} \)

To confirm the connection between the MIG power and the weld geometry the geometries of all welds were measured and presented as a function of the MIG power, see Figure 3.3.

\[ \text{Width of HAZ and the weld seam depending on the MIG power} \]
\[ \text{Depth of undercut as a function of the MIG power} \]

Figure 3.3. a. Width of the HAZ and the weld seam depending on the MIG power

b. Depth of undercut as a function of the MIG power
It is seen that both the width of the HAZ and the weld seam is increasing, as well as the depth of the undercut with increasing MIG power.

### 3.3 Influence of the lateral displacement on V-joints

In the first case, the MIG torch was displaced from the joint centre laterally up to 2 mm while the laser beam was kept in position in the centre of join. The results are shown in Figure 3.4,

![Figure 3.4: Micrographs of weld seams with a lateral displacement (b) of the arc V-joint, \( v_{\text{weld}} = 1.8 \) m/min, \( v_{\text{wire}} = 8 \) m/min, \( U_{\text{MIG}} = 32 \) V](image)

With increasing lateral displacement of the MIG torch the welds become more asymmetrical but up to a value of 1.5 mm the welds are still acceptable. When a lateral displacement is 2 mm, the distance between laser beam and arc has been too large. In this case the MIG weld seam lies completely beside the gap and two separate processes are developed. This is the case at the welding start and welding occurs only through the laser beam. During the welding process the arc is attracted by the laser beam so that the typical hybrid weld forms.

If both the MIG arc and the laser beam are moved out of position, the tolerance is considerably smaller. With 0.5 mm displacement an acceptable weld can be achieved, but with 1.0 mm displacement, the entire weld root is beside the joint, see Figure 3.5.

![Figure 3.5: Micrographs of the weld seams welded with a lateral displacement (b) of the arc and laser beam up to 1 mm, \( v_{\text{weld}} = 1.8 \) m/min, \( v_{\text{wire}} = 8 \) m/min](image)

The weld geometry does not change considerably in all the cases. At the root side where the laser process is the predominant process the displacement of more than 0.5 mm results in a root defect of the joint and consequently the welding result is not approved.

### 3.4 Weld cross section geometry of the V-joint

It is of interesting to examine how the molten material behaves and where it deposits, since material loss can be found in the fields of the undercuts and material accumulation in the top
weld seam and on the root side. The mass input through the filler wire and the real value, which can be measured in the micrographs, has been compared. One would expect that these two values should be equal since the welding speed and the wire rate was kept constant. The theoretical area of the additional material can be calculated by the following equation

\[ A_{\text{theo}} = \frac{V_{\text{wire}}}{v_{\text{weld}}} \]  

where \( V_{\text{wire}} \) is the volume flow of filler wire material in mm\(^3\)/s.

At a constant welding speed of 1.8 m/min the theoretical area (\( A_{\text{theo}} \)) can be calculated to 3.5 mm\(^2\). The real area A was measured in each micrograph and plotted as a function of the MIG power as shown in Figure 3.6.

![Figure 3.6: Measured area of additional material as a function of the MIG power](image)

It can be seen that the area decreases tendentially with higher MIG power and that the measured area of additional material exceeds the theoretical value of the material input (the horizontal line in the diagram).

### 3.5 Welding of butt joints with varying gap sizes

For butt joints with no gap, it was found that the maximum welding speed was 1.4 m/min compared to 1.8 m/min for the V-joint as shown in Figures 3.1-3.5. Different values of gap width from 0.5 mm up to 2.0 mm were also investigated, see Figure 3.7b-e.

![Figure 3.7: Micrographs of butt welds with different gap sizes](image)
The joint without gap shows no undercut but the joints with a gap shows varying sizes of undercuts. This is due to increased MIG power with increasing gap and hence the size of the undercut and the HAZ is increased as previously shown.

The relationship between necessary wire speed and gap width is shown in Figure 3.8. The welding speed cannot be increased linearly. At high speed, a large amount of filler wire has to be molten to fill the gap. This takes more time and requires lower process rates and the speed has to be reduced with wider gaps. As can be seen in Figure 3.8, a maximum welding speed of 1.6 m/min is reached for a gap width of 1.0 mm.

![Figure 3.8: Welding and wire speed as a function of the gap width](image)

**3.6 Hardness test**

The hardness value of the base material was about 170 HV and the hardness in the weld metal varied from nearly 240 HV to 320 HV, see figure 3.9a.

![Figure 3.9: a. Hardness distribution in the weld b. Maximum hardness as a function of MIG power](image)

The maximum hardness is achieved in the molten material exactly in the weld middle and the results in Figure 3.9b shows a clear trend, that the hardness is decreasing with higher MIG power.
4 Discussion

At a lateral displacement of the MIG torch up to 1.5 mm, the welds are still acceptable but they become more asymmetric. With a lateral displacement of 2 mm, two separate processes are developing and the MIG weld seam lies completely beside the gap. A few seconds after the welding start, the arc is attracted by the laser beam and the hybrid welding process initiates, which gives an acceptable weld. This is however more uncertain because the process alternates between a hybrid process and two separate processes. Anyway a permitted displacement of 1.5 mm must be sufficient for most practical applications.

One remarkable result is shown in Figure 3.6, where the measured area of additional material is plotted against the MIG power. Most of the measured values are higher than the expected theoretical value. This would mean that more material was found than was added by the filler wire. But this phenomenon is generally observed in the case of autogenous laser welding, where a reinforcement of the top and root side of the weld can be found. One reason for that is a volume change of 2.5% through the phase transformation of the the weld metal to martensite. However, the volume change of the joint cannot be sufficiently explained only with this fact. It can also be explained by a shrinking or bending of the workpieces due to the heat input.

Introducing a gap, the filler wire rate has to be increased. The welding speed can also be increased because the gap simplifies the penetration. This is true only up to a gap size of about 1 mm, when a maximum welding speed of 1.6 m/min is reached. Extrapolating the graphs of the welding speed in Figure 3.8 up to a theoretical gap width of 2.5 mm the speed would be below 0.4 m/min. Such slow welding speed is not of practical interest. Furthermore such big gaps are not usual in practical applications.

5 Conclusions

• It has been found that the MIG power has a major influence at the weld geometry. The MIG power is mainly controlled by pulsing frequency, pulsing time and voltage. A high MIG power leads to increased undercut, more porosity and increased size of the HAZ.

• The tolerance window for a lateral displacement of the MIG arc is shown to be rather large. A lateral displacement of only the MIG arc 1.5 mm from the centre of the joint gives still acceptable results, but if both the arc and the laser beam are displaced laterally, the acceptable tolerance is reduced to 0.5 mm.

• It has been found that a value of the MIG power slightly below the laser power leads to the best results.

• Butt joints with small gaps require lower welding and wire speed compared to the V-joint joints. Maximum welding speed is reached with a gap of 1 mm. Larger gaps lead to a decreased speed. It is possible to weld a gap of 2.0 mm for 6 mm thick plates.

6 Acknowledgement

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7 References