COMPARISONS BETWEEN DIFFERENT ARC WELDING TECHNOLOGIES FOR TITANIUM EXHAUST SYSTEMS MANUFACTURING

Dr. Eng. Silvia Gaiani
The use of titanium alloys for exhaust systems manufacturing in automotive industry is constantly increasing.

These advanced alloys show excellent properties for their target application:
- Good strength
- Low density
- Oxidation resistance @ high T
- Weldability
Weldability of titanium and its alloys is critical characteristic. Consequently, there are operative parameters like adequate gas shielding, correct arc length and welding speed which have to be kept under control.

In order to increase productivity and decrease the impact of heating in the proximity of welded joints, different welding technologies have been analyzed and compared:

- **Gas Tungsten Arc Welding (GTAW or TIG)**
- **Cold Metal Transfer (CMT)**
- **Gas Metal Arc Welding (GMAW or MIG)**
- **Hybrid Laser Arc Welding (HLAW)**

For better understanding which can be the benefits or the limits of every single welding technique, several specimens of overlapped joints have been welded, inspected and compared in terms of:

- Geometry
- Penetration
- Hardness profile
- Visual appearance
SUMMARY

PART I Overview of the used welding processes
- GTAW
- GMAW – CMT (cold metal transfer)
- GMAW – Pulsed arc mode
- HLAW

PART II Experimental procedure
- Raw material & type of welding joint
- Automatic GTAW welding trial “Status Quo”
- CMT welding trials and results
- GMAW welding trials and results
- HLAW welding trials and results

PART III GMAW Synergic line development
- Improvement of existing synergic lines
- Creation of a synergic line dedicated to Timetal XT alloy
- Comparison between the three different algorithms

PART IV Thermal input determination

PART V Comments and conclusions
PART I

GTAW (Gas Tungsten Arc Welding)

In automotive industry, GTAW is by far the most popular technique applied for joining titanium components, both in manual or semiautomatic conditions. In order to prevent contamination of the molten metal, an inert gas shield flowing around the torch axis is used (mainly Ar); it is also necessary to provide a back shielding flux, to protect the rear part of the weld zone.

Advantages

- The extreme versatility of the process makes it applicable to a wide variety of thicknesses and welding positions;
- Ability to control several process variables;
- Possibility to use all the materials of industrial interest;
- Good aesthetic appearance of the joint
GMAW - CMT (Cold Metal Transfer)

Arcing period: the filler metal is moved towards the pool

Filler metal dips into the pool and arc is extinguished

The rearward movement of the wire assists droplet detach

The wire motion is reversed and cycle starts again

Advantages

- Reduced thermal input thanks to the short arcing period
- Spatter free metal transfer
- The movement of the wire is digitally controlled
- Higher welding speed (~ 3 times normal MIG)
- Good weld appearance
Gas Metal Arc Welding – Pulsed arc mode

GMAW is one of the most used welding technologies applied in the automotive industry. The quality of the weld is influenced by:

- The development of dedicated synergic lines for specific alloys
- The type of gas shielding
- The Secondary gas shielding protection
- The arc length
- The pulse parameters

Advantages

- Possibility of treating almost all metallic materials of industrial interest;
- The presence of a continuous supply of material allows high productivity and limited stop machine in case of automatic welding;
- Deposition rates and processing speed much higher than those characteristic of TIG;
- Thanks to the many modes of transfer of the arc, the length of the weld thickness is extremely high, ranging from 0.5 mm to over 15 mm.
HLAW (Hybrid Laser Arc Welding)

A GMAW technology is added in tandem with a LASER, to create a new welding alternative which combines:

- Deep weld penetration
- Superior gap tolerance
- Low heat input
- Power efficiency

**Advantages**

- Modest amount of filler metal
- Reduction of heat transfer into the part
- Limitation of distortions and microstructural modifications
- High finished part's metallurgical stability
- Creation of welds with great strength and low brittleness thanks to the slower cooling rates of the GMAW
- Combining two different power sources means decreasing the nominal power of the laser source; this aspect brings a cost reduction compared to laser welding
EXPERIMENTAL PROCEDURE

Raw material & type of welding joint

The base material and also the welding wire used for realizing all the welding trials is the α-Ti alloy Timetal® Exhaust XT produced by Timet.

The plates were clamped in position using a welding jig in aluminum. Near the welding area two copper inserts are placed for increasing the heat exchange. A simple circuit for providing back shielding flux with 100% Ar gas is also present.

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>Si</th>
<th>O</th>
<th>C</th>
<th>N</th>
<th>H</th>
<th>Ti</th>
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<td>0,45</td>
<td>0,15</td>
<td>0,01</td>
<td>0,02</td>
<td>0,02</td>
<td>Bal.</td>
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</table>

The configuration of the specimens for welding trials is a typical lap joint.
Automatic GTAW welding trials: “Status Quo”

In order to have a reference sample (in terms of geometry of the weld, visual aspect and hardness values) obtained with the actual consolidated welding technology, a trials has been made using GTAW equipment.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Values</th>
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<td>Voltage</td>
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<tr>
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<tr>
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<td>-</td>
<td>100% Ar</td>
</tr>
<tr>
<td>Flow rate</td>
<td>l/min</td>
<td>12</td>
</tr>
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From every trial, two cross section specimens have been extracted, in order to evaluate penetration, geometry, and eventually welding defects.

The hardness profile (HV 0.5) shows that the increase of hardness in the HAZ and also in the weld is relatively low.
CMT welding trials and results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Welding speed (m/min)</th>
<th>Wire speed (m/min)</th>
<th>I (A)</th>
<th>U (V)</th>
<th>Arc length cor. (%)</th>
<th>Puls cor. (%)</th>
<th>Ratio CMT/puls</th>
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<td>3,9</td>
<td>01.05</td>
</tr>
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<td>78</td>
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<td>2,1</td>
<td>01.05</td>
</tr>
<tr>
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<td>6,5</td>
<td>66</td>
<td>20,2</td>
<td>-13</td>
<td>2,3</td>
<td>01.05</td>
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<tr>
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<td>5:2 + osc.</td>
</tr>
<tr>
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<td>5:2 + osc.</td>
</tr>
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</table>

The equipment used for realizing CMT and conventional GMAW trials in pulsed arc mode is the same in both cases. This first round of trials have been done using a welding program specifically developed for the titanium alloy Ti-6Al-4V (operating in synergic mode). During the trials:

- shielding gas = 50%He + 50%Ar mixture;
- constant flow rate of shielding gas = 16 l/min
- back shielding flux = 100 % Ar
- Constant stick-out = 13 mm
- Welding mode combines CMT function (negatively polarized) and pulsed arc cycles (positively polarized).
Results:

Influence of arc length correction

Influence of program type

Influence of torch movement

All the hardness values are perfectly aligned with the ones obtained from the analysis of the TIG welded joints. Also in the weld region the detected hardness is always below $235\text{ HV}_{0.5}$. 
GMAW welding trials and results

Parameters:
- Welding program for titanium alloy Ti-6Al-4V
- Gas shield mixture 50% Ar – 50% He and flow rate=16 l/min
- Back shielding flux 100 % Ar
- Constant stick out equal to 13 mm

<table>
<thead>
<tr>
<th>Sample</th>
<th>Weld speed (m/min)</th>
<th>Wire speed (m/min)</th>
<th>I (A)</th>
<th>U (V)</th>
<th>Arc length correc. (%)</th>
<th>Puls correc. (%)</th>
<th>Pulse freq. (Hz)</th>
<th>Torch Mov.</th>
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<td>5</td>
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<td>Pendular</td>
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<tr>
<td>MIG_2</td>
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<td>23.3</td>
<td>13</td>
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<td>0</td>
<td>Horizontal</td>
</tr>
<tr>
<td>MIG_3</td>
<td>0.45</td>
<td>3.3</td>
<td>33</td>
<td>21.8</td>
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<td>-2.3</td>
<td>9</td>
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</tr>
<tr>
<td>MIG_4</td>
<td>0.45</td>
<td>3.3</td>
<td>33</td>
<td>21.8</td>
<td>18</td>
<td>-2.3</td>
<td>12</td>
<td>Horizontal</td>
</tr>
<tr>
<td>MIG_5</td>
<td>0.8</td>
<td>8.4</td>
<td>79</td>
<td>22.3</td>
<td>19</td>
<td>-2.6</td>
<td>10</td>
<td>Straight</td>
</tr>
<tr>
<td>MIG_6</td>
<td>0.8</td>
<td>7.7</td>
<td>71</td>
<td>24.9</td>
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<td>0</td>
<td>10</td>
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<td>19.3</td>
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<td>Straight</td>
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<tr>
<td>MIG_9</td>
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<td>10.5</td>
<td>127</td>
<td>19.1</td>
<td>-26</td>
<td>0</td>
<td>0</td>
<td>Straight</td>
</tr>
</tbody>
</table>

* = Using a gas shield mixture 48% Ar, 50%He, 2%Co₂
° = Using a gas shield 100% Ar
Results:

- Influence of the torch movement
- Influence of the pulse frequency
- Influence of the gas shield

Also for GMAW specimens, the hardness profile measurements carried out on every cross section of the welds show hardness values perfectly aligned with the results obtained during previous analysis.
HLAW welding trials and results

Parameters:

- Trump Nd-Yag laser power source with power of 4kW combined to a conventional GMAW welding generator Fronius TransPulse Synergic 5000
- Gas shield mixture 100% Ar (16 l/min)
- Back shielding flux 100 % Ar
- Constant stick out equal to 13 mm

<table>
<thead>
<tr>
<th>Sample</th>
<th>Weld speed (m/min)</th>
<th>Wire speed (m/min)</th>
<th>I (A)</th>
<th>U (V)</th>
<th>Laser power (kW)</th>
<th>Laser focus (mm)</th>
<th>Gap (mm)</th>
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<td>128</td>
<td>17,2</td>
<td>2</td>
<td>8</td>
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<tr>
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<td>116</td>
<td>18,9</td>
<td>1,6</td>
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<td>0,8</td>
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<td>116</td>
<td>18,1</td>
<td>1,6</td>
<td>4</td>
<td>0</td>
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<tr>
<td>HL_4</td>
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<td>115</td>
<td>19,1</td>
<td>1,6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HL_5</td>
<td>2,1</td>
<td>9</td>
<td>106</td>
<td>19,6</td>
<td>1,8</td>
<td>-2</td>
<td>0</td>
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<tr>
<td>HL_6</td>
<td>2,1</td>
<td>9</td>
<td>128</td>
<td>19,6</td>
<td>1,8</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>
Results:

- The weld is really appreciable in terms of esthetic appearance.
- The laser beam play a significant role in stabilizing the electric arc.
- The speed of the process, nearly 7 times the one used for GTAW.
- The quantity of deposited filler metal is significantly lower and so also the welds dimensions are reduced compared to GTAW/GMAW technique.
- Components with large gaps can be welded.
- Hardness values are perfectly aligned with the average obtained with other conventional arc welding technologies.
- The HAZ extension is slightly reduced.
GMAW SYNERGIC LINE DEVELOPMENT

Between all the welding trials carried out with several technologies, the one which looks more promising is conventional GMAW.

- GMAW welding arc is much more stable than CMT one
- GMAW is more sensitive to parameters modification
- GMAW equipment is cheap and easily reliable on the market
- The application of GMAW technique for automatic welding with 6 axis robot is well consolidated in industry

**Improvement of existing synergic lines**

The synergic line of the alloy Ti-6Al-4V has been taken as starting base and then the algorithm has been modified to adapt the parameters to the need of the alloy Timetal XT.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Weld speed (m/min)</th>
<th>Wire speed (m/min)</th>
<th>I (A)</th>
<th>U (V)</th>
<th>Arc length cor. (%)</th>
<th>Pulse freq. (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIG_A</td>
<td>0,6</td>
<td>4,6</td>
<td>67</td>
<td>23,4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MIG_B</td>
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<td>5,6</td>
<td>85</td>
<td>23,6</td>
<td>7</td>
<td>0</td>
</tr>
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<td>MIG_C</td>
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<td>5,6</td>
<td>77</td>
<td>22,4</td>
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<td>0</td>
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<tr>
<td>MIG_D</td>
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<td>78</td>
<td>22,6</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>MIG_E</td>
<td>0,6</td>
<td>4,6</td>
<td>59</td>
<td>23,6</td>
<td>13</td>
<td>0</td>
</tr>
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</tr>
<tr>
<td>MIG_G</td>
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<td>62</td>
<td>22,4</td>
<td>0</td>
<td>6,5</td>
</tr>
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</table>
The results in terms of esthetic appearance of the weld and also concerning the geometry of the joint are significantly improved compared to the first group of trials.

Influence of welding speed on geometry of weld

1st trial : synergic line of Ti 64

2nd trial : modified synergic line of Ti 6-4
Creation of a synergic line dedicated to Timetal XT alloy

In order to develop a dedicated solution for Timetal XT alloy, several specimens of the material presenting different thickness (from 0,54 mm to 3 mm thickness) have been prepared and used to perform welding trials.

While the process in ongoing, the arc voltage, welding current and wire feed speed were continuously measured; these data, together with the droplet formation analysis, are the necessary input requested for the algorithm creation.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Weld speed (m/min)</th>
<th>Wire speed (m/min)</th>
<th>I (A)</th>
<th>U (V)</th>
<th>Arc length cor. (%)</th>
<th>Pulse freq. (Hz)</th>
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<td>20,5</td>
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<td>0</td>
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<td>XT_2</td>
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<td>23,7</td>
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<tr>
<td>XT_3</td>
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<td>6</td>
<td>80</td>
<td>20,8</td>
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<td>3,8</td>
<td>48</td>
<td>25,9</td>
<td>13</td>
<td>0</td>
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</table>

* = Using a gas shield 100% Ar
° = Using a gas shield mixture 75% Ar+25%He
Visual aspect and the geometry of the welds obtained using the new synergic line

Samples obtained with new synergic line

Macros of weld XT_3 (surface & section)

Macros of weld XT_9 (surface & section)
Comparison between different algorithms

In order to select the correct set up of the power supply during welding, very useful information is given by knowing the influence of the arc length correction on the current intensity and voltage during welding.

Parameters kept constant:
- Shielding gas mixture 50% Ar  50% He
- Welding speed = 50 cm/min
- Wire speed = 4.5 m/min
- Stick out length = 13 mm

![Graph 1](chart1.png)
**Current intensity vs. arc length correction**

![Graph 2](chart2.png)
**Voltage vs. arc length correction**
Equally important is also evaluating the influence of wire speed modification towards current intensity and voltage. In this case, the data are directly extracted from the controller of the power supply, without making any real welded sample.

Parameters kept constant:  
- Shielding gas mixture 50% Ar 50% He  
- Welding speed = 50 cm/min  
- Arc length correction = 0%  
- Stick out length = 13 mm

![Current intensity vs. wire speed](image1)

![Voltage vs. wire speed modification](image2)
THERMAL INPUT DETERMINATION

Thermal input, as preheat and interpass temperature, influences the cooling rate, which may affect the mechanical properties and metallurgical structure of the weld and the HAZ. This parameter can be defined as follow:

\[ Q = \frac{k \cdot I \cdot U}{v} \quad [\text{J/m}] \]

\[ Q = k \cdot \left( \frac{I \cdot U}{v} + \frac{L_p}{v} \right) \quad [\text{J/m}] \]

for the GTAW, GMAW, GMAW-P, CMT technology

for the HLAW technology

<table>
<thead>
<tr>
<th>Sample</th>
<th>Program</th>
<th>I  (A)</th>
<th>V  (V)</th>
<th>v  (m/s)</th>
<th>K  (-)</th>
<th>Q  (kJ/m)</th>
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<td>22,3</td>
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</tr>
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<td>MIG_G (+P)</td>
<td>Gr.5 mod</td>
<td>62</td>
<td>22,4</td>
<td>0,01</td>
<td>0,82</td>
<td>113,9</td>
</tr>
<tr>
<td>XT_3</td>
<td>XT</td>
<td>80</td>
<td>20,8</td>
<td>0,010833</td>
<td>0,78</td>
<td>119,8</td>
</tr>
</tbody>
</table>

Process Efficiency:
- GTAW: 0.67
- GMAW: 0.78
- GMAW - P: 0.82
- HYBRID: 0.76
- CMT: 0.85
The aim of this study was to evaluate a welding technology for titanium alternative to GTAW to be used for titanium exhaust systems production.

1) **CMT** process meets the target in terms of cost and easiness of automation of the process; but this technique present a strongly unstable arc and the joint is not good in terms of esthetic appearance.

2) **HLAW** technique allows obtaining good looking welds, with a relatively small seam and using very high welding speed. However, the dimensions of the welding head, which combines laser source and GMAW torch, are considerably extended. Moreover, the cost of this type of equipment is still 5-6 times more expensive than a conventional arc welding power supply.

3) **GMAW** or **GMAW+P** technologies are for sure the techniques which reach the best compromise, considering the achievable quality of the weld, the welding speed and the equipment costs. Unfortunately, it is necessary to develop a dedicated welding algorithm in order to reach the optimal set-up of parameters needed in case of serial production.
The experience carried out during the GMAW welding trials, allows to point out the following aspects:

- The type of gas shielding to be used during welding is fundamental: to obtain better arc stability, a mixture containing minimum 50% of Helium is recommended.

- To obtain stable welding conditions, and regular geometry of the joint, the arc must be quite extended. The correct value of stick out must be kept in the range of 13-15 mm.

- The best geometry and esthetic quality of the seam is achieved when the penetration depth is more than 90% of total thickness.

- Due to the single phase matrix of Timetal XT alloy, the microstructural modification and the increase of hardness in HAZ or weld zone are always limited, independently from the chosen welding parameters.
Thanks for your attention