

Orbital Welding in Critical Systems

Introduction

Orbital welding has steadily gained popularity in the last ten years, mainly due to the semiconductor industry's requirements for better gas distribution systems. These systems encompassed all the requirements of a critical system. Orbital welding did not get its start in the semiconductor industry but found its growth there. The time has come to apply orbital welding technology to a broad range of industries.

What is a Critical System?

A critical system is any system:

- Where failure is not acceptable.
- That is subject to high levels of corrosion.
- Where entrapment areas are a concern.
- Which must be purged or cleaned between cycles.
- That is used for sample analysis.
- Which handles fluids or gases that must not enter the environment.
- That handles a product sensitive to contamination.

In fact, a critical system is almost any system you may need or be asked to install.

What is Orbital Welding?

Orbital welding is an automated GTAW (Gas Tungsten Arc Welding) process; the welded material remains stationary while the welding electrode is moved around the weld joint. The process is typically autogenous, which means that no filler is used. The autogenous welding limits the wall thickness to approximately .16 in. or 4 mm.

Material Selection

There are a number of types and classes of materials available, and there is just as large a group of subclasses. You may find yourself ordering 316L, VIM/VAR, ultra low manganese, electropolished to a 5Ra max., hydrogen bright annealed OD with electrically etched mill markings when all you thought you needed was stainless steel. The following considerations are some of the most important for selecting a material:

- The material must meet your specific requirements.
- The material can be autogenously welded.
- The material has the best ID surface for your requirements.
- Other components such as fittings, valves, and regulators are readily available in the material.
- The material is readily available and is cost efficient.

The material of choice, by far, in most systems is 304L stainless steel or 316L stainless steel. The other choices include carbon steels, ferrous alloys, other stainless steels, nickel alloys, refractory and reactive metals. Whenever possible use tubing, not pipe, for your critical systems. Typically, tubing is readily

available with the requirements necessary for orbital welding in these systems. The tubing should be annealed because the weld area will be annealed after welding. The strength added by tempering will be lost in the welding process.

Material Handling and Storage

The handling and storage of materials begins when it is shipped and is complete when it is installed. Tubing can usually be ordered individually wrapped, capped, and specially cleaned. Requiring the supplier to use heavy cardboard or PVC shipping tubes will help you receive tubing in usable condition. The trucking company may keep it dry and may not even physically damage the tubing, but the individual wrapping and caps will be its only protection from high humidity and temperature changes. Limiting the effects of humidity and temperature fluctuations can be as important as maintaining the tubing surface finish and cleanliness. For example, moisture inside the tubing can cause excessive oxidation in some applications, hydrogen cracking in some materials, and a host of other ills. The material should be inspected upon arrival and stored in a climate controlled environment until you are ready to use it. Make sure anyone who handles material has been trained. The material should be separated by heat number and surface finish. You should further segregate tubing which has passed weldability testing.

Sulfur Matching and the Marangoni Effect

The chemistry of stainless steel has a direct effect on its weldability. A chief factor which contributes to its weldability is the sulfur content. The sulfur in the steel is referred to as a surface active element. The level of sulfur can make the surface tension of the weld puddle change, affecting the heat flow into the puddle. This characteristic is sometimes called the Marangoni Effect. The sulfur content of 316L, which can vary from 0 to 0.03 % by weight, has a direct affect on the penetration characteristics of the material. The weldability of stainless steel decreases as the sulfur content decreases.

Standard 316L has sulfur levels in the range of 0.015 to 0.025 % by weight. This material exhibits good welding characteristics, requiring less heat input for a set depth of penetration when compared with materials of lower sulfur content.

The weldability of 316L changes significantly when the sulfur level drops below 0.005 % by weight. These lower sulfur levels, common in 316L used in orbital welded critical system applications, change the surface tension and make weld penetration more difficult to achieve. The change in surface tension allows the heat to flow away from the center of the weld puddle. Weld penetration decreases and the OD width of the weld bead increases. The weld, in some cases, can be 50 % wider than with a higher (above 0.01 % by weight) sulfur level. To overcome the decreased penetration, weld heat must be increased, sometimes by as much as 40 %. The increased heat can reduce the corrosion resistance of the weld and cause increased grain growth in the heat affected zone. The greatest challenge occurs when materials with different sulfur levels are

welded together. The sulfur content causes both good and bad characteristics in stainless steel, but here are a few guidelines:

- When orbital welding, the sulfur content should be restricted to less than .017 % by weight.
- The tubing and components should be sulfur matched to less than a .007 % sulfur difference between the two materials. When the sulfur difference exceeds .01 %, the puddle shift may cause a lack of penetration in a portion of the weld joint.
- If you are forced to weld two materials with excessive sulfur differences, these procedures may help:
 - Use a multi-pass weld program.
 - Use a 95/5 argon/hydrogen mix on the head shield gas.
 - Use a high primary amperage with reduced percentage of the pulse cycle.
 - Use a slow rotor travel speed.
 - Move the electrode to the high sulfur side of the joint.

Use lower start amperage or longer ramp-up time with a long rotor delay to help establish penetration with minimum shift.

Ultra low Sulfur

Sulfur contents below .003 % by weight offer fewer inclusions in the metal, which in turn allow for better surface finishes. The weld surface is also improved. These benefits are most notable in electropolished tubing used in systems that handle highly corrosive gases. The cost of material and availability of machined components should be considered. The formation of dendrites that extend above the surface after the welding process is greatly reduced in this material. The weld area will be much smoother with a much lower entrapment area and much higher corrosion resistance, in most applications, than the weld area in higher sulfur materials.

Low and Ultra Low Manganese

Manganese is released as a vapor during welding and is re-deposited downstream of the weld. This is a matter of controversy but is a consideration in only the most corrosive of systems. The cost of material and availability is a major factor. Most surface deposited manganese can be removed by a hot (80°C / 180°F) DI water rinse for approximately one hour, when this is an option.

Carbon Content and Welding Stainless Steel

When welding stainless steels, carbide precipitation can occur at carbon levels above .03 % by weight. Temperature and time at temperature, as well as carbon content, play an important part in the development of carbide precipitation. Carbide precipitation reduces the corrosion resistance of the material. The L grade meets carbon content requirements in 304 and 316 stainless steels but at a cost of an approximately 15 % loss of

strength. Make sure to use pressure tables for L grade when calculating the wall thickness requirements.

ID Finishes of Stainless Steels

Passivation removes the Fe (iron) particles from the surface of stainless steel and forms a thin chromium oxide film. Passivation can be done before or after installation. It is an inexpensive and effective corrosion resistant barrier in many applications.

Electropolishing is a surface enhancement which provides for very good surface finishes with a much thicker chromium oxide barrier. Electropolishing is common in UHP systems where clean up time and ultra low contamination are primary concerns. In many cases, it is also a more effective corrosion resistant barrier, but it comes at a large cost.

Tungsten Electrode

The electrode is a major player in orbital welding. The use of standard programs and the fact that an orbital welding machine cannot make visual adjustment to differences in the grind of the tungsten make hand grinding impractical. The following are considerations when choosing an electrode and grind:

- Electrode size is a function of the current required for the weld and the orbital weld head requirements.
- Electrode grind angle is a trade off between stability of shallow angles and penetration of steeper angles. The penetration factor is not as noticeable at current levels below 100 amps, and most orbital welding is done below 100 amps average current. The shallow angle usually is preferred, but check the welder manufacturer's recommendations.
- Electrode tip diameter is again a trade off between ease of arc start (small diameter) and power capabilities, penetration, and tungsten life (large diameter). The factor is usually linear from .010 (.25 mm) to .040 (1 mm). The diameter is a matter of choice, but it must remain constant between tungsten electrodes used on the same programs.

Electrode material is again a matter of choice, but three types are the most common:

- Thoriated tungsten (ThO₂-W) 2 % has been used by hand GTAW welders for years but is not the oxide of choice for orbital welding because it is slightly radioactive, has poor restart capabilities, and short service life.
- Ceriated tungsten (CeO₂-W) 2 % is a good choice.
- Lanthanated tungsten (La₂O₃-W) is less available in the US but is an acceptable choice.

Arc Gap

The Arc Gap is a critical dimension. The arc gap, to a large degree, is controlled by the weld current and the roundness of the tubing. When the roundness of the tubing changes, the arc gap changes. The arc gap changing during the weld cycle causes

the heat input to change. This is a percentage of the change to the original arc gap. The penetration, heat input, ease of arc start, and stability of the arc are improved by narrow arc gap. The arc gap you choose is a compromise between how well your material dimensions are controlled and the optimal narrow gap. The tungsten electrode must be installed with the same gap each time to ensure repeatable performance.

Purge Gas

Individual welds can be rejected for a number of reasons, but orbital welding jobs are most often a success or failure because of purge procedures. The following information represents some of the facts:

1. Standard Grade Argon : 99.95 % : used in most general purity systems and is also the minimum purity for GTAW welding.
2. UHP Grade Argon : 99.999 % : used in high purity systems and is also the minimum purity for reactive and refractory metals.
3. Research Grade : 99.99999 % : used in ultra high purity systems
4. Electronic Grade : usually available in UHP and Research Grades Gases only : has additional requirements such as lower ppm of O₂ and H₂O and/or particle requirements.
5. Normally, ID purge gases must meet or exceed the installed system gas purity.
6. Head purge gases usually are not considered as critical.
7. Specifications calling for Electronic Research Grade Argon can usually be achieved by using UHP certified cryogenic argon with a purifier and a .003 micron point of use stainless filter.
8. Oxidation of the weld area is minimized any time the combined O₂ and H₂O levels are below 100 ppb and sufficient flow is used (2.5 feet / 7.62 decimeters per second will normally give satisfactory results with low sulfur tubing). The prepurge time should be sufficient to allow 10 changes of internal volume.
9. Argon / hydrogen, argon / helium, or many other argon mixes are available in cylinders or can be mixed on site. Sometimes the major benefits of these mixes can be achieved by their use in head purge only. Safety and cost factors should be considered.
10. The desire to go to cheaper ID purge gases, mainly nitrogen, on larger size tubing is possible but not in all materials, and N₂ is not as inert a contaminant in many systems as argon.

ID Purge Pressure and Flow Rate

The ID pressure must be controlled at the weld point, and the purge rate must be maintained. The ID purge rate for each tubing size and the heat number are set when weldability tests are performed. The ID purge pressure has a number of factors affecting the pressure (length of tubing; number of fittings or bends; amount of elevation change; and/or components such as valves, regulators, check valves, or filters). Restrictors may be

used at the purge exhaust to minimize the amount of purge gas used. The restrictor may be removed and a vacuum may be applied to the purge exhaust to maintain the ID pressure and the ID flow rate. The use of purge tables will help minimize the confusion. A typical chart is shown below:

Tube Size	Wall Thick.	Min. ID Rate	Magnehelic Pressure	Restrictor Size
1/4"	.035	7 SCFH	2.8-3.4 IWC	1/8"
6 mm	1 mm	2.5 L/M	71-86 MMWC	3 mm
1/2"	.049	15 SCFH	1.0-1.5 IWC	1/4"
12 mm	1 mm	7 L/M	25-38 MMWC	6 mm

Setting the Weld Parameters

The weld parameters may be set in a number of ways, but control must be maintained. Visual check by either couponing or using a borescope are used to set the parameters. Other non-destructive testing may be used in system weld verification.

When to verify the weld parameters:

- 1) Start of shift (in), and end of shift (out).
- 2) Change of weld parameters.
- 3) Change of material (heat).
- 4) Change of tube size or wall thickness.
- 5) Change of ambient temperature $\pm 20^{\circ}\text{F}$ (11°C).
- 6) Change of source of power to power supply to include addition or subtraction of extension cords.
- 7) Change or removal of the weld tungsten.
- 8) Any change of equipment such as weld head, weld head extensions, or power supply.
- 9) Any time that a weld discrepancy is noted by the welder.

Undercut in Orbital Welding

Undercut must not be confused with OD concavity. Undercut occurs on the edge of the weld. It will appear as a sharp and defined defect. Undercut reduces the wall thickness, and the sharp change creates an area for fatigue to occur. There should be no undercut visible to the unaided eye.

OD Concavity and Convexity

The concavity is the amount of fall in the weld area from the material surface. The convexity is the amount of rise in the weld area over the material surface. Unless these conditions exceed 15 % of the wall thickness, joint strength is not affected. Concavity and convexity are more of an indication of the ID condition of the weld. The OD of critical system orbital weld is normally held to 15 % convexity and 10 % concavity.

ID Encroachment

ID encroachment is the amount of rise in the weld area from the internal surface of the tubing. Negative encroachment is not normally allowed because it becomes an entrapment area. Positive ID encroachment is normal in the 0 to +10 % of the wall thickness when measured at the bottom of the weld.

Bead Width

The bead width is measured on the ID of the tubing. Bead width should be controlled to a minimum without increasing chance of lack of fusion caused by variation or meander. These are some of the concerns:

- The wider the bead width, the more the heat input. This causes concerns with stainless alloys, nickel alloys, refractory or reactive materials, which account for almost all materials used in orbital welding.
- The wider the bead width, the harder it becomes to maintain a good weld profile.
- When using electropolished or passivated material, the weld area is no longer treated. In a 3/4 in. system, .065 (1.65 mm) wall thickness with 200 welds, the difference between a bead width of 1 wall thickness and 3 wall thickness would be 26 inches (66 cm) of non-passivated or non-electropolished area.

Bead widths between 1.5 to 2.5 times the wall thickness are usually very successful.

ID Bead Variation

The bead variation is the amount that the ID bead width changes. The variation does not affect the weld unless it causes lack of penetration or becomes so wide as to affect the weld profile. The bead variation is affected by heat input, wall thickness, and material chemistry. Orbital welding bead variations should be controllable to less than 25 % of the bead width.

ID Bead Meander

The bead meander or snaking is the movement of the centerline of the weld from the centerline of the weld joint. The meander does not affect the weld unless it becomes excessive and causes lack of penetration. Bead meander is usually caused by the material. Contamination of the tubing, hardness changes, both metallic and non-metallic island inclusions in the weld pool, and excessive head purge are the usual causes. The bead meander should be controllable to less than 20 % of the bead width when using good materials.

Pulsed and Non-Pulsed Welds

Non-pulsed welds account for a very small percentage of orbital welds. The material used must be very low in inclusions to be successful. The perceived benefit of a non-pulsed weld is a very smooth weld surface. The drawback is that a higher average amperage must be used in most materials. The very smooth weld surface is more a factor of the material chemistry than the lack of pulse. The pulse ripple is basically parallel to the flow and is swept by it. In material higher in sulfur, manganese, and gaseous inclusions, the dendrites and craters formed in the weld area are a much greater entrapment area than the pulse ripple.

Pulsed welding has several benefits that make it popular:

- The low pulse or background amperage allows partial solidification of the weld pool which makes the weld profile more manageable.
- The high pulse amperage helps stabilize the penetration of the weld.
- The pulsing action helps the weld pool deal with both metallic and non-metallic inclusions.

The frequency of the pulse rate is the number of times the arc changes from high pulse amperage to low pulse amperage in one second. The percentage of time between high pulse and low pulse is the balance. Orbital pulsed welding usually lends itself to the high pulse being equal or shorter in time compared to the low pulse time. The low pulse is normally approximately 20 to 30 % of the high pulse amperage. Bead overlap is the percentage each high pulse overlaps the previous high pulse. The closer the pulses, the smoother the weld bead. When the frequency of the pulses becomes too high, the weld pool loses some of the benefits of pulsing. Bead overlaps of 70 to 90 %, when measured on the ID of the weld, have been very successful.

Weld Travel Speed

The penetration of the weld, the weld width, the weld puddle shape, and the solidification structure (dendrite) of the weld are affected by the number of inches per minute the tungsten travels over the tube. The fashionable trend is to make the weld at as high a travel speed as possible. The danger of this is very real. The cooling rate and pattern may cause structural integrity problems. The travel speeds for orbital welding are well known and great care should be used before abandoning them. The weld puddle shape is the key; it should be almost round to slightly oval in shape. If the weld puddle is misshapen, the dendrite pattern will change. The ID pattern may be acceptable, but the OD pattern, which cools last, will not be acceptable.

Axial Alignment of the Weld Joint

The two pieces of material should be aligned. Misalignment may cause structural strength problems due to reduced wall thickness, and will most likely cause entrapment areas and increase the possibility of lack of penetration. Alignment should be maintained to an average of less than 10 % of the wall thickness.

Weld Joint Fit-Up

Facing the ends of the tubing material is necessary to produce consistent welds. The weld joint must be flat with little or no loss of material thickness due to chamfering. The pieces must fit together with little or no gap. The maximum gap or chamfering should be less than 10 % of the wall thickness or .005 (.02 MM), whichever is less. Excessive gap or chamfering will cause loss of wall thickness in the weld and may cause lack of penetration due to weld pool shift.

ID Oxidation

There is always oxidation of the weld area and of the material adjacent to the weld. (The common term for oxidation is color.) The degree of acceptable color may range from none visible to the unaided eye under bright fluorescent lighting to no surface porosity (common term sugaring). The application and the material used are the keys. Some applications such as highly corrosive lines must have minimum oxidation and all the reactive materials must maintain an oxygen-free environment for a successful weld.

Delay

Delay is the amount of time between the initiation of the arc and the movement of the rotor. Delay will range from zero to several seconds depending on the material and its thickness. This time allows for penetration of the material and stabilization of the arc before rotor travel begins.

Single or Multi-Pass Weld Cycle

The single pass weld has gained popularity because of improvements made in material. It has the advantage of a shorter weld time and reduced heat input to the weld. These advantages are more important when dealing with stainless and nickel alloys, refractory and reactive metals, where heat input can be critical. It is also useful in helping to control ID oxidation (color).

Multi-pass welding can be an effective tool in dealing with problems of material mismatch or materials with high levels of inclusions. It is also a useful tool when dealing with very small or very thin material. The multi-pass weld has been much maligned over the past few years but can be a very useful tool with many materials and in many applications.

Weld Tail-Out or Downslope

At the end of the weld cycle, the current is slowly reduced until the arc goes out. Downslope must be of sufficient length to prevent a crater crack at the end of the weld.

Weldability Testing

The weldability test is possibly the most misunderstood test in orbital welding. Both the reason for conducting the test and the information gained from the test are misunderstood. Weldability testing confirms that the material received will make suitable welds. Any unacceptable material is rejected as soon as possible to minimize the impact on production. The purge flow rates, purge pressure, and weld schedules used should be documented and passed on to the field welders to make their job much easier.

System Components

The system you design and build should be suited for your needs and budget. The need for cleaner systems has created a new product line which includes bellows valves, diaphragm valves, and regulators. These products are available now, but you need to know to ask for them.

Equipment

The success of any contractor is tied to the choice of equipment. The design, up-time, serviceability, ease of operation, and total cost of ownership far outstrip the initial cost. The power supply should be a micro-process controlled, pulsed, DCEN unit capable of producing quality orbital welds. The equipment's size and weight should lend itself to a portable application. The weld head should be fully enclosed with strong fixturing. Fully enclosed heads provide major advantages such as system cleanliness and control of oxygen to the weld OD. Half or more of the field welds rejected are due to axial misalignment. Therefore, a combination of quality equipment and welder training is important for success.

Quality Control

The Quality Control or Training department will handle most of your craftsman training. Your QC/Training department should be one of the first groups formed and manned. Consider hiring a QC consultant to help you form and initiate this department. Look at third party Quality Assurance Representative (QAR) firms that are active in your industry and area for help. Acquire a copy of the industry specifications or create your own, well in advance of your planned start date. The specifications will govern your procedure. The procedure will ensure that everyone knows what is expected and has some idea how to accomplish the task. Build a weld library, which is a group of sample welds showing minimum bead width, maximum bead width, maximum variation, maximum encroachment, maximum OD convexity / concavity, and maximum snaking (meandering) for each size. The library may also include ID color lines that are applicable for each size and heat number. Always complete a weldability test on every size and heat number received. And, a positive procedure for keeping track of system welds and coupons on all critical systems is mandatory.

Training starts by getting your instructors, lead men, and / or QC staff trained on the orbital equipment. Training is too important a consideration not to investigate before your equipment purchase. The time and expense of training may well determine the success or failure of your orbital welding program.

Conclusions

Orbital welding has been around for twenty-five years, but its popularity in the last ten years in the semiconductor industry has highlighted its benefits. New applications are being found, and there is greater acceptance of the process in other

industries. One of the common misconceptions is “that is not needed in our industry.”

Most of the procedures developed in the semiconductor industry should apply to all orbital welding. If you have a need to join tubing or thin walled pipe, orbital welding may be in your future. The advantages of stainless tubing over small bore carbon pipe are many, and the installed cost may be substantially less. The growing need for systems that clean-up quickly and offer high resistance to corrosion from the inside or the environment in which it must exist make orbital welding one of the fastest growing segments of the welding industry. Train your welding operators well, establish a realistic procedure and follow it, establish an inspection procedure and implement it, buy the proper material and equipment, and the rest is easy.

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These are a few of the many individuals who have gladly shared their help and assistance in the past:

Mike Nolan of FST, Morgan Hill, CA

Dr. Barbara Henon of AMI, Pacoima, CA

Dr. Sunniva Collins of Swagelok Company, Solon, OH

Ernie Benway of Swagelok Company, Solon, OH

Janice Edler of IBM, Essex Junction, VT

Virginia Ryan of Dominion Semiconductor, Manassas, VA

Denny Bilodeau of Northeast Engineering, Essex Junction, VT

Byron Barefoot of High Purity Systems, Manassas, VA

Theses organizations have furnished technical data and material:

Swagelok Company, Solon, OH

AWS (American Welding Society), Miami, FL

ASM (ASM International), Materials Park, OH

TWI (The Welding Institute), Cambridge, United Kingdom

Diamond Ground Products, Agoura Hills, CA

Pall Filters, Exton, PA

Millipore Filters, Bedford, MA

Nickel Development Institute, Londonderry, NH

Valex, Ventura, CA

AMI (Advanced Microfinish Incorporated), North Ridgefield, OH

Sandvik Steel, Arnprior, Ontario, Canada

Areonex Purifiers, San Diego, CA

SEMATECH, Austin, TX

Lincoln Electric, Cleveland, OH

United Association of Journeymen and Apprentices of the Plumbing and Pipefitting Industry, Washington D.C.

To the individuals and organizations I have missed, I apologize.

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