Co-funded by the Erasmus+ Programme of the European Union

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CU 01: DED-ARC

Day 4: Influence of Process Variables on Process and Parts for Plasma Arc Welding (PAW)

Prepared By: Joseph Chamberlin

FOR SAM PILOT ATTENDEES AND TRAINERS ONLY

MM17,21

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Break	10:50 – 11:00
2. Influence of Process Variables on Process and Parts for Plasma Arc Welding (PAW) Session 2 2.1 Nozzle Orifice 2.2 Wire Position and Height 2.3 Wire Feed Speed and Deposition Rate 2.4 Wire Diameter 2.5 Torch Orientation 2.6 Arc Types 2.7 Variants (Number of Wires, Hot Wire)	11:00 – 12:30
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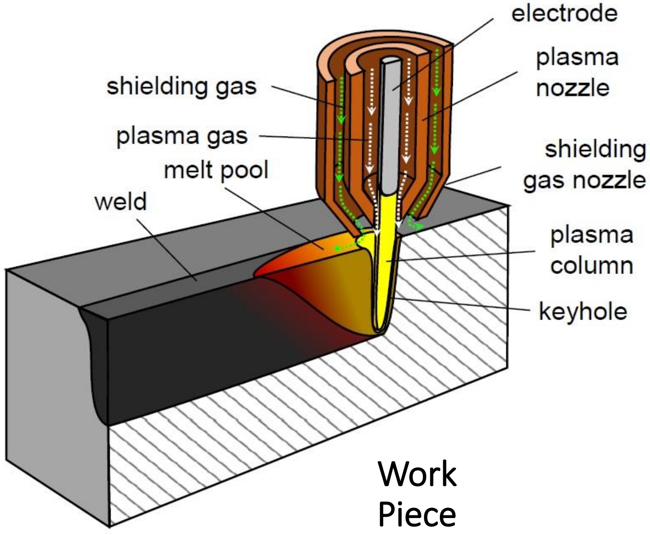
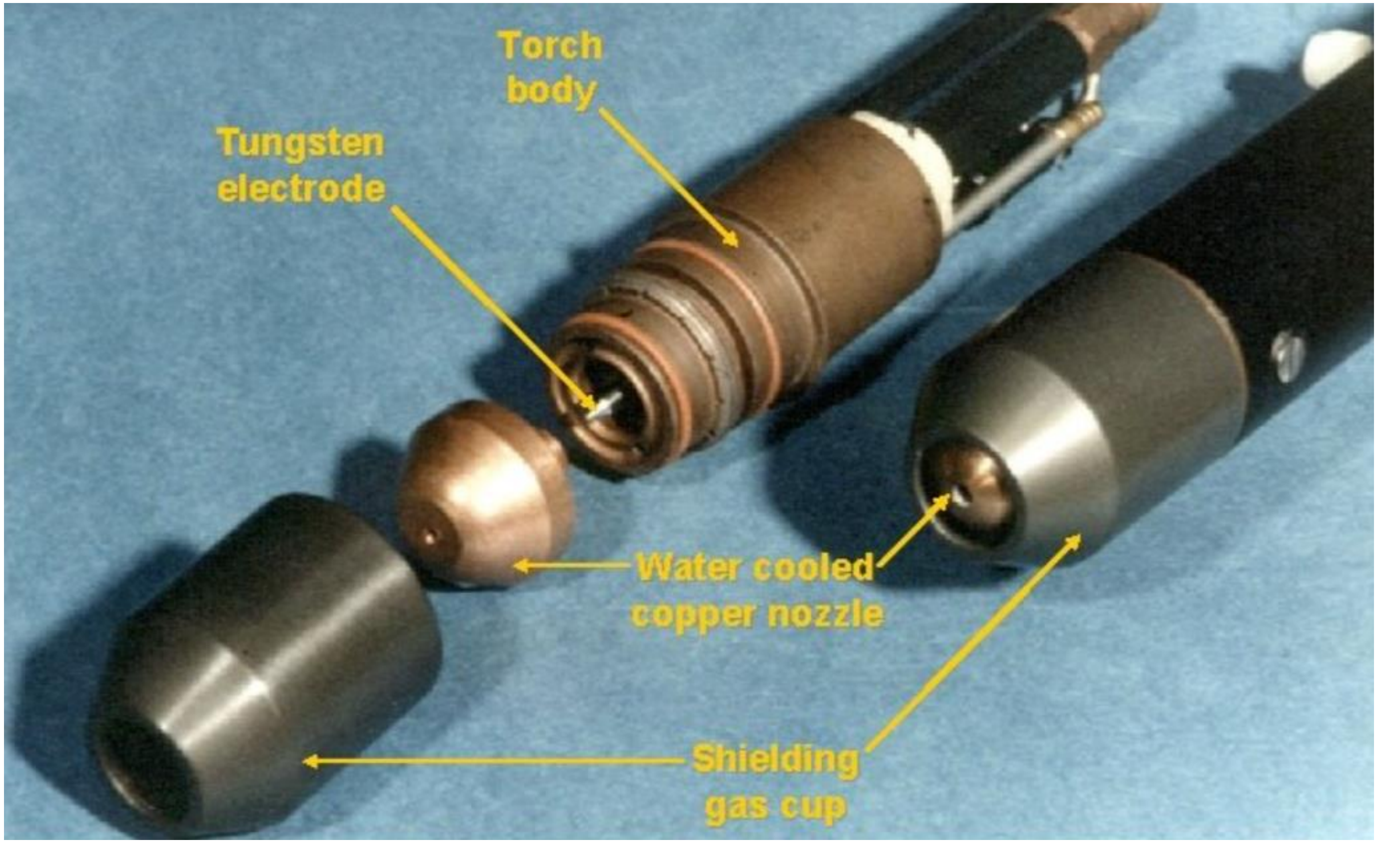
Introduction to Plasma Arc Welding (PAW)

- Arc struck between non-consumable tungsten electrode and work-piece.
- Tungsten electrode tip is enclosed in a cavity within a copper nozzle at the end of the torch.
- Pilot arc produced between the tungsten electrode and the inner nozzle using the high-frequency unit.
- Arc is formed using electrode connected to +VE OR –VE DC depending on type of PAW system
- Plasma formed within a gas shroud at tip exits through a small hole in the nozzle to form a meltpool on the workpiece.
- Inert gas (argon) is used to protect the meltpool /workpiece from oxidation.
- The head is water cooled to prevent over-heating.



Source: https://www.ionix.fi/en/technologies/plasma-processing/plasma-welding/



Source: https://slidetodoc.com/plasma-arc-welding-paw-principle-of-operation-principle/

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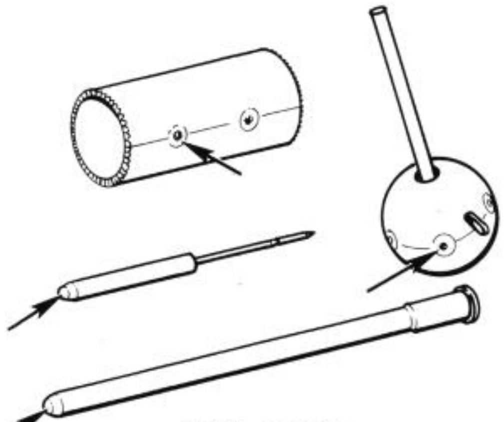
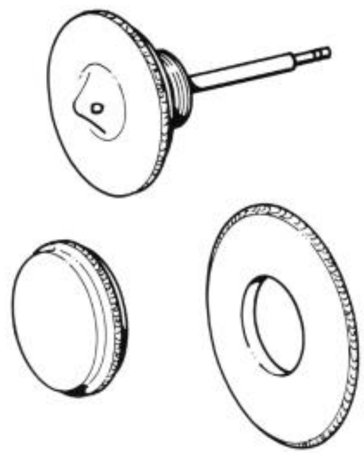
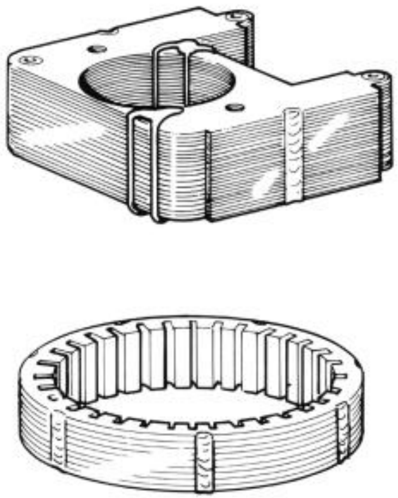
Typical PAW welds



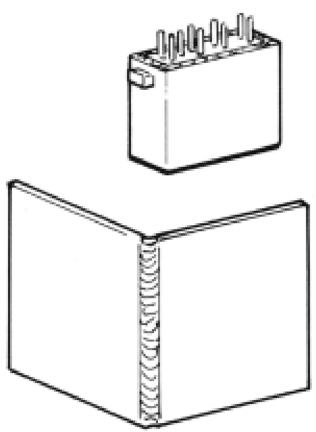
SPOT WELDS



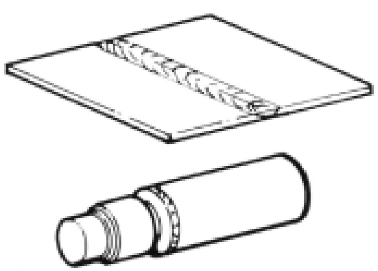
CIRCUMFERENTIAL EDGE WELDS



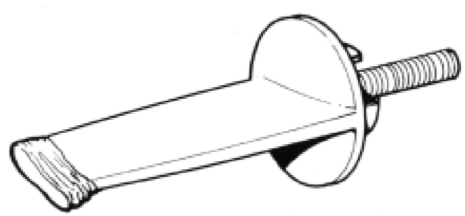
LAMINATION WELDS



FLANGE/EDGE WELDS



BUTT WELDS



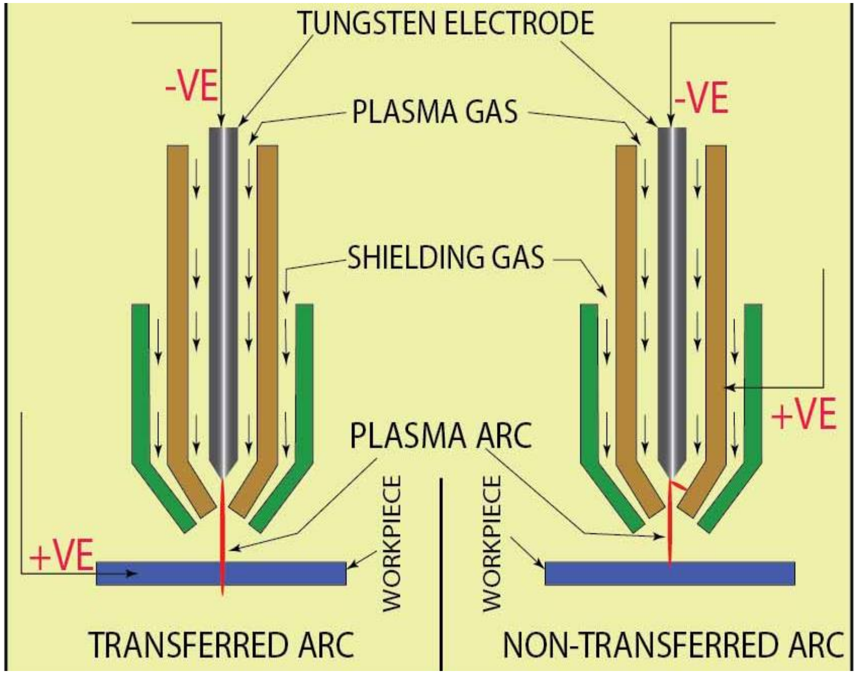
BUILD-UP WELD

Source: http://sanrexwelding.com/wp-content/uploads/2021/01/PAW-Hand-Book.pdf

In this case head has internal powder feed rather than wire feed
Repair application to provide hard surface

Source: Plasma Hardfacing

Transferred & Non-Transferred PAW



Source: https://workshopinsider.com/plasma-arc-welding/

<u>Transferred</u>

DC connections

- electrode -ve,
- workpiece +ve

Used for welding <u>thicker</u> gauge material

Pilot arc turned off once arc established with workpiece

<u>Non-Transferred</u>

DC connections

- electrode +ve,
- workpiece -ve

Used for welding <u>thinner</u> gauge material

Pilot arc continues throughout weld process

Note: For aluminium and magnesium a square wave AC supply may be used

PAW Operating Modes

Source: https://fractory.com/plasma-arc-welding-paw-explained/

Microplasma (Low current 0.1 – 15A)

- Stable arc up to 20mm.
- Used to join thin sheets up to 0.1 mm in thickness.
- Optimal for creating wire meshes with minimal distortion.

Medium Current (15 – 200A)

- Similar to TIG welding.
- Arc is stiffer since narrow nozzle opening restricts plasma.
- weld pool penetration can be increased by speeding up plasma flow rate, but this increases risk of shielding gas contamination.
- Medium current or melt-in mode offers better penetration than TIG and improved protection.
- Drawback is torch requires maintenance and is bulkier compared to TIG.

Keyhole Mode (high current over 100A)

- Increased gas flow and welding current gives powerful plasma beam “keyhole.
- Deep penetration, using a single pass (up to 10mm thick for some materials)
- Creates consistent weld pool from molten metal.

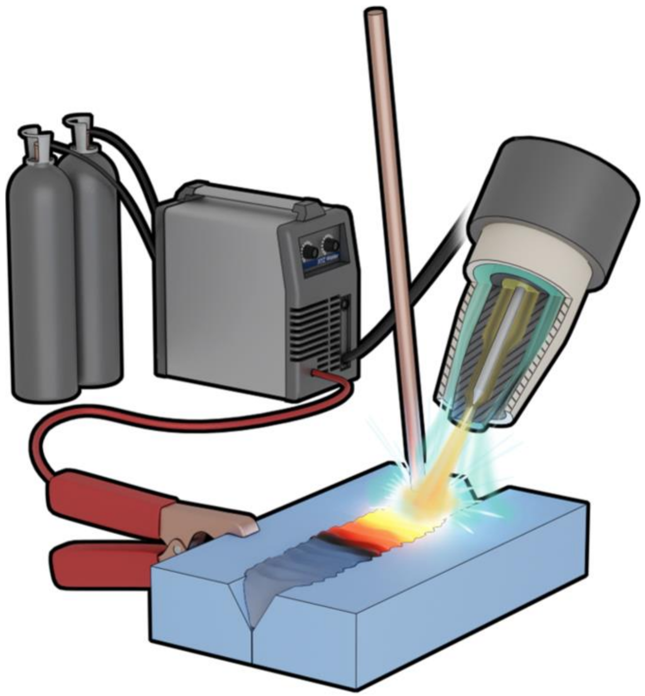
PAW-DED

- PAW adapted for DED by introducing separate wire feed on robot or CNC system

- The wire feed methods have an important influence on material transfer and deposition quality.

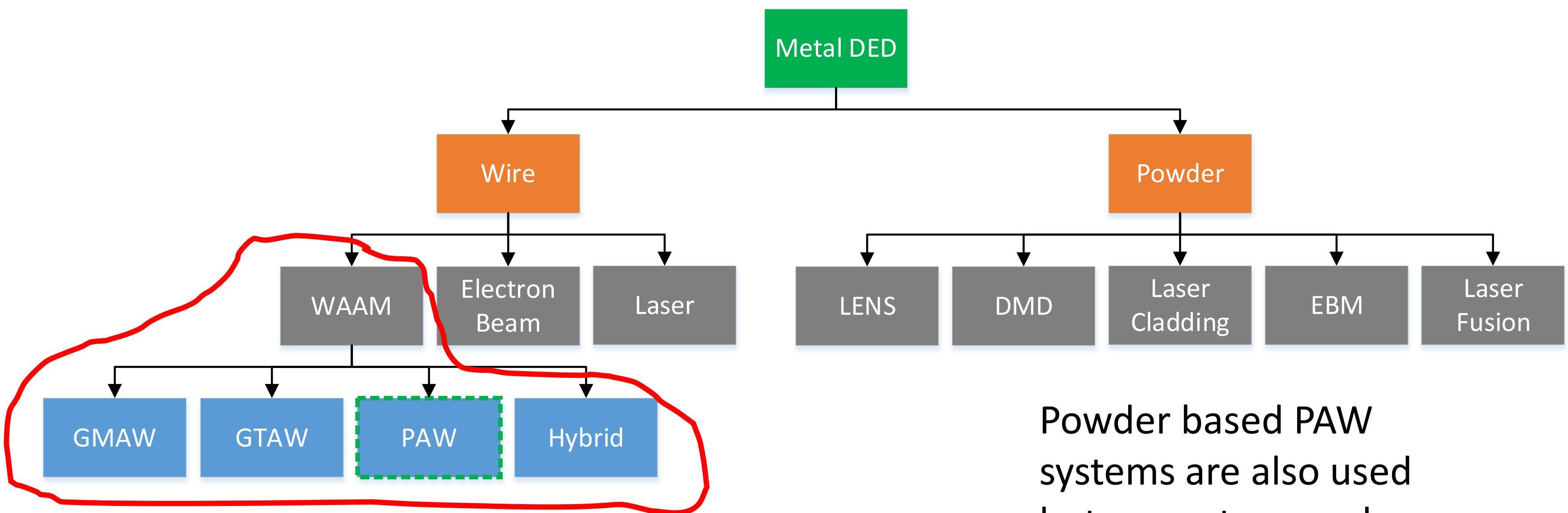
- Various wire feed directions and positions can be used, including **back feeding**, **side feeding**, and **front feeding**.

- Other important variables include wire height, feed speed, deposition rate, wire diameter and wire/torch orientation



Source: https://www.manufacturingguide.com/en/plasma-welding

PAW in the “family” of DED processes



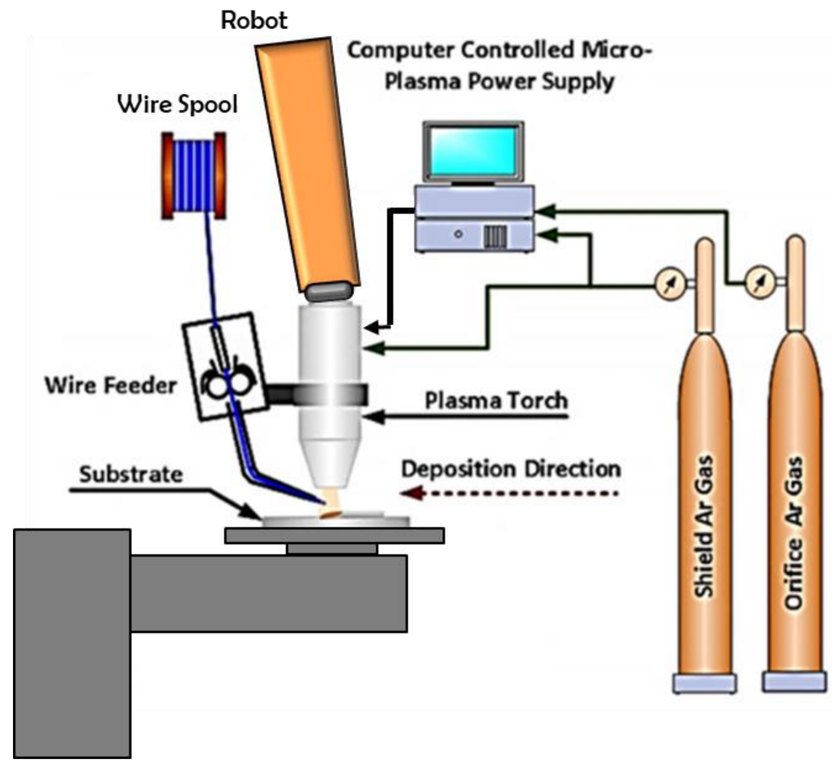
Powder based PAW systems are also used but are not a popular

Reproduced from: Zidong Lin, Kaijie Song, Xinghua Yu, A review on wire and arc additive manufacturing of titanium alloy, Journal of Manufacturing Processes, Volume 70, 2021, Pages 24-45, ISSN 1526-6125, https://doi.org/10.1016/j.jmapro.2021.08.018.

PAW-DED Hardware

Key components;

- Power Supply - High power DC supply, HF system for arc ignition.
- Shielding Gas - Argon/Helium
- Plasma Gas - Argon, Argon/Hydrogen (lower pressure/flow rate).
- Plasma Torch - Copper case and Tungsten electrode.
- Plasma Torch Coolant - De-ionized water.
- Control Unit
- Wire Spool & Feeder
- Wire
- Robot/CNC
- Worktable
- Ventilation

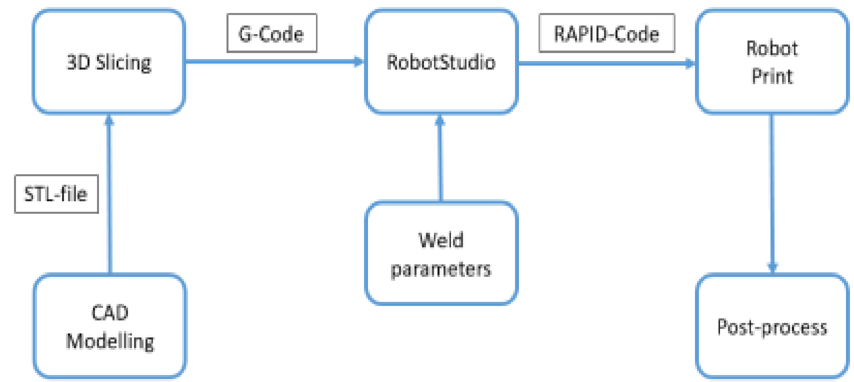


Reproduced from: S. Jhavar et al. (2016, p. 1804)

PAW-DED Workflow

Typical DED-Arcworkflow is;

- Create CAD file and export as STL file.
- Import to software (e.g. Simplify3D) where model sliced into layers.
- Toolpath is generated exported as G-code.
- Input G-code to robot software (e.g. RobotStudio) and simulate build to check for problems.
- Weld parameters are entered and stored in the robot software
- The robot code is generated (e.g. RAPID-code) that controls the robot arm, weld and worktable.
- PAW-DED build process starts



https://www.diva-portal.org/smash/get/diva2:1435037/FULLTEXT01.pdf

Source: Karlsson et al. (2020, p. 11)

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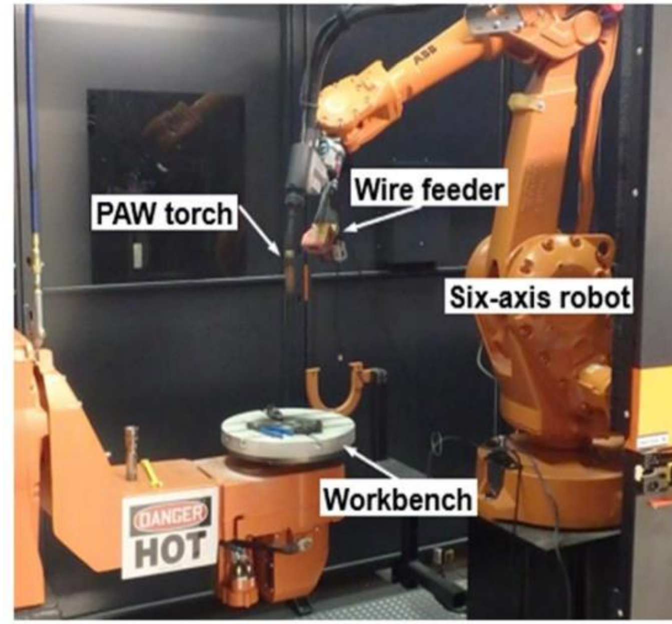
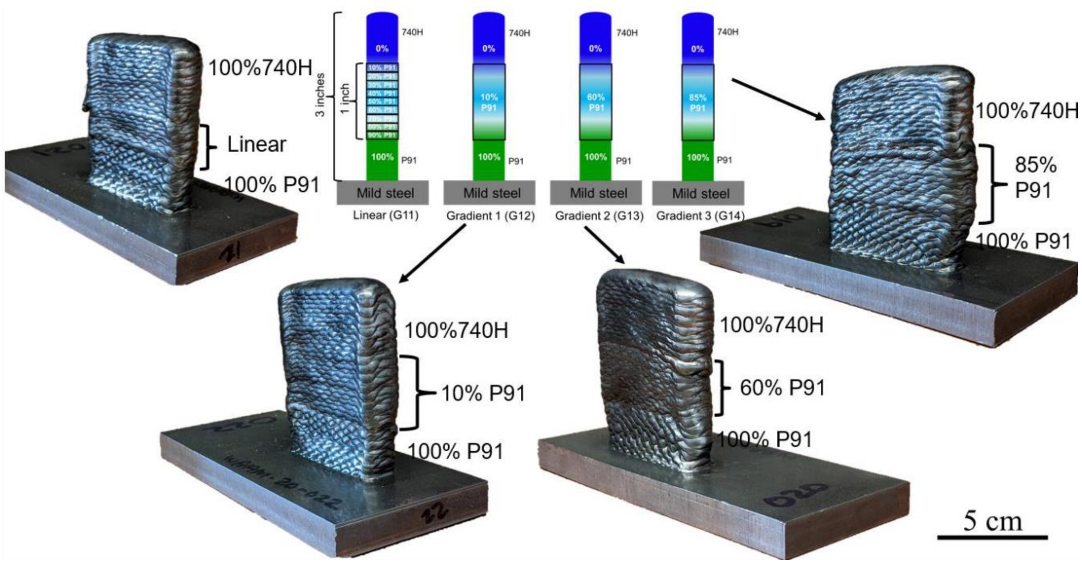
Real World Example of PAW-DED

Researcher at University of Pittsburgh assessed PAW-DED for graded structure alloy design used in fossil fuel power plants.

Materials used: P90 (Low carbon steel) and 740H (Inconel).



https://netl.doe.gov/sites/default/files/netl-file/20VPRHPM_Xiong_0.pdf



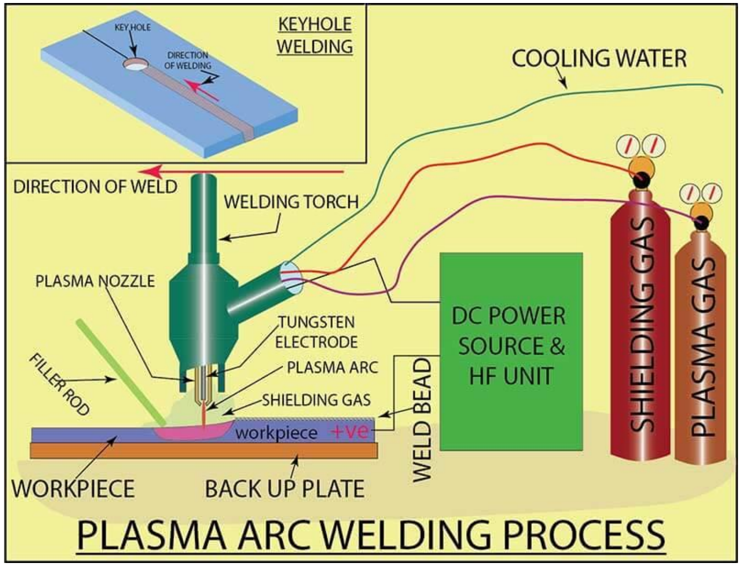
Source: W. Xiong et al (2022, p. 4)

Real World Example of PAW-DED

Image Credit: TWI

Gas Choice in PAW

Source: https://workshopinsider.com/plasma-arc-welding-vs-gtaw/



Two types of gas used Orifice (Plasma) gas and shield gas
Shielding gas is different than plasma gas.

Orifice (Plasma) gas;

- Depends on metal being welded, typically Argon or a mixture of Argon and Hydrogen (~2-5%) is used for the orifice (plasma) gas.
- Orifice gas must be inert with respect to the tungsten electrode to avoid rapid electrode deterioration.
- Argon is preferred orifice gas because its low ionization potential assures a dependable pilot arc and reliable arc starting.

Source: https://processwelding.com/blog/category/plasma/

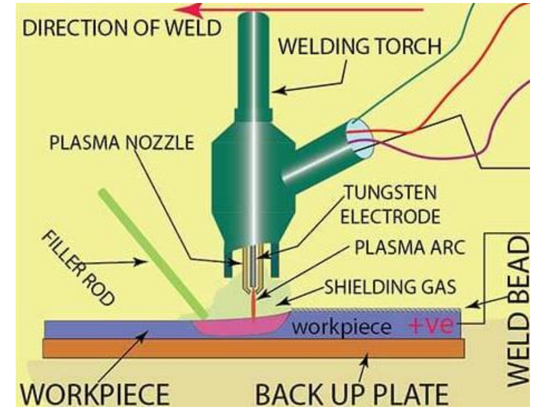
Gas Choice in PAW

Shield gas;

- Hydrogen is mixed with Argon to increase heat input into weld.
- Reduces surface tension of molten pool resulting in increased travel speeds.
- Degassing of weld pool is also facilitated so danger of gas inclusions in form of porosity is lessened.
- Hydrogen has a fluxing effect that reduces oxides formed when joining stainless steels, nickel, or nickel alloys.

BUT

- Too much hydrogen can cause porosity and cracking in the weld bead. Hydrogen content of 3% to 7% okay for most applications.



Source: https://workshopinsider.com/plasma-arc-welding-vs-gtaw/

Source: https://processwelding.com/blog/category/plasma/

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Materials for PAW

Source: Yan Li et al. Comprehensive review of wire arc additive manufacturing: Hardware system, physical process, monitoring, property characterization, application and future prospects, Results in Engineering, Volume 13, 2022, 100330, ISSN 2590-1230, https://doi.org/10.1016/j.rineng.2021.100330.

- Stainless steel, nickel and nickel alloys, copper, titanium and other reactive metals can be plasma welded in sections ranging from foil to 3–4 mm thick.
- Aluminium alloys can be keyhole welded, using solid-state power switching circuitry, to reverse polarity during welding. Surface cleanliness is important. Wire feeders supply wire at rates of 25–250 cm min-1. Good weld properties are achieved.
- Titanium and zirconium can be welded up to sections 19 mm thick using high purity argon.
- Stainless steel and nickel alloys up to 19 mm thick are welded in argon/5–8% hydrogen mixture gases.

Material Class	Alloy
Titanium Alloy	Ti6Al4V
Steel	SS316, ER90S-B91, ER304L
Nickel Alloy	Inconel 625
Aluminium Alloys	2xxx (Al-Cu) 4xxx (Al-Si) 5xxx (Al-Mg)
Copper Alloys	-

Source: https://www.open.edu/openlearn/science-maths-technology/engineering-technology/manupedia/plasma-arc-welding

Comparison of PAW, MIG/MAG & TIG DED

MIG

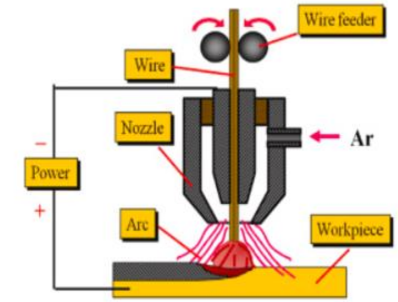
- Arc between a continuous fed filler metal electrode and work-piece
- High melting efficiency and deposition rate.

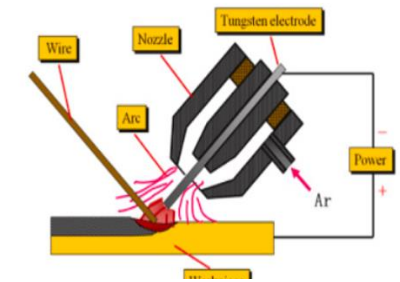
TIG

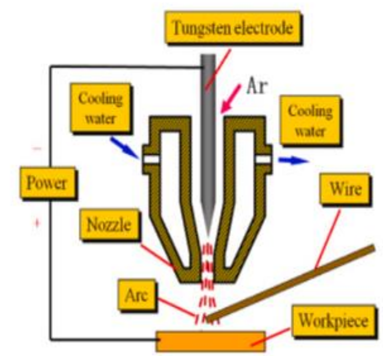
- Arc between a non-consumable tungsten electrode and work-piece.
- High quality welds with no slag or spatter and requiring little post-weld cleaning.
- Slower than MIG

PAW

- Similar to TIG
- Focused plasma arc is squeezed through hole in nozzle improving arc stability, increases heat transfer efficiency, and promotes welding speeds.
- Bulkier, more costly equipment than TIG /MIG







Source: Yan Li et al. Comprehensive review of wire arc additive manufacturing: Hardware system, physical process, monitoring, property characterization, application and future prospects, Results in Engineering, Volume 13, 2022, 100330, ISSN 2590-1230, https://doi.org/10.1016/j.rineng.2021.100330.

Advantages PAW-DED

Advantages
versatile process which gives clean/precise weld beads Due to its longer arc length it can create deep penetration high-quality welds
PAW has better welding speeds, ability to weld thick plates compared to GTAW
Distance between the torch and work-piece is not a critical as for TIG
PAW is adaptable for keyhole method of welding
Stabile and stiff arc
Adding filler metal is easier than with TIG
Energy concentration in PAW is higher than TIG
PAW achieves narrow and deep penetration (18 mm or more) depending on work-piece material
Constricted arc leads to narrow weld beads, reduced heat-affected zone (HAZ), and low distortion
Good-looking weld bead and reduced or complete elimination of finishing operations

Source: https://workshopinsider.com/plasma-arc-welding/

Disadvantages PAW-DED

Disadvantages
Two types of inert gasses required
Water cooling is essential
Equipment expensive and bulkier than for TIG
Arc voltage control is not easy which poses a problem when welding with filler wire
Welding torches used are not as readily available as in TIG
High-frequency unit power supply can interfere with electrical and electronic equipment
Shielding can be affected by draughts
Emits harmful infrared and ultraviolet rays
Skill level required for manual PAW is higher than TIG
Construction and maintenance of welding torch is critical
High noise levels during operation ~100 dB.

Source: https://workshopinsider.com/plasma-arc-welding/

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PAW Applications

Plasma arc welding is still a comparatively a new process and is yet to be introduced in many industries;

- Micro PAW process is used for welding thin sheets and wire mesh sections.
- Boiler manufacturing using stainless steel, chemical engineering industries, ship-building industry, and pre-fabrication of gasoline and gas pipelines.
- Combination of PAW and TIG is found useful for circumferential butt welding of large diameter pipes. PAW is positioned in the front to do the penetration and TIG to fill weld it.
- Welding of stainless steel and titanium pipes and tubes.
- Submarine manufacturing, electronic component manufacturing, and manufacturing of jet engines.
- Aerospace industries and cryogenics.
- Plasma welding is usually used for longitudinal seam welds of rolled pipes (6 to 8 mm wall thickness)
- Large food vessel food and beverage industries can use plasma arc welding for seam welding.

Commercial / semi commercial PAW-DED Systems

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Norsk Titanium

- Rapid Plasma Deposition® (RPD®)
- Titanium wire
- Enclosed argon gas atmosphere
- Part build size: 900mm x 600mm x 300mm

- Bead:
  H = 3–4 mm
  W = 8–12 mm

- Deposition rate: 5–10 kg/hour

Source: https://www.norsktitanium.com/media

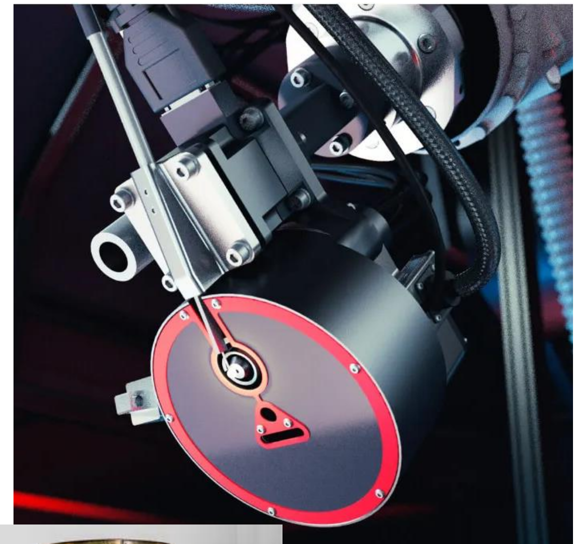
NORSK TITANIUM

-
- [Norsk Titanium Technology Video - YouTube](https://www.youtube.com/watch?v=JNGXVQsjTwA)
- https://www.youtube.com/watch?v=JNGXVQsjTwA

WAAM3D

- Plasma Transferred Arc (PTA)
- End effectors measure temperatures, provide melt pool imaging and with the local-shielding option they also protect reactive materials from oxidation.
- Also feature automatic positioning of the wire within the plasma arc, to further ensure consistent deposition.

Presentation by WAAM3D tomorrow



Source: https://www.waam3d.com/hardware

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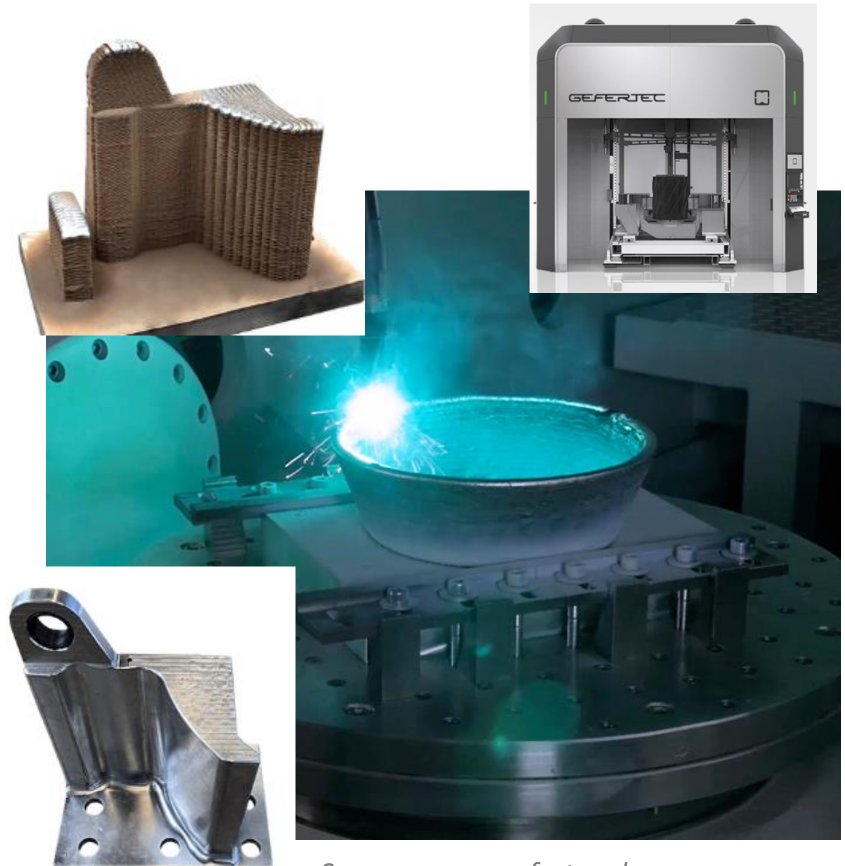
Gefertec

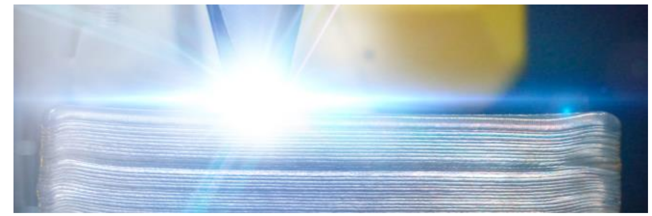
- Optional 3 or 5 motion axes systems.
- Temperature tracking by integrated Sensortherm pyrometer.
- Arc cooling system for local cooling by cooling gas.
- Automatic welding torch cleaning system.
- Titanium module.
- Arc 60x – 5-axis machining: Production of metallic components up to 0.8m³ with a maximum mass of 500 kg.
- Arc 40x – 5-axis machining: Production of metallic components up to 0.06m³ with a maximum mass of 200 kg.



Source: www.gefertec.de

Prodways

- Large metal additive manufacturing in titanium for structural parts.
- Closed loop supervision system of production parameters.



Source: prodways-raf.com

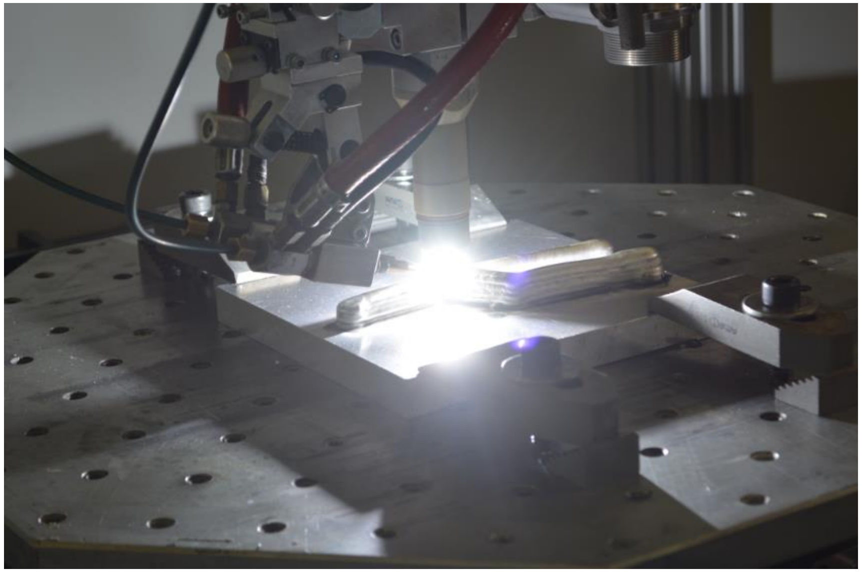
SBI Produktion

Metallic 3D Printer (M3DP)

Uses a plasma arc to 3D print metal parts.

For quality assurance M3DP is equipped with a 3D scanner.

After each layer, a 3D scan of the part is made to test against the original mode for geometrical deviations.



https://youtu.be/iua5Fbo6-m4

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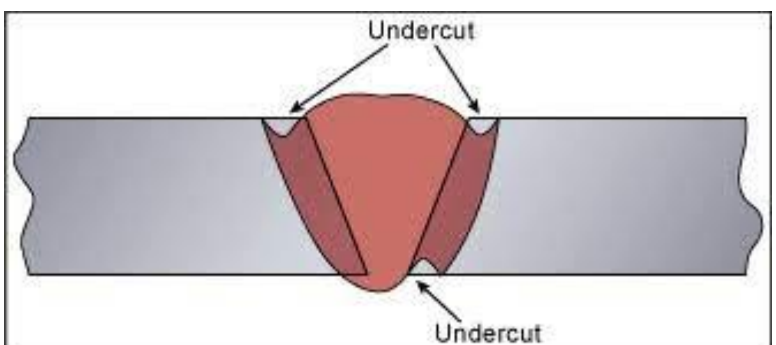
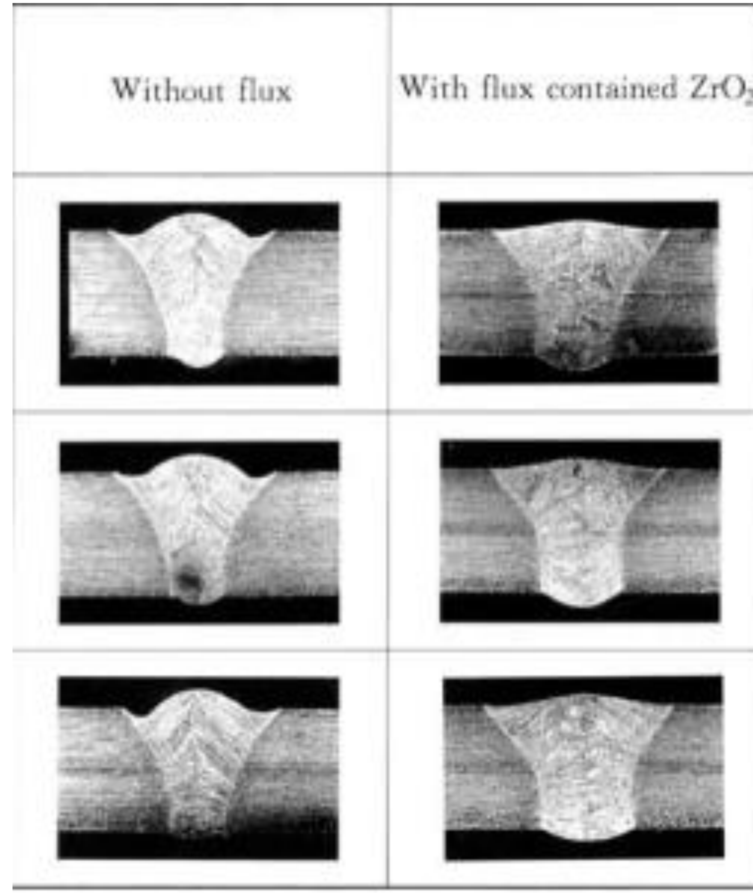
Common PAW Defects

Most common defects are tungsten inclusions and undercutting.

Tungsten inclusions occur when the welding current exceeds the capabilities of the tungsten electrode and small droplets of tungsten get entrapped in the weld metal.

Undercuts are generally associated with keyhole mode PAW welding and can be avoided by using activated fluxes such as ZrO_2, TiO_2, SiO_2, and Cr_2O_3.





Macrostructure of PAW welds of Type 304 stainless steel.

https://weldknowledge.com/2015/10/03/plasma-arc-welding-paw-with-activated-flux/

PAW - Health and Safety

Source: https://workshopinsider.com/plasma-arc-welding/

All arc welding processes, including PAW, can be dangerous
Must consider electric current, electric arc, hot components, welding fumes, thermal radiations, etc.
Welder has to wear leather hand gloves, long sleeve jackets, shoes, good-quality welding helmets (with flip-able welding glasses), and a mask (if there is no provision of built-in protection from fumes in the helmet).

- PAW process gives out harmful infrared and ultraviolet rays that are harmful to human beings. In addition to this, there is high noise of 100 DB, which is harmful to the people around. Hence, special protection is required due to higher radiation and noise during welding.
- The open-circuit voltage used in PAW is high, and safety measures are required to overcome electrical hazards.
- The welding enclosure should have good ventilation for the quick exit of the toxic gases formed during welding. Also, the welding enclosure must not contain inflammable/combustible items like fuel, oil, paper, etc.
- Conventional standard welding helmets have dark plates on the front to prevent exposure to thermal radiation. The latest helmet designs have a liquid crystal-type faceplate that automatically darkens when exposed to the welding arc.
- The place of PAW welding should have a suitable fire extinguisher nearby.

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PAW Parameters

- Power Source Characteristics
- Current Type and Polarity DC (+), DC (-), AC and Pulsed
- Voltage
- Arc Length
- Travel Speed
- Plasma and Shielding Gas Type and Flow Rate
- Electrode Shape and Sharpening Angle, Chemical Composition and Diameter
- Nozzle Orifice
- Wire Position and Height
- Wire Feed Speed and Deposition Rate
- Wire Diameter
- Torch Orientation
- Arc Types (Transferred and Non-Transferred)
- Variants (Number of Wires, Hot Wire)

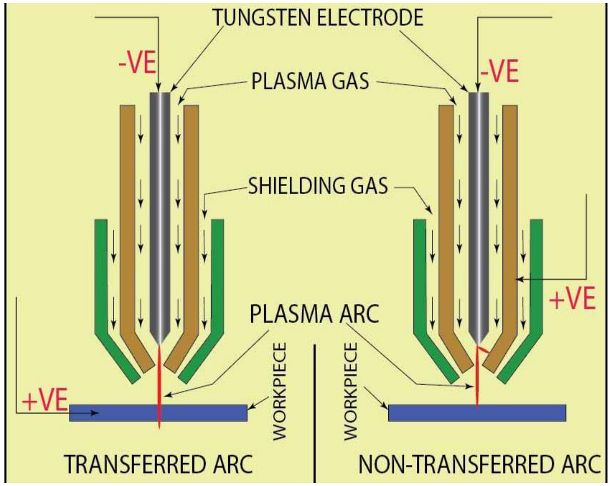
Transferred & Non-Transferred PAW

Transferred
DC connections
- electrode -ve, (straight polarity)
- workpiece +ve

Used for welding thicker gauge material
Pilot arc turned off once arc established with workpiece

Non-Transferred
DC connections
- electrode +ve,
- workpiece -ve

Used for welding thinner gauge material and some temperature sensitive materials
Pilot arc continues throughout weld process



Source: https://workshopinsider.com/plasma-arc-welding/

Note: For aluminium and magnesium a square wave AC supply may be used

PAW power requirements

Normally operated with a DC, drooping characteristic power source (either +Ve or –Ve electrode)

Plasma arc is not readily stabilised with sine wave AC so square wave could be used for aluminium and magnesium

Special-purpose switched DC power sources are available.

By imbalancing the waveform to reduce the duration of electrode positive polarity, the electrode is kept sufficiently cool to maintain a pointed tip and achieve arc stability.

[Plasma Arc Welding - TWI (twi-global.com)]

Arc starting

In PAW the arc is initiated using a high frequency supply.

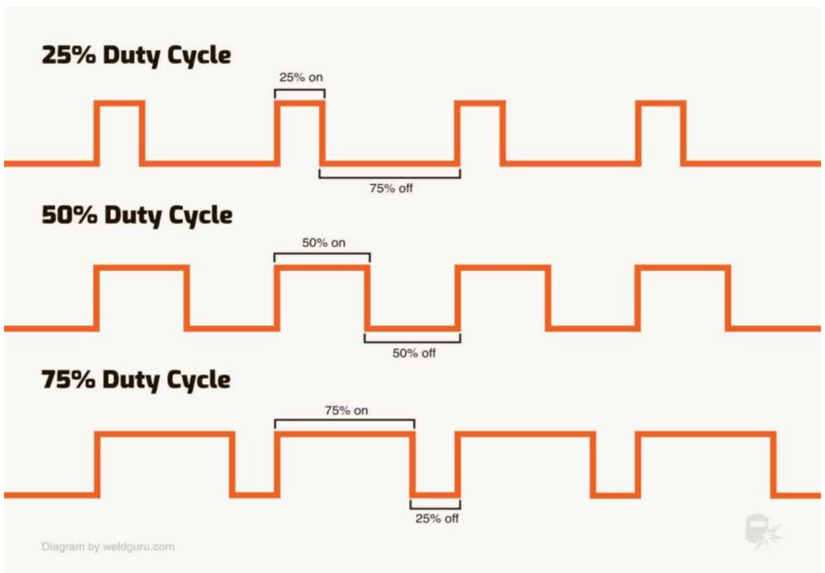
HF generator is incorporated into the power supply.

This pilot arc is either held within the torch body during the weld in the case of non transferred arc.

Or in the case of plasma transferred arc (PTA) this pilot arc is switched off once the arc has been initiated with the workpiece.

PAW - Power Source

- Recommended that constant current drooping characteristic power source that supplies DC welding current be used; that said AC/DC power can also be used.
- When welding very thin metals, it should have a minimum target current of 2A. A maximum of 300A is workable for most plasma welding projects.

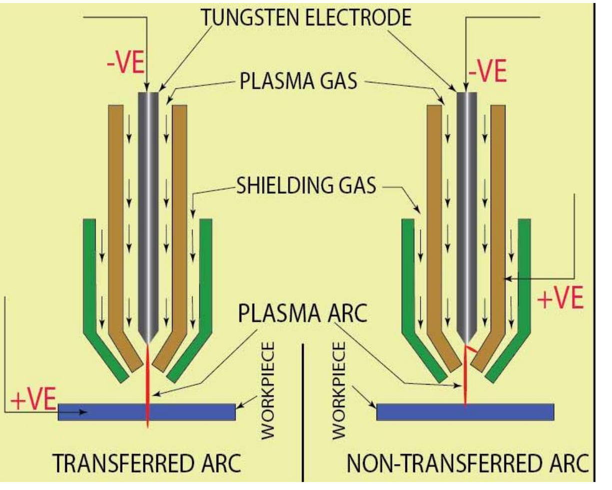


The welding duty cycle is the percentage of a 10-minute interval during which the welding power source can output the rated amperage continuously. E.g. a welder with a duty cycle rating of 200A at 60% can output 200 amps for six minutes before needing to rest for the remaining four minutes of the 10-minute interval.

Welding machines go into thermal overload mode when you exceed the duty cycle limit while welding. The arc power cuts off while the cooling fan keeps running to help dissipate heat away from the sensitive parts inside your welder.

Source: https://weldguru.com/duty-cycle-in-welding/

PAW – Current Type & Polarity



Source: https://weldguru.com/duty-cycle-in-welding/

- Transferred arc = +ve electrode
- Nontransferred arc = -ve electrode
- AC (usually square wave) for Al and Mg alloys.

Voltage

- A direct current power source (generator or rectifier) having drooping characteristics and open circuit voltage of 70 V or above is suitable for plasma arc welding.
- Open circuit voltage is the voltage that exists between the electrode and the work-piece when welding is not in progress.
- Rectifiers (converts AC into DC) are generally preferred over DC generators.
- Working with helium as an inert gas needs open circuit voltage above 70 V.
- The higher voltage can be obtained by series operation of two power sources; or the arc can be initiated with argon at normal open circuit voltage and then helium can be switched on.
- Typical welding parameters for plasma arc welding are as follows:
    - Current 50 to 350 A
    - Voltage 27 to 31 V
    - Gas flow rates of 2 to 40 liters/minute (lower range for orifice gas and higher range for outer shielding gas)

Source: University of Salford

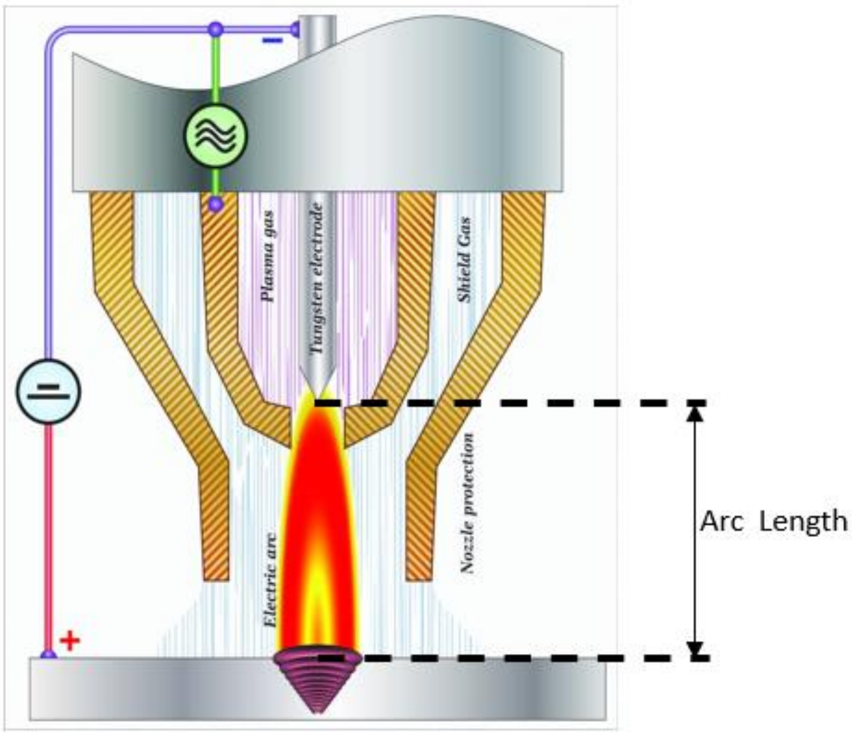
Arc Voltage

- All welding processes that use an arc, seek to control the arc current and voltage but controlling the voltage across the arc is not really possible.
- The arc has a voltage, and that voltage is based on arc length and whatever gaseous or particulate elements are in the arc.
- The arc voltage can only be changed by changing the arc length or changing the gaseous elements in the arc, it cannot be controlled by any power supply as it's a physical phenomenon.
- With TIG and PAW the arc voltage can only be adjusted with arc length so torch placement sets the arc voltage.

Source: https://weldingweb.com/vbb/threads/6860-Some-thoughts-about-Arc-Voltage?p=63648

Arc Length

- Important variable in all arc welding processes
- Arc length is distance between tip of electrode and surface of work-piece.
- Arc length controls the “spread” of the weld.
- Too short and weld bead will be tall, narrow, and “cold” leading to lack of fusion.
- Too long will give increased spatter, likely undercut defects at the toes of the weld. Resulting weld will be wide and flat. May suffer from reduced penetration, since the arc energy is being spread out, rather than being able to “dig” down into the base metal.



Source: https://ewi.org/gas-metal-arc-welding-basics-welding-current-welding-voltage/

Arc Length

- Arc length relates directly to the effective width of arc, where it contacts the metal being welding.
- The constricted arc in PAW results in a much more columnar-shaped arc. The arc expands only slightly with an increase in arc length.
- This minimizes the effect of arc length variation on energy density and minimizes the need for Arc Length Control (ALC) or Arc Voltage Control (AVC).
- ALC/AVC are commonly used in GTAW to ensure consistent spot size and energy density.
- Using PAW in the medium current range is similar to using GTAW, but the arc tends to be stiffer and less affected by changes in arc length with PAW. This allows for longer arc lengths to be used.

Source: https://workshopinsider.com/plasma-arc-welding/

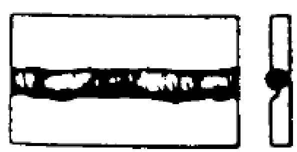
Source: https://www.thefabricator.com/thewelder/article/arcwelding/plasma-arc-welding-the-advantages-of-paw-welding

Travel Speed

- Speed welding arc is moving relative to work-piece and typically measured in millimeters per minute.
- Plays a direct role in amount of heat input into work-piece.
- Lower speeds does not mean higher penetration. Large weld pool will tend to roll in front of arc providing a "cushion" and reducing penetration into the base metal.
- Too slow can also lead to an excessively wide weld bead and slag inclusions. When welding thinner materials, excessive heat transfer caused by slow travel speeds can, even, cause burn-through.
- Too high and the arc may not have enough time to adequately melt the base material. Leading to a thin, narrow weld with poor fusion and penetration.

Source: https://www.airproducts.expert/uk/maxxgases/optimising-weld-travel-speed.php

Sources of weld defects

	PROBLEM: SUNKEN BEAD, UNDERCUT, TOO MUCH PENETRATION REASON: WELDING CURRENT IS TOO HIGH, OR TRAVEL SPEED IS TOO LOW
	PROBLEM: BEAD IS TOO SMALL, PENETRATION IS TOO LOW REASON: WELDING CURRENT IS TOO LOW/PLASMA GAS FLOW RATE IS TOO LOW/TRAVEL SPEED IS TOO HIGH
	PROBLEM: UNDERCUT AND IRREGULAR EDGES REASON: PLASMA GAS FLOW RATE IS TOO HIGH
	A GOOD WELD: PROPER BEAD SIZE, EVEN RIPPLES, GOOD PENETRATION. ENABLING FACTORS: CORRECT CURRENT, EVEN TORCH MOVEMENT, PROPER ARC VOLTAGE, AND CORRECT FLOW RATE OF PLASMA GAS.

Source: https://mewelding.com/plasma-arc-welding-paw/

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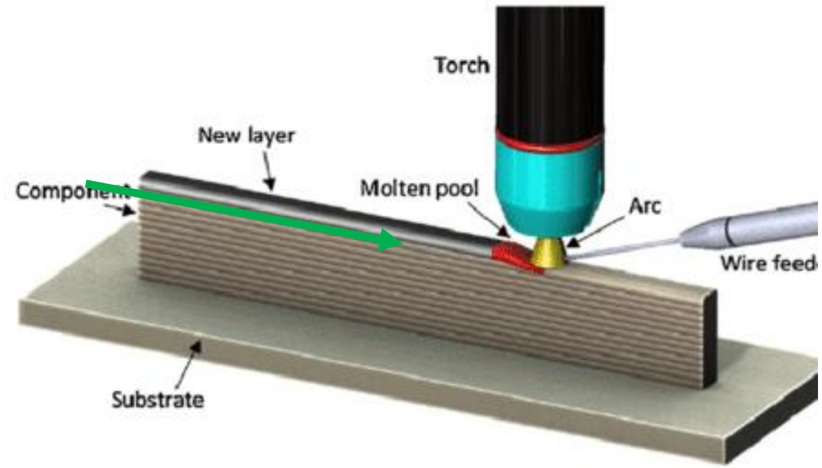
PAW- Travel Speed

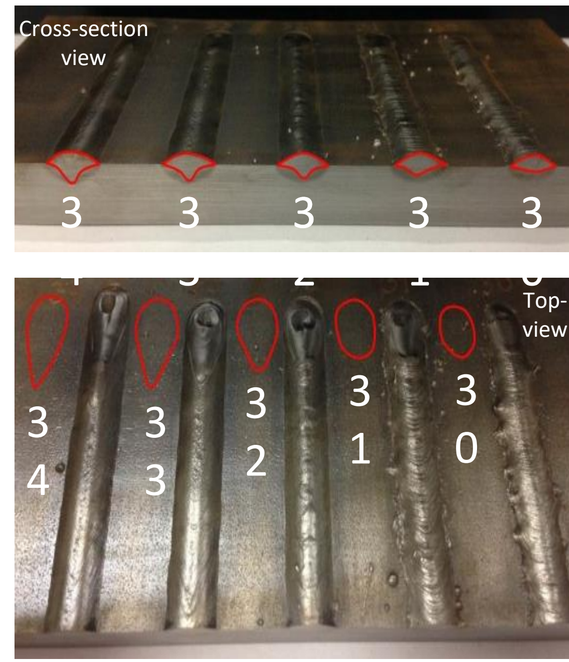
- In PAW, the welding conditions for different materials mainly differ mainly by travel speed.
- The higher heat concentration and plasma jet enables higher travel speeds compared to other arc welding processes.
- PAW travel speeds typically range from 120 mm/min to 1000 mm/min.



Source: Yusuf et al. 2019

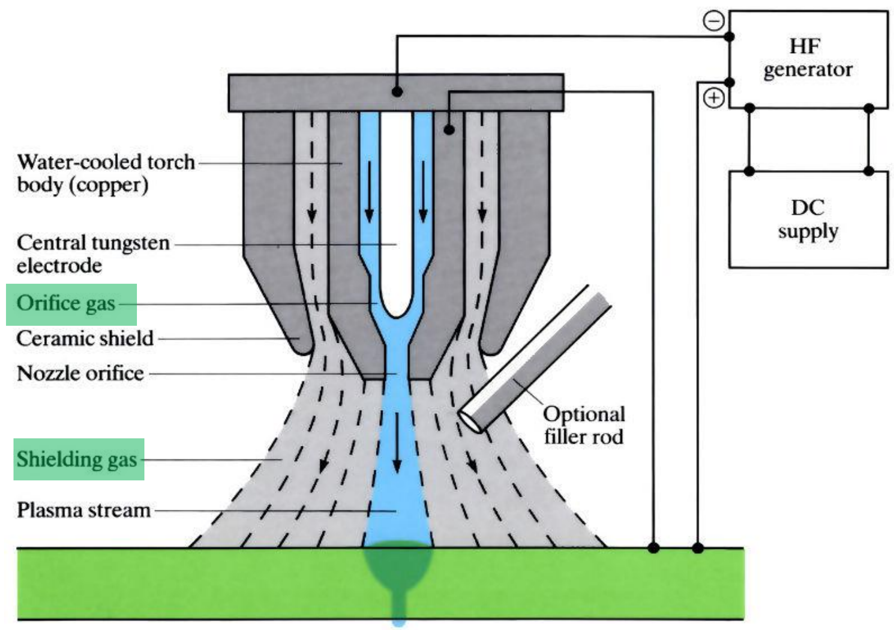
Effect of Travel Speed

- Increasing travel speeds means heat input must be managed to keep weld bead geometry consistent.
- Slower travel speeds result circular or oval solidification pattern.
- Faster travel speeds result in a solidification pattern that is circular on leading edge but v-shaped on trailing edge.
- At slower travel speeds, the arc is directly above the center of the weld pool. Filler metal is deposited into the center of the weld pool and it acts as a large cushion to the incoming filler and reduces penetration.
- At faster travel speeds, the arc is typically at the leading edge of the weld pool resulting in the filler material directly impacting some of the base material promoting deeper penetration and limits the cushioning effect.



Source: https://ewi.org/gas-metal-arc-welding-basics-travel-speed-and-contact-to-work-distance-ctwd/

Plasma and Shielding Gas Type and Flow Rate

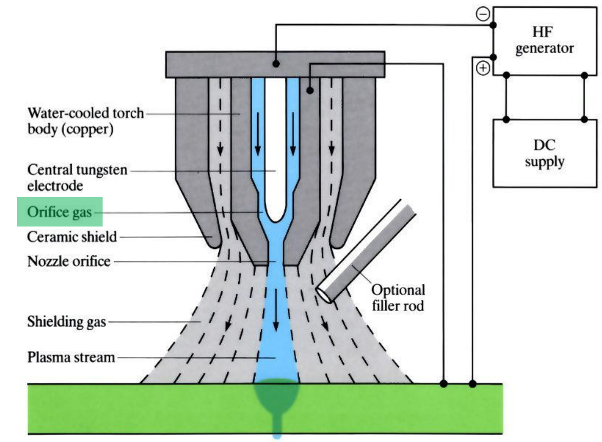


Source: https://www.open.edu/openlearn/science-maths-technology/engineering-technology/manupedia/plasma-arc-welding

Orifice (Plasma) Gas

Argon is the preferred plasma gas.

- Totally inert so will not form chemical compounds with other materials at any temperature or pressure.
- Low ionization potential assures reliable arc starting and a dependable pilot arc.
- Provides good arc stability and an excellent protective blanket for the tungsten electrode.
- Flow rate range approximately 0.18 l/min - 2.4 l/min

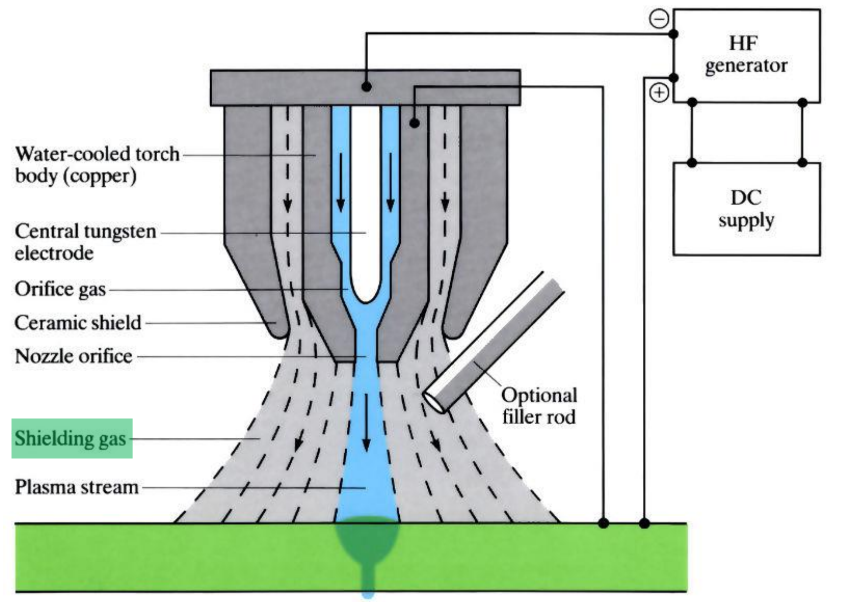


Source: https://www.open.edu/openlearn/science-maths-technology/engineering-technology/manupedia/plasma-arc-welding

Source: http://sanrexwelding.com/wp-content/uploads/2021/01/PAW-Hand-Book.pdf

Shield Gas

- In some cases, argon may not perform satisfactorily due to higher arc voltages that are used in plasma welding (18-32V).
- Where the weld puddle is not fluid, slight undercutting occurs, and/or surface oxidation of the weld is noticed.
- Use of **argon/hydrogen, helium or argon/helium** mixtures may be necessary.



Source: https://www.open.edu/openlearn/science-maths-technology/engineering-technology/manupedia/plasma-arc-welding

SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Co-funded by the Erasmus+ Programme of the European Union

Shield Gas - Argon/Hydrogen (~95/5%)

- Addition of small amounts of Hydrogen increases heat input to weld puddle.
- Provide hotter arc assisting in both penetration and weld puddle fluidity.
- Torch parts life will be lower compared to using Argon alone.
- Reduces surface tension of molten pool, resulting in increased travel speeds and degassing of the weld pool is also facilitated so that the danger of gas inclusions in the form of porosity is lessened.
- At higher welding speeds, undercutting also avoided and a smoother weld surface is achieved.
- Hydrogen reduces oxides formed when joining stainless steels, nickel and high nickel alloys.
- Generally thinner the work-piece, the higher the permissible percentage of Hydrogen in a gas mixture that can be used (up to max 15%) .
- With increased current welds and reduced travel speeds on thicker materials, the Hydrogen can become entrapped in the weld causing embrittlement
- The flow rate range is approximately 4.7 l/min – 9.4 l/min.

Shielding Gas – Helium

- Helium can also be used as a shielding gas.
- Compared to argon shielding of helium increases the weld heat by approximately 25%.
- This is due to higher ionization potential of helium, which in turn increases the arc voltage.
- Helium commonly used when welding aluminum alloys, copper alloys and thicker sections of titanium.
- These materials will dissipate heat more rapidly and need the assistance of the helium.
- The flow rate range is approximately 7.1 l/min - 18.8 l/min.

Source: http://sanrexwelding.com/wp-content/uploads/2021/01/PAW-Hand-Book.pdf

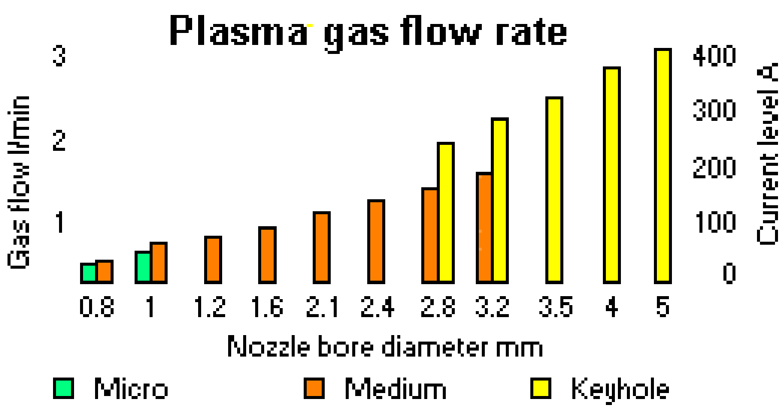
Shielding Gas - Helium/Argon (~75/25%)

- The addition of Helium to Argon produces a hotter arc for a given amount of welding current.
- A mixture must contain at least 40% Helium before a significant change in heat can be detected.
- The argon has a tendency to stabilize the arc. Mixtures containing more than 75% of Helium will provide results very similar to pure Helium.
- A mixture of 75% Helium and 25% Argon is used in applications for thicker segments of titanium or copper alloys.
- Arc starting may become more difficult with the use of helium or helium mixtures.
- The flow rate range is approximately 7.1 l/min - 18.8 l/min.

Source: http://sanrexwelding.com/wp-content/uploads/2021/01/PAW-Hand-Book.pdf

Shielding Gas - Flow Rate

- Flow rates for plasma gases are generally between 0.1 L/min to 5 L/min.
- Flow rates for shielding gases are usually in the range of 5 L/min to 15 L/min for low-current applications.
- For high-current welding, flow rates of 15 L/min to 32 L/min are used.



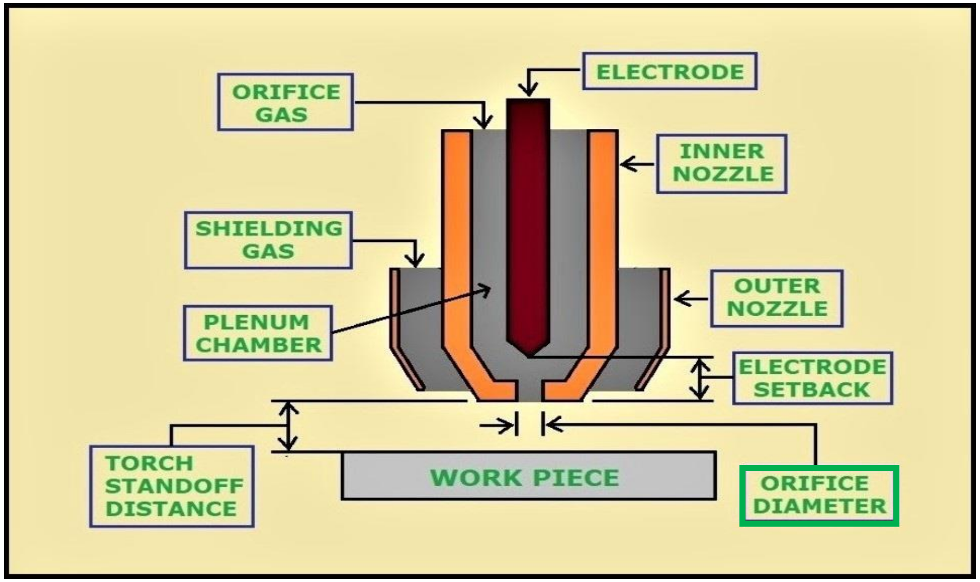
Source: TWI

Source: http://sanrexwelding.com/wp-content/uploads/2021/01/PAW-Hand-Book.pdf

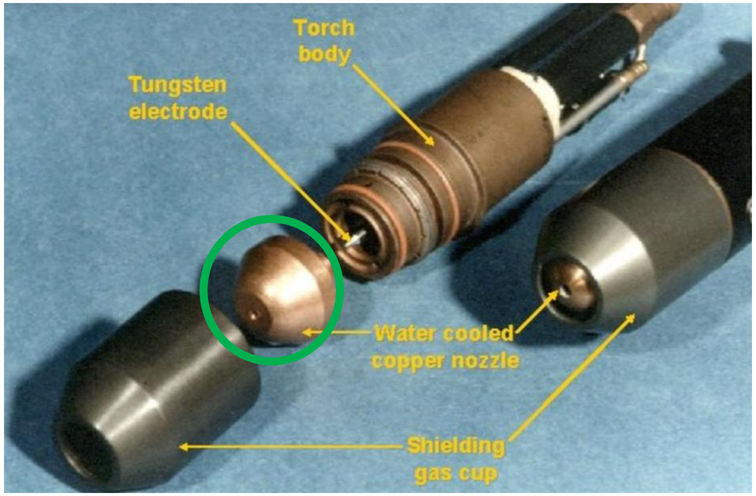
Pause for break

This project has been funded with support from the European Commission. This communication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

PAW – Inner Nozzle



Source: https://www.weldingandndt.com/plasma-arc-welding-paw/



Source: https://slidetodoc.com/plasma-arc-welding-paw-principle-of-operation-principle/

Nozzle Orifice

- Nozzle helps to shape and direct the plasma arc.
- Nozzles come in a variety of shapes and sizes, and the right nozzle for a particular welding application will depend on the type of material being welded, the thickness of the material, the desired welding speed, and other factors.
- Orifice diameter is diameter of hole in nozzle through which the plasma arc passes.
- This measurement is important because it can affect the welding process in a number of ways.

Source: https://weldingtech.net/nozzle-diameter/

Selection of Size of Nozzle

There are a few factors that determine the size of the welding nozzle to be used:

- **Thickness of the material being welded**: Thinner materials may require a smaller orifice diameter to prevent the plasma arc from piercing through the material. Thicker materials may require a larger orifice diameter to allow for more heat to be transferred to the material.

- **Desired welding speed:** Faster welding speeds may require a larger orifice diameter to prevent the plasma arc from becoming unstable.

Other factors that can affect the size of the orifice diameter include the power of the welding machine and the type of gas being used.

Source: https://weldingtech.net/nozzle-diameter/

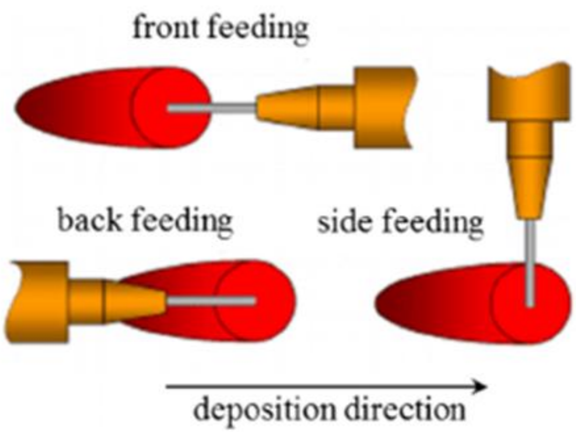
Effect of nozzle diameter on PAW welding process

- Smaller orifice diameter may result in a narrower plasma jet and can be used to weld thinner materials.
- Larger orifice diameter may create a wider plasma jet and can be used to weld thicker materials.
- Nozzle diameter can affect amount of heat transferred to the workpiece.
- Smaller orifice diameter will result in less heat being transferred to the workpiece.
- Orifice diameter can also affect plasma arc;
  - Smaller orifice diameter may create a more stable plasma arc
  - Larger orifice diameter may create a less stable plasma arc.

Wire Feeding

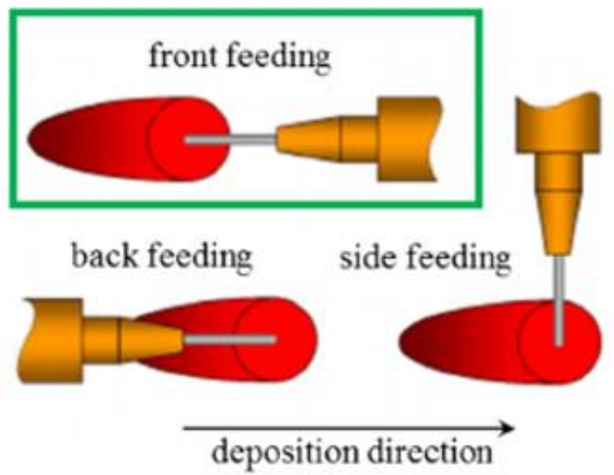
The PAW process requires external filler material, it is very sensitive to variations in the welding position:

- **Front feeding** – the wire is positioned at the leading edge of the weld pool.
- **Back feeding** – the wire is positioned at the trailing edge of the weld pool.
- **Side feeding** – the wire is positioned at the side of the welt pool.



Wire Position and Height

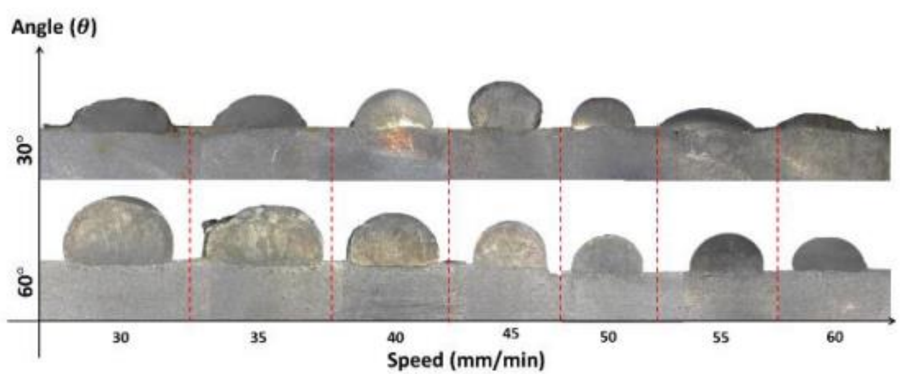
- PAW filler wire is typically front fed i.e. to the leading edge of a plasma weld puddle, as in the TIG.
- Wire-height is generally NOT as critical with PAW because wire can lift off the work-piece and melt into plasma stream without contaminating the electrode.
- However, wire placement is still important because the wire can ball-up when lifted from the work-piece
- For non-linear geometries, the wire feeder must rotate around the welding torch to keep the wire feed location stable in front of the weld pool and to ensure consistent deposition.

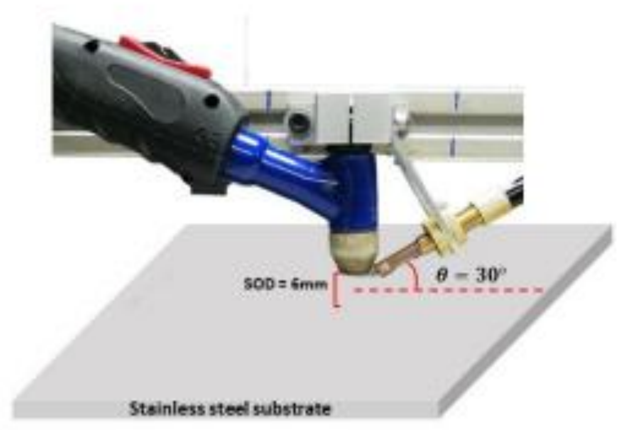


Wire Position and Height

Research conducted by Rosli et al (2021) focused on micro (low current) PAW WAAM with wire feeding angles at 30° and 60 ° at various speeds.

- The aim was to obtain continuous layers and reducing the differences in the layer height.
- Stainless-steel wire (SS316) with a diameter of 1.2 mm used to deposit a single weld bead onto 6 mm thick substrate.
- Results indicate a wire feed angle of 30° produced inconsistent deposition whereas a feed angle of 60° produced a more uniform deposition.



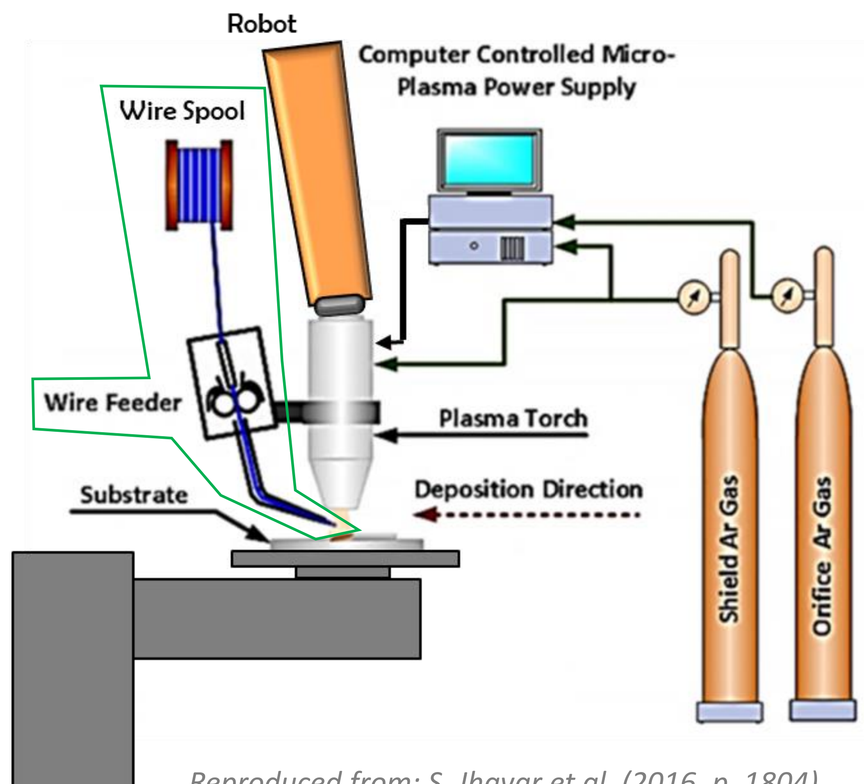


Source: Rosli et al (2021)

Wire Feed Speed

- Wire feed mechanism required for PAW-DED.
- Wire feed adjust from 250 mm/min to 3180 mm/min.
- As with TIG conventional filler wire-feed systems (cold wire) can be used with PAW.
- Filler metal is added to the leading edge of the weld pool or the keyhole.
- Most systems use a predetermined feed rate, although more sophisticated controllers like those used in robotic systems can manipulate the wire-feed speed to provide a consistent weld profile.

Source: Welding Handbook (Ninth Edition Volume 2)



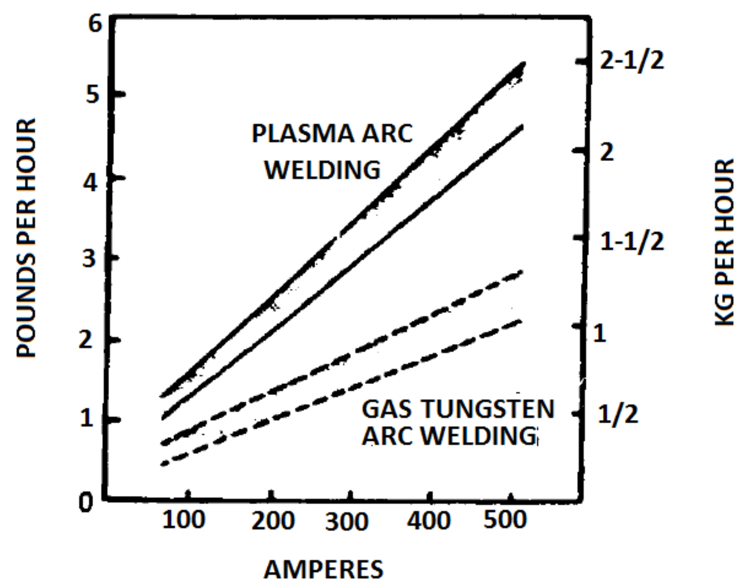
Reproduced from: S. Jhavar et al. (2016, p. 1804)

Wire Feed Speed Control

- A wire-feed system can alleviate occurrences of undercut or under-fill when welding thick materials.
- Can also improve weld bead uniformity by providing a steady addition of filler metal.
- Hot-wire feed systems can also be used and should feed wire into trailing edge of weld pool.
- A popular technique when using pulsed-current welding is to syncronised movement of filler material with pulsing of plasma arc current. When automated or mechanized, this process is colloquially known as dabber welding because of the back-and-forth movement of the filler. It is widely used by the aerospace industry to repair thin sections, for example, in building up the edges of labyrinth seals on gas turbine engines

Deposition Rate

- Rate of linear travel is higher in PAW than GTAW, owing to the high heat intensity of the plasma. This also means that rate of weld metal deposition is higher in PAW.
- The figure shows a comparison between the deposition rates of GTAW and PAW.
- Wang et al (2021) found that for PAW (with Ti64) with the same heat input, the deposition rate increased linearly with the wire size due to the increasing melting efficiency.



Source: https://mewelding.com/plasma-arc-welding-paw/

Wire Feed Speed and Deposition Rate

- One of the effective ways of improving deposition rate is to increase the wire feed speed (WFS) whilst increasing the energy input by using a higher current.
- For a given energy input, in order to feed the material more quickly, there are different combinations of the wire size and WFS.
- For example, we can use either a thin wire with a high WFS or a thick wire with a low WFS.
- Moreover, with the same deposition rate and energy input, the bead shape and its quality is dependent on the melting behavior of the wire.

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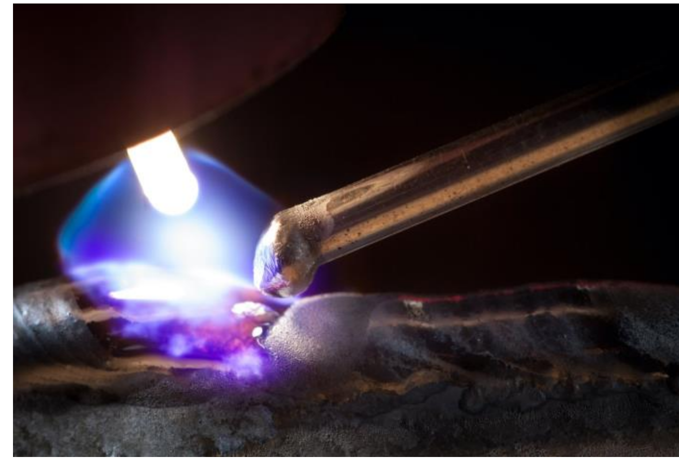
Wire Diameter

- Diameter of the rod depends on the thickness of the base metal and welding current.
- Plays an important role in melting efficiency of wire and metal transfer mode, which is a key factor in improving deposition rate of WAAM.
- Smaller diameter wires typically require higher feed rates to ensure sufficient deposition.
- Larger diameter wires typically have slower feed rates to ensure sufficient deposition, although in both cases it can be dependent on the job requirements.

Source: Wang et al (2021)



Source: https://weldguru.com

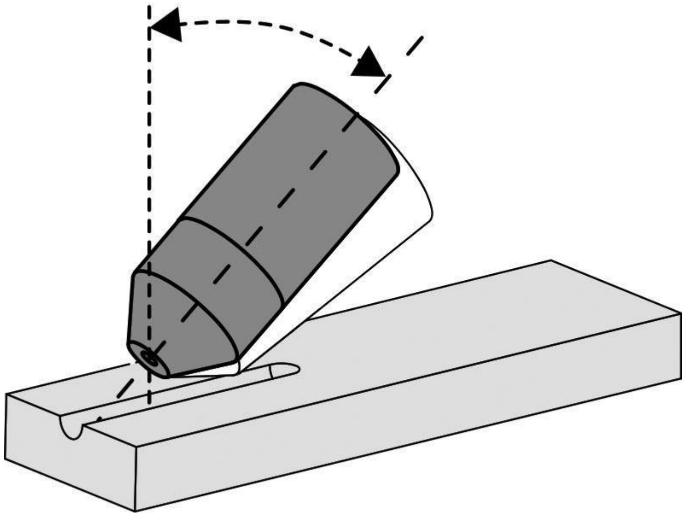
Wire Diameter (cont.)

- However, all the effects of wire size on process characteristics and deposition rate in Plasma based WAAM are not well understood.
- Wang et al (2021) found that for PAW (Ti64), the weld bead geometry obtained with a thinner wire had a higher aspect ratio compared to a thicker wire.
- This can be attributed to the difference in the distribution of the energy between the wire and the work-piece.

Source: Wang et al (2021)

Torch Orientation

- The torch angle towards the substrate is critical and affects various conditions due to the heat loss and the flow force applied to the droplet.
- According to Chen et al., the difference in torch angle affects the welding pool in a horizontal and vertical direction.
- Chen et al used micro-PAW with an aluminum alloy that was known to produce weld pores.
- They investigated the effect of varying the torch angle on the porosity within the weld.



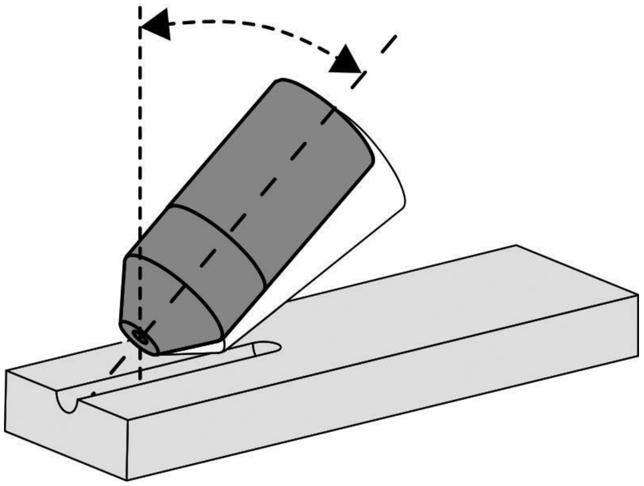
Source: https://www.canadianmetalworking.com/

Source: Rosli et al (2021), Chen et al (2020)

Torch Orientation (cont.)

- When the axis of the welding torch nozzle moved from the direction that was perpendicular to the sample towards the direction that was parallel to the sample and along the length of the weld.
- If the change in the torch angle was very little (≤ 5°), the number of weld pores did not change.
- Thereafter, as the torch angle increased, the number of weld pores decreased.
- As the torch angle increased from 0°, the shape of the molten pool also changed from a circle to an ellipse.
- When the torch angle increased, the melting area not only became elliptical but also larger and the density of the arc power decreases.

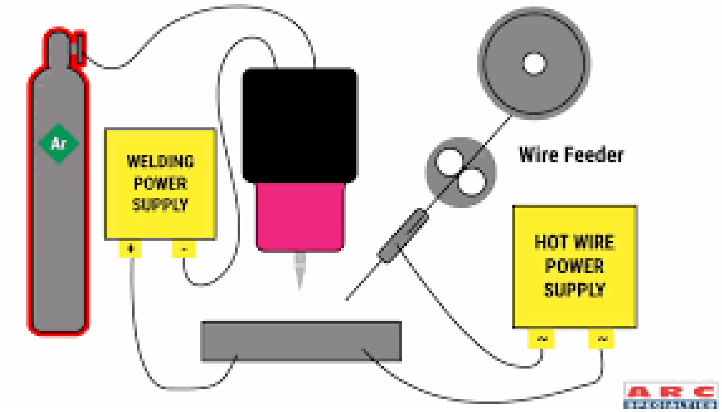
Source: Chen et al (2020)



Source: https://www.canadianmetalworking.com/

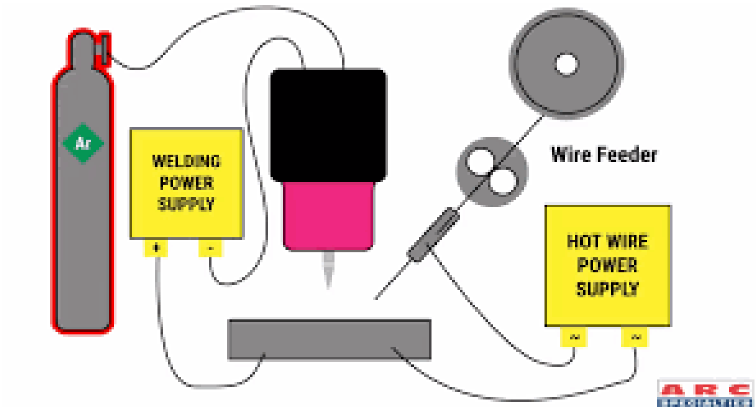
Variants (Hot-Wire)

- Hot-Wire PAW is a variant which is typically used in melt-in welding mode.
- The key distinction is in the name, where the wire is pre-heated close to its melting temperature.
- The wire is heated by running a current through it before being introduced into the weld.
- The key effect of Hot-Wire is that it reduces the required heat input of the torch, leading to increased welding productivity.
- This productivity can manifest itself in a couple of ways either in increased welding speed or increased weld penetration depth.



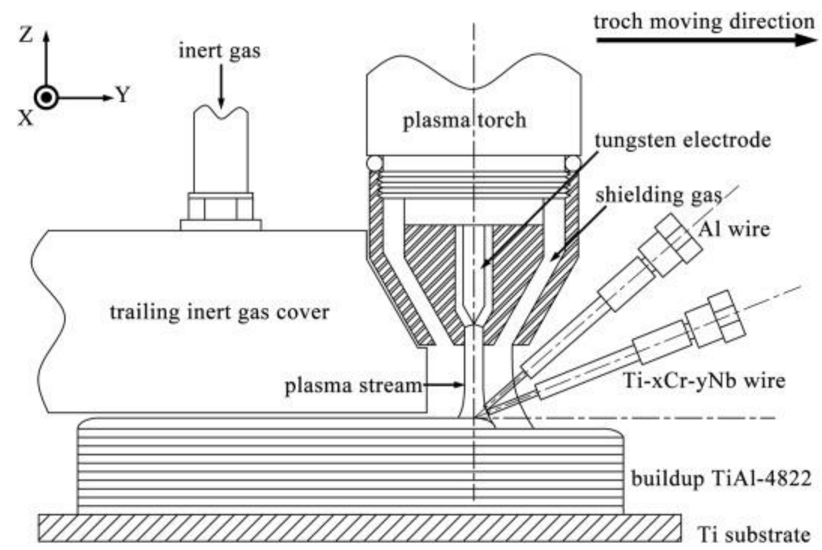
Variants (Hot-Wire) cont.

- It also has the consequence of reducing weld dilution, or the mixing of the substrate metal with the weld metal.
- Hot wire requires additional ancillary equipment to pre-heat the wire.
- The ancillary equipment is commonly available as hot-wire processes can all use the same feeder equipment.
- It is of particular interest in WAAM, both plasma and TIG based systems.



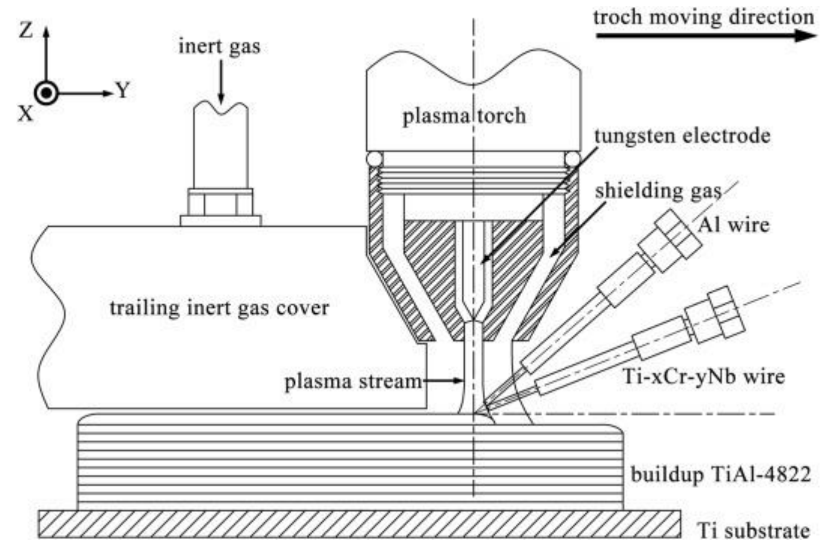
Variants (Twin-Wire)

- Twin wire PAW is most employed in DED, its means of operation is essentially identical to PAW other than with the addition of a second wire.
- The usual purpose of this is to achieve an alloyed deposited weld bead.
- This process has been investigated in producing Titanium Aluminide by Zhou et. al.
- Their conclusions were that it was possible to produce TiAl based alloys using TW-PAW which had comparable parameters to other production methods and full density.



Variants (Twin-Wire)

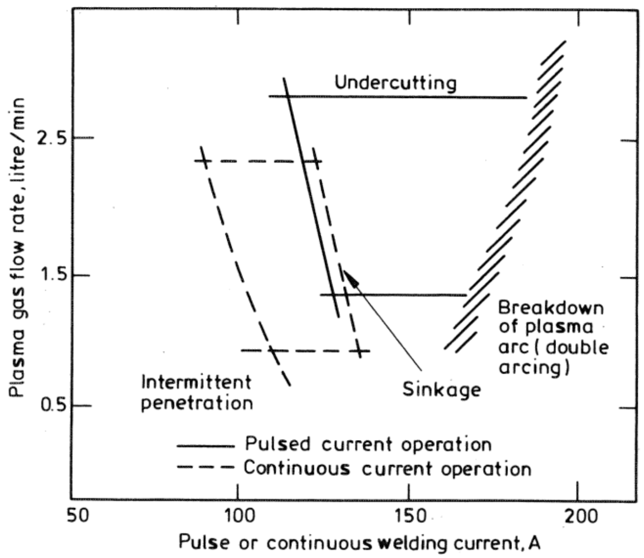
- The effects have been investigated in a variety of other alloys.
- It has generally been shown to enable control of the alloying composition of the weld deposition by varying the feed rate of the wires in steels by Akyel et. al. and in Functionally Graded steel-copper by Rodrigues et. al.
- Use of hot-wire feeding is common in TW-PAW because having two cold wires can create issues with achieving sufficient heat input.



Co-funded by the Erasmus+ Programme of the European Union

Variants (Pulsed PAW)

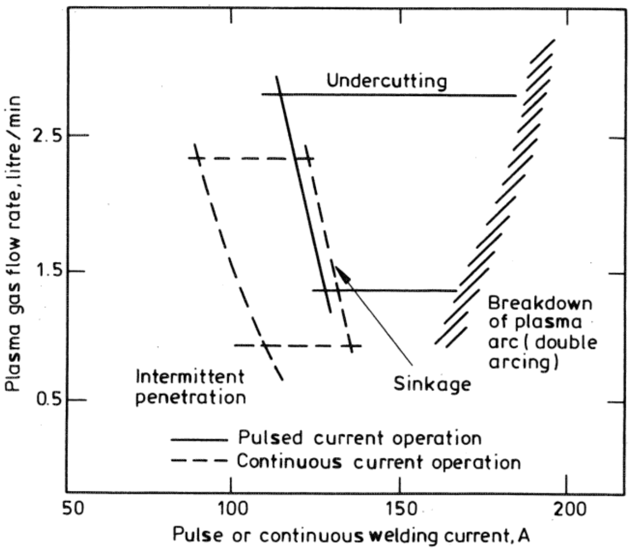
- Pulsed PAW is a mode of welding where a high current is applied for a predetermined pulse length
- The current is then cut and a pilot arc is maintained to allow the weld pool to solidify while the shielding gas flow continues.
- Then the plasma is pulsed again, and it continues in a series of discrete pulses which overlap to form the weld.



Variants (Pulsed PAW) Cont.

Advantages of PPAW is similar to those for other forms of pulsed welding.

- It allows rapid penetration of the workpiece owing to the high current input.
- It allows fine control over the weld penetration depth. This control comes from the definition of the total energy input of the "pulse".
- It is more robust against variations in some of the the welding parameters. As shown in the processing window chart to the right. This is particularly advantageous to keyhole welding as in continuous welding the keyhole is more easily disrupted and collapses.



The issues with PPAW are chiefly that it has a slower throughput rate and that it adds additional cost to PAW, which is already expensive as a welding process.

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Questions?

Thank you