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1. Preface

Among industrial joining processes, orbital TIG welding has meanwhile become a well-established method, although a considerable lack of information about the various possibilities of this challenging technique still remains in public. Aerospace industry, aviation, high speed trains, nuclear industry, pharmaceutical industry, food industry, tiny microelectronic devices - just to name a few of the most exciting applications - rely on orbital welding, but the equipment to ensure our daily supply with electric current, oil and gas also depends on orbital welding techniques. In this booklet basic information is provided about the orbital weld process and the related equipment: technical approach, advantages, common and special applications, but also restrictions and limits. To give an idea how reality looks like, the text is illustrated by numerous application examples. Tables and designs shall help engineers and welding experts, as well as project managers, to get quick answers whether orbital welding could offer solutions corresponding to their needs. To get specific answers to your questions, consult the customer service team.

2. What is orbital welding?

Whenever high quality results are required, orbital welding is the first choice for the joining of tubes. The welding torch - in most cases, the TIG-welding (Tungsten Inert Gas) process is used - travels around the tubes to be joined, guided by a mechanical system. The name orbital welding comes from the circular movement of the welding tool around the workpiece.

Generally, orbital welding technique covers two main fields of application:

- Tube to tube / pipe to pipe joining.
- Tube to tube sheet welding.

In the first group, all kinds of tube joining are included: butt welding and welding of flanges, bends, T-fittings and valves, i.e. the entire tubing and piping requirements.

The second group concerns the manufacturing of boilers and heat-exchangers and comprises the different welding tasks related to tube to tube sheet welding operations.

3. Recapitulation of the TIG (GTAW) process

An electric arc is maintained between the non-consumable tungsten electrode and the workpiece. The electrode supports the heat of the arc; the metal of the workpiece melts and forms the weld puddle.

The molten metal of the workpiece and the electrode must be protected against oxygen in the atmosphere; an inert gas such as argon serves as shielding gas.

If the addition of filler metal becomes necessary, filler wire can be fed to the weld puddle, where it melts due to the energy delivered by the electric arc.
3.1. Advantages/Inconveniences of the TIG (GTAW) process

3.1.1. Advantages
1. Nearly all metals can be joined.
2. Different kinds of steel, stainless steel included, can be welded as well as refractory or wear-resistant nickel alloys, aluminium, copper, gold, magnesium, tantalum, titanium, zirconium, and their alloys; even brass and bronze can be welded in certain cases; if filler wire is applied, workpieces consisting of dissimilar alloys or batches can also be joined together.
3. All welding positions are possible.
4. The process is very stable and reliable; the occurrence of weld defects can be reduced to less than 1%.
5. No slag or fumes are developed during welding.
6. The affecting weld parameters can be adjusted in a wide range and mostly independent one of each other.
7. TIG welding can be carried out with or without filler wire.
8. The arc voltage, which is directly related to the arc length, and the weld current intensity offer a wide range of variations and can be controlled automatically.

3.1.2. Inconveniences
1. Compared to other arc welding processes, the deposition rate of the TIG process is relatively low.
2. Time-intensive and costly development is necessary to determine the weld procedures and the exact values of weld parameters which are necessary to control the process.
3. The welding equipment is sophisticated; it requires much more capital investment cost than gear for manual welding.

3.2. Types of weld currents

Two kinds of current are applied in the TIG welding technique:

▸ Direct Current (DC) is most frequently used to weld nearly all types of materials.
▸ Alternating Current (AC) is preferred to weld aluminium and aluminium alloys.

If DC is used, the electrode is connected as cathode to the negative terminal of the power source; this configuration is named DCEN or Direct Current Electrode Negative. In this case, the electrons of the electric arc flow from the electrode with negative polarity to the workpiece with positive polarity. Up to 70% of the released energy is considered to heat up the workpiece, which means an efficiency of 0.7 (useful energy/released energy).

The configuration DCEP or Direct Current Electrode Positive is not used in the TIG process except of some very special applications in aluminium welding. In this mode however, most of the heat is transmitted to the tungsten electrode, so already at low weld current intensities, very large electrode diameters, compared to TIG DCEN, become necessary to carry off the heat.

In the AC mode, the electrode is switched periodically between positive and negative polarity. During the time of positive polarity the tungsten electrode acts as the anode, due to the cleaning effect produced, the oxide layer on the surface of the workpiece will be destroyed. During the time of negative polarity the tungsten electrode acts as cathode, the heat necessary to melt the aluminium is applied to the workpiece; in this phase the electrode can then cool down.
3.3. **Tungsten electrodes**

3.3.1. Types of electrodes

Tungsten is a highly refractory metal with a melting point of 3,410 °C. It withstands the heat of the electric arc and keeps its hardness even if it becomes red hot. In the past, thoriated tungsten electrodes have been widely used for TIG welding, but as thorium is a low-level radioactive element, special grinding equipment is required to ensure a safe disposal of the grinding particles.

Today, different alloyed tungsten electrodes are preferred, e.g. Ceriated or Lanthanated types, which are free of any radioactivity. In addition, their performance is comparable to that of thoriated tungsten electrodes.

3.3.2. The Electrode grinder

To get the precise end preparation and sufficient repeat accuracy which is necessary to maintain a stable arc and a consistent level of weld penetration, a special electrode grinder should be used.

The design of the grinder must ensure that the grind marks on the tapered part run in correct alignment with the grain structure of the electrode: lengthwise. This guarantees better ignition and improved arc stability.

3.4. **Filler metals**

The application of filler wire may become necessary under the following conditions:

1. The welding seam must be reinforced.
2. If carbon steel or mild steel have to be welded.
3. In case of a preparation of the tube ends, for example a J or V preparation.
4. To prevent metallurgical failure if the tubes to be welded are made of dissimilar metals or alloys.
5. If the alloys change their composition or structure during welding.

Alloying elements can evaporate during the weld process or form a new compound. For example, chromium carbide is developed if chromium combines with carbon. The resulting lack of metallic chromium can cause an unwanted loss of corrosion resistance at the heat affected zone.

A well-known example is the welded connection between carbon steel and Stainless Steel 316, where a filler wire made of Stainless Steel 309 or nickel base alloy Inconel 82® is added.
3.5. Gases

3.5.1. Welding gases

Argon is commonly used as shielding gas in the TIG process. It provides good arc striking characteristics and excellent arc stability even at low amperages, the energy of the arc is confined to a narrow area. Argon is also compatible with all types of base materials.

Shielding gas for standard TIG welding purposes should have a purity of 4.5, i.e. a purity level of 99.995%. Metals which are classified as delicate to weld for example; titanium, tantalum, zirconium and their alloys require a purity of at least 4.8, which means a purity level of 99.998%.

To increase the weld energy, 2% to 5% hydrogen can be added to the argon. Besides a higher energy input of 10% to 20% resulting in a better penetration and faster welding speeds, argon/hydrogen mixtures have reducing properties helping to protect the molten metal against the influence of oxygen from the surrounding atmosphere. However, mild and carbon steels absorb hydrogen with the possible result of porosity and cold cracking, so the use of hydrogen containing gas mixtures is not recommended; for the welding of aluminium and titanium they are strictly forbidden.

The weld energy can also be increased by argon/helium mixtures with helium contents of 20%, 50% or 70% or even pure helium. Helium has no detrimental effects on titanium, so it is used especially to weld the pure metal or titanium containing alloys.

Mixtures of argon, helium and nitrogen are used to weld Duplex and Super Duplex steels.

Unlike argon, helium is a good heat conductor. The arc voltage under helium is much higher than under argon, so the energy content of the arc is strongly increased. The arc column is wider and allows deeper penetration. Helium is applied for the welding of metals with high heat conductivity like copper, aluminium and light metal alloys. As helium is a lightweight gas, compared to argon its flow rate for identical gas coverage must be increased two to three times.

The following table indicates the qualification of different welding gases and mixtures according to the base materials to be joined:

<table>
<thead>
<tr>
<th></th>
<th>Ar</th>
<th>Ar + H₂</th>
<th>Ar + Hé</th>
<th>Ar + N₂</th>
<th>He</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel / Carbon steel</td>
<td>***</td>
<td>**</td>
<td>**</td>
<td>*</td>
<td>**</td>
</tr>
<tr>
<td>Austenitic steel</td>
<td>***</td>
<td>**</td>
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<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Duplex / Super duplex steel</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Copper</td>
<td>***</td>
<td>X</td>
<td>***</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Aluminium</td>
<td>***</td>
<td>X</td>
<td>***</td>
<td>*</td>
<td>***</td>
</tr>
<tr>
<td>Titanium</td>
<td>***</td>
<td>X</td>
<td>***</td>
<td>X</td>
<td>***</td>
</tr>
</tbody>
</table>

** Ar  Argon
N₂  Nitrogen
H₂  Hydrogen
He  Helium
*** Recommended
** Possible
* Not to be used
X Prohibited
3.5.2. Backing gases

Most applications of orbital welding require an outstanding quality to the inside of the root, as this is the part of the weld which will be in direct contact with the transported medium. To avoid any risk of oxidation, before, during and after the welding operation the hot metal at the inside of the tube must be prevented from coming in contact with oxygen in the atmosphere. Depending on the material to be welded, reducing components like N₂ or H₂ are added to the backing gas. The most typical backing gases and mixtures applicable for the different base metals are:

<table>
<thead>
<tr>
<th>Material</th>
<th>Ar</th>
<th>N₂</th>
<th>Ar + H₂ ou N₂ + H₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel / Carbon steel</td>
<td>***</td>
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<tr>
<td>Austenitic steel</td>
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<tr>
<td>Duplex / Super duplex steel</td>
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<tr>
<td>Copper</td>
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<tr>
<td>Aluminium</td>
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<td>X</td>
</tr>
<tr>
<td>Titanium</td>
<td>***</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ar</th>
<th>Argon</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>H₂</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>***</td>
<td>Recommended</td>
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<tr>
<td>**</td>
<td>Possible</td>
</tr>
<tr>
<td>*</td>
<td>Not to be used</td>
</tr>
<tr>
<td>X</td>
<td>Prohibited</td>
</tr>
</tbody>
</table>

3.6. Weld energy

3.6.1. The Influence of heat input

The heat input cannot be measured, but only calculated; its quantity is used e.g. to compare different weld procedures for a given weld process. The heat input influences the cooling rate and the HAZ (Heat Affected Zone) of the weld. A lower heat input allows us to obtain faster cooling rates and a smaller HAZ. With fast cooling rates, microstructure modifications of the base metal like grain growth or precipitations can be minimised, avoiding the loss of too much mechanical strength or corrosion-resistance. For many materials, e.g. sophisticated heat-treated and stainless steels, the heat input is limited by the specifications of the manufacturer.

In manual welding, to obtain a particular heat input, the welder must keep the arc length continuously at a specified level, by that the arc voltage remains constant at the desired weld current intensity. But additionally, as the heat input is influenced significantly by the travel speed, the manual welder must finish the weld within a fixed period of time. Only well-trained welding staff with excellent skills is able to meet these requirements.

In automatic Gas Tungsten Arc Welding, the process parameters arc voltage and weld current intensity, as well as travel speed and wire feed rates are controlled and kept constant by the microelectronic devices functioning within the power source, so the demand to respect a specified heat input does not cause any problems.
3.6.2. Formula to calculate heat input

The energy per unit length of the weld (Heat Input) $HI$ released by the electric arc during welding is calculated using the following equation:

$$HI = 60 \times U \times I / S$$

$HI$ = heat input [J/mm or J/in]

$U$ = arc voltage [V]

$I$ = current [A]

$S$ = travel speed [mm/min or in/min]

Using the above cited equation for heat input calculation, the characteristics of the applied weld process are not taken into account. A weld process dependent efficiency coefficient "$r$" allows us to calculate a more comparable heat input values for different weld processes:

$$HI = 60 \times U \times I \times r / S$$

In publications, the coefficient "$r$" for TIG (GTAW) welding, is expected to be in the range of 0.6 to 0.8, i.e. 60% to 80% of the energy released by the electric arc heats up the workpiece while 20% to 40% escape by radiation, heating up of the torch, the shielding gas etc.

Expert information:
To calculate the average weld current $I_{\text{average}}$ when using pulsed current for orbital welding applications, the following formula has to be applied:

$$I_{\text{average}} = (I_h \times T_h + I_b \times T_b) / (T_h + T_b)$$

$I_h$: Pulse current  
$T_h$: Pulse time  
$I_b$: Background current  
$T_b$: Background time  

![Diagram of pulse current and average current](image)
4. Reasons to select orbital welding

The decision for the use of mechanised or automatic orbital TIG welding can be taken for different reasons: economic, technical, organisational, and others may be more or less important or even become the decisive factor. The orbital welding process offers a large range of benefits which qualifies it for industrial applications. The major advantages are:

4.1. Increased productivity compared to manual welding

Compared to manual TIG welding, the mechanised or automatic process leads to enhanced productivity. Repetitive work in the shop or complicated assembly jobs on-site - orbital welding equipment guarantees that approved weld sequences are reliably repeated, hence time-consuming repair work will be reduced to a minimum.

4.2. Consistent excellent weld quality

Generally, the weld quality obtained by mechanised equipment is superior to that of manual welding. Once an adequate weld program has been developed, the weld cycle can be repeated as often as necessary, without deviations and virtually without weld defects.

4.3. Required skill levels of the operators

Certified welders are difficult to find and well remunerated. However, after appropriate training, skilled mechanics are able to operate orbital welding equipment perfectly and get excellent results. By using this equipment expenditure on personnel can be reduced.

4.4. Environment

Orbital welding can be executed even under harsh environmental conditions. Restricted space or access, lack of visibility, presence of radiation; once the weld head is positioned properly, the weld can be accomplished without problems from a safe distance; often supported by a video transmission.

4.5. Traceability – Quality Control

Modern orbital welding equipment is designed for real-time monitoring of the affecting weld parameters; a complete weld protocol can be generated and stored or output as a printed document. Sophisticated data acquisition systems operate in the background, if they are connected directly to a superior quality management system; automatic data transfer takes place without any interruptions to the weld procedure.
5. Industries which apply the orbital TIG welding process successfully

5.1. Aircraft industry

In the aircraft industry, which was the first one to recognize the importance of orbital welding for their purposes, more than 1,500 welds are necessary to complete the high pressure system of one single plane. Manual welding of the small, thin-walled tubes is extremely difficult; finally the required consistent joint quality cannot be guaranteed. The only solution is to establish welding procedures using orbital equipment. In this way, the parameter values are reliably controlled by the equipment and the final welds meet the same quality level as the qualified test welds.

5.2. Food, dairy and beverage industries

The food, dairy and beverage industries need tube and pipe systems meeting delicate hygienic requirements. Full penetration of the welded joints is necessary; any pit, pore, crevice, crack or undercut can become a dead spot where the medium is trapped and pathogenic bacteria growth, (Listeria etc.), can occur. Smooth surfaces everywhere inside the tubes enable successful cleaning and complete sterilisation of the system. The requested surface quality can only be ensured if orbital TIG equipment is used to weld these critical joints. Therefore, most standards and specifications oblige nowadays the manufacturers of hygienic installations to apply this process.

5.3. Pharmaceutical and biotechnology industries

Plants in pharmaceutical industries must be equipped with pipe systems for the transport and the treatment of the product and for the safe supply of clean steam and injection water. For injection water and its derivatives that are intended for injection into the human body, the purity requirements are particularly high. Any traces of corrosion are absolutely forbidden, the corrosion resistance of these welds must not be undermined, especially not by partial overheating of the base material. Joints made by orbital welding qualify for extended corrosion resistance. Additionally, to avoid any subsequent oxidation or corrosion, their smooth surface can be passivated.
5.4. Fabrication of semi-conductor devices

For the fabrication of semi-conductor devices, electro-polished stainless steel tubes are installed as process gas lines, mostly with an OD of 6.3 mm and a wall thickness of 0.9 mm. The ultra-pure process gas must pass the tubes without picking up moisture, oxygen, particles or other contaminants. The acceptance criteria for these installations are very stringent: uniform welds with small weld beads to minimize the weld surface in the tubes, full penetration on the ID, absence of discoloration, etc. Only experienced operators working with reliable orbital welding equipment are able to perform this task, often even under adverse conditions on site.

5.5. Chemical industries

A considerable part of plant equipment for chemical industries are manufactured and installed by means of orbital welding. Chemical apparatuses comprise of tubes, heat exchangers and converters which are made of corrosion-resistant or refractory metals or alloys of titanium, zirconium, nickel, chrome etc.; not to forget the whole range of different stainless steel types. As the service life of the installations depend directly on the quality level of the welded joints, strict control and traceability of the weld process are required by customers, inspection bodies and standards authorities. For the assembly of one heat exchanger, hundreds or even several thousand faultless welds have to be carried out, so here orbital welding becomes a must to ensure the expected results.

5.6. Power generation

For the safety of power stations the whole range of orbital joining techniques are applied: tubes with small diameters for sensing and control purposes must be connected, heat exchangers and other components are manufactured using orbital tube to tube sheet welding, and thick-walled tubes for operation under high pressure and temperature must be assembled on site. The welding procedures and the weld quality are generally under constant surveillance of the respective authorities and external organisations, the required complete documentation and traceability is ensured by the provision of orbital equipment with online data acquisition systems.
6. Specificities of the orbital weld process

6.1. Typical Welding Positions

The denominations for pipe welding are specified by the ASME code, section IX, and the European Standards EN 287 / EN ISO 6947, both refer to the position of the tube to be welded.

![AWS 1G ISO PA](image1)

![AWS 2G ISO PC](image2)

![AWS 5G ISO PG (/1) PF (/2)](image3)

![AWS 6G ISO H-LO45](image4)

6.2. Pulsed current

The essential characteristic of successful orbital welding is the necessity to control the bath of molten metal during the whole weld cycle, taking into account the continuously changing situation in the process. An orbital weld of the PF / PG or 5G (fixed tube) type for example must meet at each moment the following conditions:

1. Alteration of the weld position and hence of the influence of the force of gravity.
2. Alteration of the thermal state of the workpiece.

The most effective measure to keep the control of all weld positions during the orbital weld cycle is to use a pulsed weld current. Basically, a pulsed weld current toggles between two different levels of intensity:

- During a time period $T_h$ the weld current remains at a high level $I_h$; here the volume of the weld puddle increases to its maximum.
- During a time period $T_b$ the weld current remains at a lower level $I_b$, allowing the weld puddle to cool down and to decrease its volume to a minimum, which mitigates the awkward effects of the force of gravity.

Pulsed current is advantageous for a major part of orbital welding applications, making the determination of welding parameters easier and faster. However, if thick-walled tubes of significant diameters with wall-thickness over 10 mm and tube diameters above 114 mm are to be welded, the level of the low current intensity may approach that one of the high intensity, which results almost in an un-pulsed current.
6.3. Programming of sectors

In many cases, the only use of a pulsed weld current is not sufficient to obtain acceptable orbital weld results. The parameters must be adapted with regard to the actual requirements of the weld. The course covered during the weld cycle is hence divided into different zones, which are called sectors. The weld parameters are modified if the border of one sector to the next is crossed.

To explain the sector layout, a circle of 360° as symbol of the cross-section of the tubes to be welded is divided into four sectors, each covering 90°. The first sector begins at the starting point D of the orbital weld, in this case at the 10.30 position, and ends at the 01.30 position.

Each sector corresponds to a specific welding position:

- sector S1 from 0° to 90° flat position;
- sector S2 de 90° à 180° vertically down position;
- sector S3 de 180° à 270° overhead position;
- sector S4 de 270° à 360° vertically up position.

Depending on the weld position and the thermal conditions of the workpiece, which is heated up perpetually by the energy input of the electric arc, the parameter values are modified at the beginning of each sector.

In the orbital weld practice, most often the sectors are not divided as regularly as shown in the example. The number of sectors can also vary due to the different welding applications.

7. Hardware Components of Orbital Welding Equipment

Independently of the welding tasks to be carried out, orbital welding equipment is generally composed of the following components:

- A programmable system controller and a remote control unit, (distinct or as integrated as part of the Welding Head).
- The Welding Head.
- A wire feeder unit, if required by the application.

In any case, the performance of the equipment depends on the design of the aforementioned components.
8. Programmable system controllers

8.1. General

A power source for orbital applications is composed of several subassemblies with specific functions each:

- One Power Inverter to supply the welding current. Today, state of the art sources are of the inverter type.
- Programmable control unit which is generally based on an integrated PLC.
- Cooling circuit for the torch and the welding and clamping tools.
- AVR-system (actual value recording) recording each welding sequence.

The power sources for orbital welding can be divided in 2 categories with specific fields of application.

8.2. Portable power source FPA 2020

The smallest power source with a weight of less than 30kg delivers weld currents up to 200 Amperes; it is operated on a 230Volt single phase supply. The programming and parameter development is carried out via an intuitive graphic user interface and a full function remote control unit.

The man-machine-interface allows a comfortable management of weld cycles, programs and weld parameters, sector-programming is supported as well. The gas solenoid valve for the purging gas can be switched from the remote control (on / off).

Orbital power source FPA 2020
The FPA 2020 is equipped to handle up to four axes of control, i.e. four devices can be programmed and controlled: the shielding gas flow, the weld current intensities and pulse rates, the travel speed of the welding head, and wire feeding operations. A closed loop Cooling System is present to operate water-cooled orbital Weld Heads and Welding Tools and is integrated as part of the machine.

Furthermore the FPA 2020 allows us to find matching weld programs, (if the user specifies basic information about size and material of the tubes to be joined), using a touch screen. The system consults its in-built database to find similar applications or suggests weld parameters determined by progressive calculations.

**8.3. System controller FPA 2030 with power source**

Medium-sized power sources for orbital welding are too heavy to be carried; they are mounted on a carriage to keep them mobile. These power sources are for connection to three-phase 400 Volt outlets or feature a multi-voltage input, they generate welding currents up to 500 Amperes. For the dialog with the operator, the power sources are equipped with a convenient man-machine interface and a full function remote control unit.

Medium-sized power sources are designed to handle up to six axes, which can be programmed and controlled. Usually these axes are attributed to the shielding gas flow, the weld current intensities and pulse rates, the travel speed of the welding head, the wire feeding operations, and Arc Voltage Control & Oscillation. The purging gas can be switched on / off from the remote control as well.

Orbital system controller FPA 2030 with power source
9. Orbital welding heads

9.1. Tube to tube welding heads

9.1.1. Closed chamber welding heads

Closed chamber welding heads are especially designed for autogenous welding of tubes without filler wire; their different sizes cover a range of diameters between 1.6 mm and 168 mm (ANSI 1/16" to 6"). Besides austenitic stainless steel, metals susceptible to oxidation like titanium or zirconium and their alloys can be welded with excellent results. Depending on the application, one or two pairs of clamping shells or TCIs (Tube Clamping Inserts) are needed to fix the closed chamber head on to the tubes to be welded.

9.1.2. Open welding heads of the U type

Open welding heads were conceived as a tool for orbital TIG welding with or without filler wire. The diameters of the tubes to be welded cover a range from 8 mm up to 275 mm (ANSI 5/16" to 11").

Open welding heads of the U-type are equipped with a TiG-torch with gas diffuser. Sufficient gas protection is achieved only at a zone around the torch which is covered by the shielding gas streaming out of the gas lens. During the welding process, the arc can be watched and controlled directly by the operator. The asymmetrical design of the open heads allows welding to be carried out at a very short distance to a wall or a bend.

The positioning of the welding torch can be carried out manually or by means of motorized slides (Arc Voltage Control and oscillation).
9.1.3. Carriage-type welding heads

Open orbital welding heads of the carriage type travel around the tubes or pipes on appropriate rails or tracks, which can be mounted on any tube OD from 114 mm (3 1/2") upwards. The wall thickness of the tubes and pipes concerned always requires multi-pass welding, the robust design of the carriage weld heads enable them to carry the necessary equipment such as a heavy duty driving motor, a torch with an AVC and oscillation device and a wire feeder bearing spools with a weight of up to 5 kg. Additionally, video cameras can be mounted, allowing the operator to watch and safeguard the weld process.

Due to the application, these welding heads can be equipped with TIG torch with gas lens, assuring the protection of the zone covered by the shielding gas.
9.2. Tube to tube sheet welding heads

9.2.1. Enclosed orbital tube to tube sheet welding heads without filler wire

Enclosed welding heads are designed for TIG welding (GTAW) of tube to tube sheet applications, if they can be accomplished without filler wire. With these weld heads, flush or slightly protruding tubes with a minimum internal diameter of 9.5 mm (3/8") can be welded, the maximum diameter being 33.7 mm (1 1/3").

The weld is carried out in an inert atmosphere inside a welding gas chamber, providing very good protection against oxidation.

For clamping, a mandrel is inserted into the tube to be welded and expanded mechanically.

By means of a weld lance which is mounted at the front of the weld head, internal bore welding can be carried out at tube I.D. between 10 mm and 33.7 mm (13/32" and 1 1/3").

9.2.2. Open tube to tube sheet welding heads with or without filler wire

Open orbital tube to tube sheet weld heads which can be used with filler wire cover the whole range of applications from tubes with an I.D. of 10 mm (13/32") up to tubes with a maximum O.D. of 60 mm. The TIG torch travels around the tubes, which can be protruding, flush or recessed.

The welding heads are equipped with a TIG-torch with gas diffuser. A sufficient gas protection is achieved only at the zone around the torch which is covered by the shielding gas streaming out of the gas lens. If oxygen sensitive materials need to be welded, the gas protection can be improved by installing a gas chamber.

The welding heads can be equipped with an integrated wire feeder unit. A pneumatic clamping device can be used to hold the weld head in working position on the tube plate, enabling several welding heads to be operated by just one person. Welding lances allow the operator to carry out internal bore welding with gapless joints behind a tube sheet or a double tube sheet.
10. Wire feeder units

Generally, a wire feeder unit can be integrated into the orbital welding head or specified as an external wire feeder unit. The choice of the feeding unit depends on the availability of the filler wire, which must be available on suitable spools; furthermore on the conditions of use, the constraints of the application and the requested mobility of the equipment.

11. Functionalities of the orbital welding equipment

11.1. Gas management

There are two possibilities when controlling the gas management of an orbital welding installation:

1 - A manually adjustable pressure reducer with flow meter, installed at the gas supply, (cylinder or network), an electric valve which can be opened and closed by the control unit of the power source.

2 - An adjustable pressure reducer is installed at the gas supply (cylinder or network), an electronic device inside the power source controls the gas flow rate. Power sources for orbital welding are equipped to control up to three gases: two welding gases and one additional gas, e.g. backing gas. The so-called Bi-Gas function of a power source allows the unit to change the type of welding gas when the electric arc is initiated, which is especially advantageous if helium is used as shielding gas. To avoid frequently occurring problems caused by ignition difficulties under helium, the ignition is initially carried out under argon and, after the arc has become stable, the welding gas supply is switched to helium.

Depending on the standard of the particular orbital welding equipment, the welding gas flow is continuously monitored. In case of an interruption of the welding gas supply, the ignition of the arc is blocked. If during welding the gas flow rate drops below a factory-adjusted value, the weld cycle will be aborted automatically. By this measure, severe damage of the workpiece and equipment is avoided.
11.2. Current

11.2.1. Arc ignition

The standard method of striking an arc is to apply high voltage surges. The column of shielding gas between the electrode and the workpiece becomes ionised and takes on conducting properties. As a consequence an arc is struck and the weld current begins to flow. This ignition method is the common standard for all types of orbital welding equipment.

This ignition technique is limited by the cable length between the power source and the welding head, which depending on the kind of application, must not exceed 30 m to 25 m. If the welding head is equipped with an AVC device, a so-called Touch & Retract can be carried out instead. The torch is moved towards the workpiece until the tungsten electrode touches its surface. Smoothly afterwards it is drawn back (lifted). The potential to initialise the weld current is applied in the same moment. Once the arc is struck the torch can be moved to the programmed arc length. Any tungsten inclusion in the weld seam is reliably excluded.

11.2.2. Welding current

The welding current is one of the affecting parameters of the TIG process; therefore its intensities must be controlled accurately by the power sources. A precision of ± 1 Amp is guaranteed if the welding current intensity rests below 100 Amps, for intensities exceeding 100 Amps a precision of 1% is ensured. To meet the requirements of the different applications, dissimilar current types are supplied by the power sources:

- Un-pulsed current (1): no variation of the current intensity
- Pulsation (2): this current is commonly used for standard orbital TIG welding; the maximum frequency of pulsations, who makes sense, is 5 Hz (with wire).
Downslope
To avoid a crater occurring at the end of the weld, the welding current cannot be interrupted instantaneously. During a downslope, the weld current intensities are decreased linearly to values between 30 A and 4 A, afterwards the current is shut off. The higher intensities are adapted to tubes with a more significant wall thickness.

11.3. Torch rotation

During welding the torch must rotate with the desired linear travel speed around the tube or pipe. Standard orbital welding applications require a linear travel speed range between 50 mm/min and 200 mm/min.
In most cases the travel speed remains un-pulsed, but it can also become pulsed and synchronized to the weld current pulsations. It is possible to program different speeds during base and pulse current. Usually, as in the case of step pulsed welding, rotation stops (V=0 mm/min) during the high current level, whereas during the base current period the torch moves forward.

The achieved speed precision is 1% of the programmed value. Welding equipment can be operated using impulse emitters or tachometer encoders on request.

These pulses are also processed by the control system of the power source to identify the actual position of the torch relative to the start point, which means that the programming of a weld cycle can be carried out using angular degrees instead of time spans. Intuitive programming is possible because one tour of the torch always covers 360° per pass, independently of the linear welding speed and the tube or pipe diameter.

### 11.4. Wire feeding

Power sources for orbital welding are equipped to control different types of wire feeder units; the attainable wire speeds range from 0 to 8,000 mm/min, a precision of about 1% is attained.

Standard functions of wire feeding which are managed by all power sources are the control of the wire start and stop as well as a pulsed feeding rates. The wire feeding pulses can be synchronised to the pulses of the weld current; the wire speed is kept at a high level when the weld current is at its high level, and is decreased during low level current. The independence between wire speed and weld current offered by the TIG process allows the reversal of synchronisation; the wire is fed at a high speed when the current intensity is low; the wire arrives at a small weld puddle and melts with resistance. The mechanical stability of the wire can be used to push the bath of molten metal to get a convex root pass surface at the inside of the workpiece.

At the end of welding, a wire retract function allows the reversal of the feeding direction. The wire end is drawn back a few millimetres, avoiding the formation of a terminal wire ball or, even worse, the wire resting stuck in the weldment.

Expert information:

1. Common diameters of wire for welding purposes range between 0.6 mm and 1.2 m; the best choice for standard orbital welding is a proper wire with 0.8 mm diameter.

2. The melting rate of the wire depends not only on the precision of the wire feed speed, but also on the precision of the wire itself: a variation of 0.02 mm at a wire with a diameter of 0.8 mm represents a difference of already 5% of added metal.
11.5. AVC (Arc Voltage Control)

11.5.1. Theoretical approach

During welding, it is important to keep the arc length constant; but there are no simple methods to measure it. In any case, if the welding conditions do not change, each particular arc length corresponds to a related arc voltage. This phenomenon is used to control the distance between the electrode and the workpiece during welding.

The characteristic of arc voltage at different arc lengths and welding current intensities are shown in the graph below:

At an arc length of 1 mm, the arc voltage measured between the electrode and the workpiece at different welding current intensities is characterised by the black line.

The red line shows the result of the same measurement at an arc length of 2 mm.

- Rule n°1: at the same weld current (I -b) an increase of the arc length provokes a higher arc voltage (increasing from U1-b to U2-b).
- Rule n°2: if the arc length is maintained (weld current intensity exceeds I mini) and the weld current increases (from I -b to I -h), the arc voltage also increases (from U1-b to U1-h).
- Rule n°3: if a different type of shielding gas is used (with other weld parameters remaining unchanged), the arc length will change: if the shielding gas changes e.g. from argon to an argon-hydrogen mixture, the arc becomes significantly shorter.
- Rule n°4: if the geometry of the electrode differs (taper angle, tip diameter), the arc length at a given weld current changes or, at a constant arc length, the arc voltage changes.
- Rule n°5: if a pulsed weld current is applied, the arc voltage pulsations are not proportional.

Each change of the weld current intensity provokes a peak of the arc voltage which is commonly known as overshoot.
11.5.2. AVC features

As for most orbital welding applications, a pulsed current is applied; the rules 1 and 2 must be taken into account, making specific adjustments necessary to get a stable arc length.

- Restriction of the voltage measurement to the period of the low or of the high welding current. During the period without measurement the AVC slide is temporarily blocked, the electrode position does not change. The adjustment is simple, only one parameter value is requested to get a stable arc length.

- Extended arc voltage measurement during the period of the low and of the high welding current. This type of AVC control can be used if thermal pulsing (pulse frequency < 10 Hz) is applied.

- To get optimal results with minimised AVC-related torch movements, there are more system parameters that can be set. These parameters are (beginning with the most important):
  - Sensitivity of the control system
  - Speed of the electrode movement
  - Switch-off time at the beginning of each current pulse to eliminate the effect of overshoot (rule no. 5).

11.5.3. Programmable distance between electrode and workpiece

Besides the AVC control, the torch position can be determined by the programmed distance between electrode and workpiece function. Here, starting from a reference value, the torch is moved by a motorized slide over the selected distance in mm to the desired height.

The mentioned function is often used to get the electrode in position e.g. with tube to tube sheet applications or, if special welding tools are used, to follow the complex surface geometry of a workpiece in piggyback position.

11.6. Oscillation

If a weld preparation is applied to the tube ends, the groove to be filled becomes relatively wide, especially in the case of an increased wall thickness. Different to the stringer bead technique, where several passes are required to complete one layer, the groove can be covered completely by one layer if the torch is moving perpendicularly from one side to the other between the sidewalls of the weld prep. This movement is generated by a motorised slide and controlled by the oscillation system.
Parameters needing to be set to get the correct oscillation are width and speed of the stroke, as well as the dwell time, during which the torch remains at the end points of its movement next to the sidewalls of the groove.

It is possible to synchronise the torch oscillation with the pulsed current. For example, to increase the penetration at the sidewall, the high current intensity value is maintained continuously during the dwell time.

11.7. Remote control unit

The remote control unit is a device to enable the communication between the welder or operator and the equipment. All commands necessary to manage the welding equipment are directly accessible.

- Out of weld cycle
  During the mode, all movements of the equipment can be controlled: torch rotation, torch movement towards the workpiece or centring above the weld seam (AVC and oscillation), etc.

- During weld cycle
  The mode allows adjusting of the welding parameters as necessary, (if allowed by the program), to modify the torch position by means of AVC and oscillation functions if available. The remote control unit display actual welding information such as measured welding current and arc voltage, travel and wire speed, angular torch position, welding program, segment number and time elapsed since the weld cycle start.

11.8. Cooling Unit

With the exception of some devices designed for special applications, Orbital Weld Heads are generally water-cooled. The Power Source provides integrated closed-loop water cooling circuits.

In all cases, the flow of the cooling liquid is continuously monitored to avoid damage to water cooled units, such as the torch and the power source will be switched off if a failure occurs.
12. Weld cycle programming

12.1. Program structure of a weld cycle with 4 axes

Depending on the application and the type of orbital welding equipment, the programming of a weld cycle can be more or less complex. In all cases, the program structure is always built up following the same scheme of logical and chronological rules. As an example, the program of a standard weld cycle including filler wire, but without AVC and oscillation, is summarized.

<table>
<thead>
<tr>
<th></th>
<th>Start of the weld cycle (triggered by the Start button of the remote control unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Shielding gas flow during the programmed pre-flow time before the ignition of the arc</td>
</tr>
<tr>
<td>2</td>
<td>Ignition of the arc and beginning of the starting current.</td>
</tr>
<tr>
<td>2 to 4</td>
<td>Delay of the rotation.</td>
</tr>
<tr>
<td>2 to 5b</td>
<td>Delay of the wire feeding.</td>
</tr>
<tr>
<td>3</td>
<td>Begin of the pulsed weld current upslope.</td>
</tr>
<tr>
<td>4</td>
<td>Begin of the torch rotation*.</td>
</tr>
<tr>
<td>5</td>
<td>Begin of the main current phase.</td>
</tr>
<tr>
<td>5b</td>
<td>Begin of the wire feeding.</td>
</tr>
<tr>
<td>6</td>
<td>Segment slope.</td>
</tr>
<tr>
<td>6b</td>
<td>Begin of a new segment where the weld current and the wire feeding are modified</td>
</tr>
<tr>
<td>7</td>
<td>Begin of the weld current downslope. Generally, the downslope is positioned at 360° + 5° to 10° of overlapping to re-melt the beginning of the weld seam and to ensure a perfect joint at the end of the weld</td>
</tr>
<tr>
<td>7 - 7b</td>
<td>Wire post feeding (for filling the crater)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>7b</td>
<td>End of wire feeding* (and wire retract if programmed). Generally, the end of wire feeding is positioned at approx. 360°</td>
</tr>
<tr>
<td>8</td>
<td>End of the torch rotation, begin of the end current.</td>
</tr>
<tr>
<td>9</td>
<td>Weld end.</td>
</tr>
<tr>
<td>9 to 10</td>
<td>Time period of post-gas flow to protect the weld zone of the workpiece until a sufficiently low temperature has been reached and to protect the hot tungsten electrode against oxygen of the atmosphere.</td>
</tr>
<tr>
<td>10</td>
<td>Shielding gas stop and end of the weld cycle.</td>
</tr>
</tbody>
</table>

* Depending on the expected result the functions may be programmed in a different chronological order.
12.2. Interfaces for the programming of weld cycles

A recently introduced user-friendly Graphical User Interface, (GUI), for orbital welding equipment based on a PLC has been developed. The virtual synoptic is presented on a 5,7" touchscreen; it allows not only the complete weld data management but offers all functions to assist the operator with the development and finish of any orbital welding program. Some of the features are listed below:

- Complete documentation of the work-piece data
- Creation of chained weld cycles to carry out a complete multi-pass weld sequence
- Detailed description of boundary parameters, i.e. mechanical adjustments of devices, type and characteristics of gases used, electrodes, filler wire etc.
- Computer-aided optimisation of welding parameters for tube to tube and tube to tube sheet applications
- Automatic generation of programs for orbital fusion welding.

12.3. Offline programming

The programming of weld cycles for very complex applications and research tasks are carried out offline by means of a personal computer without connection to the system controller.

The FPA-Xplorer software is designed for the management of FPA 2020 and FPA 2030 Orbital programs and files. The intuitive structure of the program enables the user to access, edit and update data quickly and easily from a central PC. This is carried out via four tabs in which device properties, programs, actual values or alarm and event messages can be edited. With certain versions of the FPA 2030 Orbital control, data can also be accessed online.

The welding software is designed for a Windows™ environment.
13. Real time data recording

13.1. In summary

If a quality assurance system such as ISO 9000 has to be respected; only calibrated equipment can be used for the manufacturing of certain components.

The expression calibration is specified by regulating standards. It means that measuring instruments installed in the power source or within the connected devices of the welding equipment have to meet special requirements, they must be related to national or international standards or certified reference materials.

Calibration needs specific testing equipment and procedures and can only be carried out by an approved organisation, for example the manufacturer of the welding equipment, the quality assurance division of the user, or an independent external company.

13.2. Integrated real-time data recording

During a weld cycle, the essential parameters values of weld current intensity, arc voltage, travel speed and wire feed speed are measured and memorised cyclically. To allow a complete documentation of the weld, a weld cycle report including these measurements and the actual date and time can be printed whenever a weld cycle has been completed.

The weld cycle programs can be documented. The printouts may be used to verify that all parameters are set correctly and provided as proof for quality assurance purposes. The printout contains the program name, the parameter values and the range of modification allowed to the operator during the weld process by means of the remote control unit.

```
13.1. REAL TIME DATA RECORDING

- Parameter values measured and recorded cyclically.
- Printouts document weld cycle details.
- Calibration ensures accuracy.
```

13.2. INTEGRATED REAL-TIME DATA RECORDING

- During weld cycles, essential parameters recorded.
- Printouts for verification and quality assurance.
- Calibration necessary for ISO 9000 compliance.

---

**REAL TIME DATA RECORDING**

---

**Printout:** 06/12/20 16:42:11.97

**Operator:** FMA 1

**Program:** Fronius

**Seat No.:** 3

**Head:** MU-III 8-94

---

**Shielding gas pre f1:** 2.0 sec

**Shielding gas post f1:** 2.0 sec

---

<table>
<thead>
<tr>
<th>Pos</th>
<th>Seg</th>
<th>v-Rot</th>
<th>Inf</th>
<th>LG</th>
<th>Volt</th>
<th>v-Wire</th>
</tr>
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<tbody>
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<td>0.0</td>
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<tr>
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<tr>
<td>315</td>
<td>1</td>
<td>34.0</td>
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<td>0</td>
<td>0.0</td>
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<tr>
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</tr>
</tbody>
</table>

**Total time:** 00:03:1 min

---
13.3. Actual value recording (AVR)

Parameters such as values for pulsing current, background current, arc voltage, travel speed, wire feed speed, actual segment, torch-position are recorded. The progress of the weld cycle can be monitored and occurs as a graph on the display. The data acquisition system allows the operator to set limits for the different weld parameters. In this case, the concerned parameter values are continually compared to a previously recorded defect-free sample weld.

14. Tube to Tube welding

14.1. Applications

Fusion welds of thin-walled tubes cover a wide range of applications. Clients include for example: semiconductor industry, biochemistry, instrumentation, food and beverage, pharmaceutical industry, chemical/sanitary industry, and aeronautics/aerospace. In most cases, the tubes are made of austenitic stainless steel, but nickel alloys as well as titanium and its alloys can also be found. The range covers diameters from 1.6 to 170 mm; with wall thicknesses of varying between 0.2 and 3.2 mm.

14.2. Equipment

Preferentially, fusion welds are carried out using machines such as the FPA 2020 or FPA 2030 system controllers, combined with enclosed orbital welding heads. Depending on the application, the enclosed welding heads can be divided in 2 groups.
14.2.1. UHP enclosed chamber welding heads

Welding heads of the UHP type provide distinct reduced radial and axial dimensions; they are especially adapted to the welding of small diameter tubes. These welding heads are designed in a modular structure. The drive motor is integrated into a unique handle and can be combined with 3 gear modules UHP 250-2 for tube sizes up to 6.35 mm (1/4”), UHP 500-2 for up to 12.7 mm (1/2”), and UHP 1500 for diameters up to 33.7 mm (1 1/3”). Interchangeable clamping cassettes for example allow preparation of the work pieces independently in advance. The handle with the motor is only attached during the time which is necessary to accomplish a weld.

Clamping cassettes and flexible Tube Clamp Inserts (TCI) made from titanium are perfectly adapted to fit the typical standard outside diameters of tubing used in semi-conductor applications or pure gas supplies. The asymmetric shape of the weld head allows the joining of fittings with a short stick-out, and fixture blocks ensure reliable centring, alignment and clamping of all kinds of common micro-fittings.

The UHP weld heads are specially designed to meet the requirements of high purity applications. Inside the weld head, the shielding gas is flowing separately through a high purity gas circuit and arrives directly at the weld zone without any contact to gears or rotating parts. Thus, the danger of particle contamination is significantly reduced.
14.2.2. MW enclosed chamber welding heads

The MW range of enclosed welding heads has been exclusively designed for autogenous welding without wire. They fit tube O.D. between 6mm and 170mm. In addition to the perfect weld quality which can be obtained with these kinds of welding head, the inbuilt cooling circuit, together with the high temperature-resistant materials used in their construction, provide a considerable increase in productivity. Fast operation is ensured by the remote control unit buttons which are integrated comfortably into the handle.

Fittings and accessories with a short stick-out can be welded by means of an elbow-kit with off-set electrode holder.

14.2.3. Open welding heads

Open welding heads can be used to weld with or without filler metal. Two important differences compared to enclosed welding heads should be pointed out:

The gas protection does not cover the whole welding zone, but only a limited zone around the torch. This can cause problems in case of applications where oxygen-sensitive metals or alloys have to be welded.

The straight length of the workpiece at the clamping side of an open welding head is much more important than the length needed by enclosed welding heads.
14.3. Calculation of weld parameters values

Depending on the diameter and wall thickness of the tubes to be joined the parameter values for fusion welding without wire can be calculated. The calculations are based on formulas developed for stainless steel of the 300 series (e.g. 316 L), but the results can be transposed for other materials.

In any case, the validity of the calculated results must be confirmed by test welds. Materials with the same designation, and of an equal nominal composition, may still have very different welding properties (see also chapter 14.7 - Chemical composition and repeatability of welds).

14.4. Joint preparation

Autogenous orbital welding requires a precise butt end preparation of the tubes. To obtain such precise square edges, the preparation should be carried out with a special bevelling machine. Burrs must be removed completely and the tube ends must fit exactly without any gap. No grease, moisture or other types of contaminations are allowed around the welding zone.

Before the welding process can be started, the tubes must be positioned without misalignment and fixed by tack welding. During the tack welding, to avoid any discoloration or oxidation inside the tubes, they must be purged with backing gas. Due to the high melting temperature of chromium oxides blue or dark spots originated by tack welds can provoke a lack of fusion during the final weld operation.

The diameter of the tack welds must remain smaller that the width of the final weld seam. To ensure the complete re-melting of the tacking points during the welding process, the tack welding operations have to be carried out without filler wire.

Internal mechanical fixing devices can be helpful for positioning and welding, these devices are often connected to systems to control the backing gas flow rate; they are advantageous when used if SMS-fittings have to be joined for applications of the food and beverage industry.

Expert information: To reinforce the mechanical strength of an autogenously welded seam, additional material can be obtained by a preparation of one tube end with an overlapping collar ①. Another possibility is to place a welding insert into the gap between the tubes ②. A thoroughly selected choice of the insert alloy allows welding dissimilar materials which otherwise cannot be joined by autogenous welding.
14.5. **Electrode preparation**

To maintain a constant and compact form of welding arc, tungsten electrodes which will be used for mechanised or automatic welding should be prepared with a tapered end. The diameter of the electrode, the grinding angle "A" and the diameter "M" of the flattened tip depend on the weld current intensity. The grinding angle "A" should have a value between 18° and 30°, the flattened tip diameter should be prepared between 0.1 mm and 0.5 mm. Higher weld current intensities request a larger grinding angle and greater flattened tip diameter.

The length of the electrode must be calculated and cut dependant on the type of weld head, the OD of the tubes to be welded and the specified arc length. In many cases it is difficult to prepare the electrodes with the necessary precision on site even by using an electrode grinder. The purchase of ready-to-use electrodes on the market is often considered to be an efficient and economic solution.

Expert information: The tungsten electrodes should always be changed preventively, so a considerable amount of welding problems and defects (arc instabilities, ignition difficulties) can be avoided. Delicate applications sometimes require the electrode to be changed after each weld.

<table>
<thead>
<tr>
<th>Electrode diameter</th>
<th>Direct current [A]</th>
<th>Alternating current [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Straight polarity DCEN</td>
<td>Reverse polarity DCEP</td>
</tr>
<tr>
<td>0.020&quot; 0.05 mm</td>
<td>5-20</td>
<td>10-20</td>
</tr>
<tr>
<td>0.04&quot; 1.0 mm</td>
<td>15-80</td>
<td>20-30</td>
</tr>
<tr>
<td>1/16&quot; 1.6 mm</td>
<td>70-150</td>
<td>10-20</td>
</tr>
<tr>
<td>3/32&quot; 2.4 mm</td>
<td>150-250</td>
<td>15-30</td>
</tr>
<tr>
<td>1/8&quot; 3.2 mm</td>
<td>250-400</td>
<td>25-40</td>
</tr>
<tr>
<td>5/32&quot; 4.0 mm</td>
<td>400-500</td>
<td>40-55</td>
</tr>
<tr>
<td>3/16&quot; 4.8 mm</td>
<td>500-750</td>
<td>55-80</td>
</tr>
<tr>
<td>1/4&quot; 6.4 mm</td>
<td>750-1100</td>
<td>80-125</td>
</tr>
</tbody>
</table>

Electrode diameters to be selected for different welding current intensities
14.6. Backing gas

During orbital welding, the inner surface of the tubes must be protected against oxidation. Therefore, the interior of the tube system is purged by backing gas. The purity of the backing gas depends on the required weld quality. Before the weld can be started, a sufficient purge time must elapse, allowing the backing gas to remove the oxygen out of the system. The remaining oxygen content of the backing gas can be analysed at the outlet; if it has decreased to an acceptable value, the welding operation can begin. Usually in the case of UHP applications (Ultra High Purity) the oxygen level must fall below 10 PPM (Parts per Million), i.e. less than 0.001%.

Expert information: The supply of ultra-pure process gas requires that it passes through the tubes without being contaminated by moisture, oxygen, particles or other contaminants.

During welding, the specified values of flow rate and internal pressure of the backing gas must be respected and kept constant. The internal pressure must be controlled because excessive pressure will produce a root weld with a concave surface at the outside or, even worse, cause a weld bead short circuit.

If tubes with small diameters below 9.52mm (3/8”) are welded, the internal pressure can be used to prevent any excess of convexity or inside diameter reduction.

Expert information: A light heat tint, due to remaining oxygen in the backing gas, can be removed by passivation.

14.7. Chemical composition and repeatability of the welds

Several problems occurring during the welding of stainless steel can be caused by low sulphur content of the base metal. The sulphur content influences the surface tension of the molten metal, high sulphur grades are characterized by a narrow deep weld profile. Low sulphur contents cause a very wide but shallow weld bead with drastically reduced penetration, which can be explained by a phenomena named the Marangoni effect.

If a workpiece with very low sulphur content should be joined to a second one with high sulphur content, the arc can be deflected completely to the part with the lower sulphur content, thus excluding any acceptable standard weld operation. In some cases, a double non-stop run of the welding procedure may solve the problem.
15. Tube to Tube or Pipe to Pipe orbital welding with filler wire

15.1. Applications

For several reasons, it can become necessary to apply filler metal in orbital welding procedures:

- Wall thickness of the tubes requires a preparation of their ends
- Tubes or pipes to be welded are made of different base metals
- The weld must be reinforced
- Strength and/or corrosion resistance are compromised by fusion welding.

Tube-to-tube welding applications with the addition of filler wire are often demanded in the field of energy production (power plants) and chemical or petrochemical industries. A wide range of base materials are used:

- Plain carbon steel
- Low-alloyed chromium or chromium manganese containing carbon steel
- High-alloyed chromium nickel steel (austenitic or with an austenite-ferrite crystal structure)
- Nickel base alloys (like e.g. Inconel®-alloys or Hastelloy®-alloys)
- Titanium and its alloys.

Although the tube dimensions differ very much, the great majority is to be found in the range of:

- 26.9 mm and 219 mm (¾” and 8”) diameter
- 2.77 mm to 12.7 mm wall thickness

15.2. Choice of the equipments

For orbital welding with additional filler wire, standard equipment with 4 controlled axes (shielding gas flow, weld current intensity, torch rotation speed and wire feeding speed) or with 6 axes (4 axes + AVC and oscillation) can be used.

Independently from economic or other project-related considerations, the table below shows the technical requirements for 4 or 6 axes equipment to be used:

<table>
<thead>
<tr>
<th>Criteria</th>
<th>4 axes</th>
<th>6 axes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall thickness to be welded</td>
<td></td>
<td></td>
</tr>
<tr>
<td>small (&lt; 4 mm)</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>medium and thick (&gt; 4 mm)</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Accessibility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>reduced</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>free</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Weld sequence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>simple</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>difficult</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Level of automation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>low</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>high</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>
In the case of reduced accessibility of the work area, equipment with 4 controlled axes should be preferred. If easy implementation of the welding tool is required, the equipment with 6 controlled axes should be the choice that is always recommended.

15.3. Weld preparation

The standard preparation for the manual welding of tubes, bends, T-pieces and flanges is a V-joint with a gap. For different reasons, this type of preparation cannot be used for orbital welding (a gap is inapplicable in orbital TIG welding, tack welding points are impossible to remove, backing gas protection cannot be obtained, etc.).

Preparations for orbital welding are always designed as a joint without any gap at the root face. For accessibility reasons, the angles of standard V preparations have to be increased to 30° or even 37°. With this type of joint a regular penetration cannot be obtained; on the contrary, depending on the weld position significant concavities occur.

To avoid these problems, and to get the desired uniform penetration, a J preparation with a collar of the width L and the thickness T has to be selected. Indications about the recommended geometry of the preparation with respect to the tube diameter and thickness are given in the table below:

<table>
<thead>
<tr>
<th>Tube range ( (\text{mm}) )</th>
<th>Angle ( (°) )</th>
<th>Collar ( (\text{mm}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall thickness ( (\text{mm}) )</td>
<td>A</td>
<td>T</td>
</tr>
<tr>
<td>( 3 &lt; E \leq 6 )</td>
<td>( 30° )</td>
<td>1</td>
</tr>
<tr>
<td>( E &lt; 6 )</td>
<td>( 20° )</td>
<td>1,5</td>
</tr>
</tbody>
</table>

**Expert information:**

For automatic welding, the I.D. is often machined to get a thickness T with an acceptable tolerance (± 0.2 to 0.3 mm).

To ensure the necessary precision and repeatability of the weld preparation, machines for mechanical tube end preparation must be used. Two types of machines are available on the market:

- Stationary installed equipment designed to be used in the workshop
- Electric or pneumatic mobile machines which can be hand-carried to machine small batches or to be used on site.
To remove all traces of Rust as well as Oil, Carbon or Calamine Oxide Scale, the inside and the outside of tubes made from carbon steel must be machined.

Expert information: Metals which can be magnetised must be inspected: no remnant of magnetism or at least a very low flux density (less than 3 gauss) is acceptable. Otherwise, welding problems or defects (lack of penetration, lateral sticking or porosity) can occur.

### 15.4. Positioning of the tubes

Before orbital welding can be started, the tubes must be positioned and tack welded; generally a maximum misalignment (high/low) of half of the land thickness $T$ is tolerated. In order to avoid penetration faults during the laying of the root pass, tack welding must be carried out without, or at least with very low wire input. The prepared tube ends must perfectly fit together: no gap is permitted.

If stainless steel, nickel base alloys or titanium and its alloys have to be welded, a protection by backing gas is obligatory. In fact, carbon steel can be welded without backing gas, but a lower repeatability and an increasing repair rate of the welds must be accepted.

### 15.5. Multilayer welding

Two different methods can be applied to carry out multilayer welding. Which one can be used, depends on the features of the available equipment:

1. With four controlled axes, only the stringer bead technique with narrow weld seams first placed side by side and then super-positioned ① can be applied. In special cases, e.g. fillet welding (2G or PC) or even at 45° (6G or H L045), even if equipment with AVC and oscillation is available, the stringer bead technique is used.

2. Equipment with six controlled axes allows the movement the torch laterally. Passes with torch oscillation can be superimposed and/or laid side by side ②.
Multilayer welding with the stringer bead technique is quite complicated and time-consuming, as the process has to be interrupted after each pass and mechanical adjustments need to be made: the lateral position of the torch and the distance between the previous pass and the electrode must be corrected. These adjustments can only be executed if the particular parts of the welding head are accessible in its working position.

Welding equipment with six controlled axes significantly reduces the time required for manual interventions. With the AVC function the distance between electrode and workpiece is controlled, the oscillation allows coverage of the entire joint width or to position the torch laterally. Once the torch is positioned above the joint, the electrode will be centred in the gap automatically. The different passes of a weld can be chained, the winding up of the hose and supply cables can also be executed automatically, and so the operator is not distracted by repetitive actions and can fully concentrate on supervising the welding process.

15.6. AVC requires precise electrode geometry

If tungsten electrodes are used for automatic orbital welding, it must be ensured that their geometry remains absolutely the same. Even small variations of the shape or dimension cause significant changes of the arc voltage, which is used as a base value by the AVC control (see chapter 11.5.1). The difference of the arc voltage will be transformed by the AVC control to a different arc length which provokes differences of the melting bath size.

Expert information: An increased arc length provokes the loss of the arc pressure and can cause poor penetration and a concave surface geometry. If the arc length is too short, the electrode will be rapidly deteriorated.

15.7. Backing gas

For the manual welding of carbon steel a backing gas protection is not mandatory, the inside of the tubes is protected by the shielding gas passing through the gap at the bottom of the V joint.

In the case of orbital welding with a J-preparation without any gap at the root face, backing gas protection is strongly recommended. The formation of refractory calamine, which occurs distinctly if steel with higher manganese silicon content is welded, can be suppressed. Thus a better repeatability of the weld will be achieved. The backing gas types to be used for different base metals are listed at chapter 3.5.2.

15.8. Boundary parameters

The importance of boundary parameters, i.e. parameters which are not directly programmed at the machine, is often underestimated in orbital welding. The consequences are low repeatability of the welds and a decreased productivity. Some of the boundary parameters are listed below:

- Shielding gas: type, purity, flow rate
- Backing gas: type, purity, flow rate
- Gas lens: type and size
- Ceramic nozzle: size, diameter and length
- Electrode: type, diameter, end preparation and stick out
- Wire: grade and diameter; cast n°, entry angle, impact point
- Inter-pass temperature
- Ground cable position and connection.
15.9. Geometrical adjustments

For all applications the geometrical adjustments concerning the torch and the wire guide must be carried out thoroughly and documented clearly.

1. The angle between the tungsten and the arriving wire should be adjusted to a value between 50° to 80°.
2. The wire distance De-f to the electrode should be adjusted between 1.5 mm and 3 mm. For the root pass the larger value is recommended to use the kinetic energy of the wire to push the weld bead through and obtain some root convexity. For the filler and cap passes it is recommended to reduce the distance to 2 mm. By this, the wire is closer to the arc and melts easily. More wire can be fed and cold wire defects are avoided.
3. The wire stick-out Sf should be adjusted between 8 and 12 mm. If this distance is too short the wire nozzle will burn or stick. If the distance is too great the wire can twist in any direction and, for example, contaminate the tungsten electrode.
4. The arc gap H should be adjusted between 2 and 3 mm. In the case of 6 axes equipment the distance will be controlled by the AVC device. For a root pass weld the arc gap can be reduced to 1 mm.

15.10. Possibilities to increase the performance of orbital TIG welding

Orbital GTAW welding with cold wire is an adequate choice for standard applications which require high quality levels but compared to other arc welding processes, the deposition rate of the TIG process is relatively low (0.15 to 0.5 kg/h). In order to boost the efficiency of the process it is possible to use the hot wire technique.

15.10.1. Hot wire TIG welding

Increasing productivity without quality losses can be achieved using the hot wire TIG process. In this case, the filler wire is heated up by an additional current. This hot wire current is supplied by a second power source. The hot wire technique leads to appreciable higher deposition rates, i.e. 1 kg/h for orbital welding and much more for cladding applications.
16. Orbital tube to tube sheet welding

16.1. Range of materials and tube dimensions

Nearly all weld-able metals and alloys are used in the field of tube to tube sheet applications, but the range of the tube dimensions is relatively restricted. Their diameter range covers 12.7 mm to 101.6 mm, the wall thicknesses are between 0.5 mm and 5 mm. Most of the tube diameters measure between 19.05 mm (3/4") and 38.1 mm (1.5") with wall thicknesses between 1.65 mm and 3.4 mm.

Boilers and heat exchangers are used in all kinds of industries, whereas the heaviest equipment is found in the plants of the chemical or petrochemical industries and in electric power stations.

16.2. Welding equipment

In most cases, the welding equipment used for tube to tube sheet welding is strictly adapted to the kind of application and the desired level of automation:

1 - Welding equipment featuring three controlled axes (gas, current, rotation) is composed of a stationary installed power source* and an enclosed welding head. This equipment allows for the execution of fusion welding without addition of filler wire.

* Portable power sources are rarely used for these applications: there is no need for the machines to be carried.

2 - The welding equipment, including four controlled axes (gas, current, rotation, wire), is composed of a stationary installed power source* and an open welding head. The equipment is suitable for single pass welding; two passes must be welded in two separate steps.

3 - The welding equipment fitted with five controlled axes (gas, current, rotation, wire, AVC) is composed of a power source designed to control 6 axes and a welding head of the type TS 2000 or TS 60 with AVC configuration. The equipment allows the chaining of two passes with filler wire, the raising of the torch between the first and the second pass can also be programmed and is carried out without interruption of the weld cycle.

Example of a three axes application with a TS 25 welding head
16.3. Specific requirements of tubes and weld preparations

Compared to manual welding, the planning of the orbital tube to tube sheet welding requires some more specific attention:

1. The tubes have to be seamless (or with flattened weld); concentricity faults between the inner and the outer diameter must be limited to a minimum to allow the repeatability of the electrode positioning. With standard applications, (flush, protruding or recessed tubes) the torch is aligned at the inside of the tube whereas the welding is carried out at the external diameter. Concentricity faults would cause unacceptable variations of the distance between workpiece and electrode and thus directly alter the arc length.

Expert information: To get optimised centring tools for the tube to tube sheet welding heads, each order must be accompanied by information about the depth of the expansion and the tube diameter at the expanded zone as well as the original diameter.

2. As with V-joints it is virtually impossible to ensure reliable melting of the base of the tube edge, especially in the vertically down position, (fusion defects are to be seen on macrographic sections), these joints have to be replaced by J-preparations.

3. In some cases, if a good thermal conduction is requested, the play between the tube and the bore must be eliminated by a slight expansion of the tube. Play is necessary for the assembly of the apparatus before the welds are carried out, but if clearances become too great, problems of repeatability may occur. However, it is difficult to specify a maximum amount of play; it depends on the demanded weld quality and the thickness of the tube.

4. The contact zone between the tube and the tube sheet must be clean. Grease, oil or other residues from the tube manufacturing or machining can cause the formation of unacceptable blowholes, with outlets on the surface or enclosed in the welds.

5. A strong expansion of the tubes inside the tube sheet must never be carried out before automatic welding. A strong expansion (with or without longitudinal grooves in the bore) causes almost always explosive degassing effects which make automatic welding impossible.
16.4. Welding of flush tubes

Depending on the application, orbital welding of flush tubes with or without filler metal is possible. Different joint designs are shown below:

1 – Standard preparation
2 – J-preparation
3 – V-preparation
4 – Relief groove

Most often the type 1 preparation is carried out for the welding of flush tubes; rarely the type 4 is used. In case of tube diameters between 10 mm and 25 mm or 10 mm and 32 mm the use of especially developed welding heads, for these applications without filler wire, is recommended.

It is the operator’s task to position the welding head and to start the weld cycle. The complete sequence is carried out automatically; the operator is not needed any longer at this machine. Thus, one operator can work simultaneously with several welding heads.

Typical application: Condensers of thermal-electric power plants. Here, the tubes with a wall thickness of about 1 mm are made of titanium whereas the tube sheet is designed and manufactured as titanium-cladded steel plate.
16.4.2. Welding of flush tubes with addition of filler wire

Welding equipment fitted with four or five controlled axes can be used for this application; the open tube to tube sheet welding head should be configured with devices adapted to the requirements:

- Integrated or external wire feeder unit
- With or without AVC
- With or without shielding gas chamber (for the welding of titanium or zirconium)
- Torch angle of 0° or 15°.

Expert information: The AVC function is recommended especially for the welding of flush tubes.

Generally, the tube end preparations are of the type 1, 2 or 3. If a preparation of the tube sheet is carried out, the V-joint can be avoided. With this type of preparation, there is always the risk of incomplete penetration of the root. A J-preparation (with or without radius) should be preferred, if the depth of the bevelled edge exceeds 1.5 mm, the tube end should be positioned at the half of it. The maximum value of the tube end to be recessed is 50% of the tube thickness, the tube becomes flush by the weld.

Depending on the dimensions and the required weld thickness one or two passes are necessary. One tour of the torch is always applied in case of a pass for tightness; the layers for mechanical resistance often require a second tour.

Example of welding flush tubes to a tube sheet with a TS 2000 welding head

16.5. Welding of protruding tubes

Protruding tubes are always welded with addition of filler wire, but in some cases the weld is beginning with a fusion pass. As shown below, different joint designs are possible.

A - Standard preparation without groove
B – J-preparation
C – V-preparation
Welding equipment fitted with four or five controlled axes can be used for this application. Depending on the pitch and the protruding distance, the torch inclination may be varied. Standard torch angles are 15° or 30°:

- torches with an angle of 15° are preferentially used in case of thin-walled tubes (1.6 mm to 2.11 mm), thus melting the inside can be avoided
- torches with an angle of 30° are applied for thick-walled tubes (from 2.5 mm onwards) if there is sufficient space with regard to the tubes around (reduced pitch).

In any case, to avoid melting down the tube edge, the tube length measured from the ground of the groove must exceed at least 5 mm.

Remarque: If equipment fitted with five controlled axes is used, the AVC has to be operated in the relative height mode. Thus it is possible to adjust the distance between electrode and tube plate to get the best result, independently of the torch position.

Example of welding protruding tubes to a tube sheet with a TS 2000 welding head

Special attention must be paid to the training of the operators; differently to orbital tube-to-tube welding, where the mechanical adjustments of torch and wire guide are carried out in the same plane, tube to tube sheet welding requires three-dimensional operation.
16.6. Welding of recessed tubes

Different joint designs are shown below:

D: Standard preparation without groove

E: J-preparation

F: V-preparation

G: Welding behind the tube plate

Welding equipment fitted with four or five controlled axes and an open tube to tube sheet welding head can be used for the application D, E and F.

The preparation of the type G is frequently used in the petrochemical industry; welding equipment with six controlled axes and a welding head with separate clamping device have to be used. This type of application generally requires a specific project to study the best adaptation of clamping tools and welding procedures.

Expert information: Different to those applications with protruding tubes, in the case of recessed tubes a V preparation of the tube plate is possible. If joint preparations of the type E or F are applied, the tubes may protrude slightly from the base of the groove.

Depending on the dimensions, and the required weld thickness, one or two passes are necessary. One tour of the torch is always applied on the first pass for tightness; layers needed for mechanical strength and wear resistance will often require a second tour.

Particular application: Welding behind the tube plate of a double-walled collector for air-cooling or fluid condensation. The AVC operation is indispensable to make the weld in this application.

Welding behind the tube plate of a double-walled collector
16.7. Internal bore welding behind the tube sheet

To avoid gap corrosion between the tube and the tube sheet, gapless joints are welded from the inside of the tubes at the backside of the plate. This type of application requires extended accuracy of the workpiece preparation and welding. Some possible joint designs are shown below:

X: Standard without groove  
Y: Preparation with relief groove, without recess  
Z: Preparation with relief groove, with recess

A joint preparation of the type X is not recommended: the greater mass difference between the tube and the plate excludes the possibility to achieve a sufficient penetration. The joint preparation of the type Y overcomes the penetration problem by creating a welding zone with a better balanced mass of the tube and the plate.

For three reasons, by the joint preparation of the type Z the weld conditions become quite similar to those of a standard orbital tube-to-tube weld operation:

- By the recess the tube is aligned on the bore.
- Melting down the collar offers some additional metal which increases the mechanical strength of the weld.
- The concave form of the weld is reduced.

Expert information: Unlike classic tube to tube sheet applications, the internal bore welding operations behind the tube sheet require a gas protection of the root, (at the outside of the tube). Only with a preparation of the type X, where the tube end is positioned sufficiently deep in the bore (e.g. half of the tube wall thickness), a root protection is not necessary. The protection can be provided by flooding the entire apparatus with inert gas or, if the backside of the plate is accessible, by a local protection applied tube after tube.

With a tube I.D. of more than about 35 mm, the use of welding tools with filler metal is possible.
If relatively thick walled tubes of 3 mm to 3.6 mm, (depending on the base material), are to be welded, a horizontal weld position with the plate at the bottom with the Weld Head also horizontally positioned, is recommended.

The distance from the face of the plate to the welding joint must be very precise, (close tolerance). The operator cannot see the torch position inside the tube, he has no possibility of adjustment and he cannot watch the welding process.

The weldability problems resemble those discussed in Chapter 1.4 for tube-to-tube fusion welding.

17. Conclusion

At the end of this booklet, it remains to underline once again the importance of orbital TIG (GTAW) welding if sophisticated applications require reliable outstanding joint quality. For several decades, the company has developed and manufactured appropriate gear and can offer a wide range of standard machines or adapt it for specific demands. The modular design of the devices, i.e. welding heads and power sources, allows the proposal of tailor-made solutions to exigent customers, always taking into consideration the special constraints of the particular project.

Welding equipment fitted with three or four controlled axes can be used for this application, in the case of a joint preparation of the type X, five controlled axes are necessary. The welding heads must be equipped with a particular lance for internal bore welding.

Similar application: If nipples have to be welded on a collector, (this is typical application in the field of power plant equipment construction), identical base materials are used, and the joint preparation and the precautions to be taken are similar to those of internal bore welding behind the tube sheet.

The sales department, the engineering and the application service would highly appreciate participating in your welding activities.