An Analysis of the Types of Welding in Cryogenic Manufacturing

Keshav Mohta

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Introduction

Cryogenics is a branch of engineering that deals with extremely low temperature fluids (less than -150 °C). This includes liquid argon, nitrogen, natural gas, oxygen, helium, etc. The biggest challenge in this industry is maintaining the low temperatures required for these liquids.

INOX India Limited, part of the INOX group, was established in 1992 and is one of the largest manufacturers of cryogenic equipment. With operations in 3 countries, INOX offers a wide variety of cryogenic products. They use various innovative and cutting-edge engineering techniques to provide both standardised and customised solutions for different customers. They are the only Indian company that is providing research equipment for global scientific research projects. Some of their clients include ISRO, Wrocław University of Science and Technology (WUST), ITER, etc. INOX's products are being used in gaseous helium coolers, nuclear fusion reactors, storage solutions, transport lines and much more.

I had the opportunity to intern at INOX's Kalol Plant near Vadodara, Gujarat, specifically in Unit 12 - Cryoscientific Division. This is one of the most technologically advanced divisions of the company. Most of the other units work on mass manufacturing standardised cryogenic products which are sold to the public, but Unit 12 makes custom products for esteemed clients. Here, the design is custom made as per a client's requirements and then manufactured to meet the specifications. It is a research-intense division with projects in atomic plasma research, defence projects and other scientific research. A large part of their work is in aerospace. They have built rocket propellant storage and delivery systems, satellite launch facilities, helium transfer lines, cryogenic cooling systems and more.

Applications of cryogenics to different industries

Cryogenics are widely used in lots of fields. Some of the main ones are detailed below.

Aerospace: Most rocket fuel comprises liquid hydrogen and liquid oxygen, which require cryogenic tankers for storage. Additionally, cooling the extremely high temperatures created in rocket launches uses advanced cryogenic cooling technology. Gaseous helium testing is also used to ensure there are no leaks in any flying equipment.

Automotives: To fit parts into tight places during manufacturing, they can be supercooled such that they shrink and can be placed easily and then expand later upon returning to room temperature to fit tightly. This cooling process uses liquid nitrogen, which requires cryogenic storage.[1]

[1] "Bekijk al Onze Projecten in de Industrie," Demaco Cryogenics, n.d., https://demaco-cryogenics.com/nl/industrieen/space/.

Healthcare: Some biological tissue/blood samples need to be refrigerated at very cold temperatures for which cryogenics are used. Additionally, cryotherapy has various medical applications including in pain relief, healing wounds, skin conditions, weight loss, etc and requires the use of liquid industrial gases. For making MRI machines, cryogenic liquids are used to create superconductivity.

Glass/Ceramics: Cryogenic thermal insulation is applicable during the melting stages of glass/ceramic manufacturing. During the sculpting of glass/ceramic objects, an inert environment is required which is maintained by argon/nitrogen/helium, all cryogenic liquids.

Food & Beverages: Liquid CO_2 is used to create carbonated beverages. For ice cream, liquid nitrogen is used to cool quickly. Packaging food items requires the creation of a modified atmosphere of inert gases like argon/nitrogen which are cryogenic in liquid form.[2] Additionally, for chilled storage of food items, cryogenic liquids can be used.

Pharmaceuticals: Cryogenic liquids are used to preserve vaccines before injection. Antibiotics, serums and other medicines are freeze dried using liquid nitrogen to remove water and form tablets.[3]

Liquified Natural Gas (LNG): Natural gas is a popular fuel used for cooking, heating water, air conditioning, electricity generation, etc. However, being gaseous makes it difficult for LNG to be stores in large quantities. Liquifying it at around -256 °C allows it to occupy 600 times lesser volume, making it more efficient to transport.[4]

Hydrogen: Liquid hydrogen (LH2) is used for storage in hydrogen fuel systems, a more environmentally friendly fuel. This LH2 storage and transport requires manufacturing of multi-layer insulated tanks because LH2 has a very low boiling point at -252.8 °C.

Nuclear Fuel: Both nuclear fission and fusion produce immensely high energies which can increase temperature up to 600 °C and 1.5 million °C respectively[5]. Such processes require large and efficient cooling systems, which can be provided by cryogenic liquids.

Welding in cryogenics

Most cryogenic vessels are made of stainless steel, especially ASME S30200, ASME S30400, ASME S31600 and its variations. These are specifically austenitic stainless

[2] "Food & Beverage Industry| INOXCVA," INOX India Pvt. Ltd., accessed April 2024, https://inoxcva.com/food-and-beverages.php.
[3] "Food & Beverage Industry| INOXCVA," INOX India Pvt. Ltd., accessed April 2024, https://inoxcva.com/food-and-beverages.php.
[4] "Liquified Natural Gas (LNG)," PetroWiki, January 15, 2018, https://petrowiki.spe.org/Liquified_natural_gas_(LNG).
[5] "What Kind of Temperature Is Produced at the Core of a Nuclear Fission or Fusion Reaction? | Socratic," Socratic.org, accessed April 2024, https://socratic.org/questions/what-kind-of-temperature-is-produced-at-the-core-of-a-nuclear-fission-or-fusion-#.

steels. Austenitic steels contain a significant percentage of Chromium, 15-20%, which hardens the steel and makes it more corrosion-resistant. This makes them particularly useful for cryogenic applications because they retain ductility and strength even at very low temperatures.

ASME 31600 specifically contains additional molybdenum which enhances corrosion-resistance and is used for more long-term cryogenic projects involving even lower temperatures. Further, molybdenum also improves the machining ability of steel. It can also maintain its properties at high temperatures, especially important in welding.

The best way to attach two metals, especially strong metals like stainless steel, is to weld them together. Welding is more than just an attachment; it is a joint that fuses the base metals themselves to each other with the help of a filler material.

Welding two pieces of metal together requires extreme precision. The two pieces of base metal first have grooves made in them, to create space for a filler metal to fill in. Then, the base metals are placed side-by-side and heated to very high temperatures (1700-1800 °C), such that the edges of the base metals melt. A filler metal, which is selected based on the chemical composition of the base metals, is also heated to melt and filled into the gap. A welder must skilfully weave the filler metal to fill up the entire gap between the two base metals. Eventually, within a matter of seconds the base and filler metals cool back into solid state and form a permanent fused joint. This joint is termed a weldment.

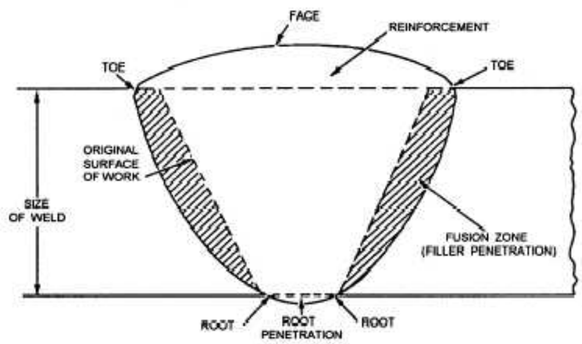


Figure 1: Parts of a Weldment[6]

In the diagram above, we see a weldment. This joint is attaching two pieces of base metal laterally. We see grooves made into both base metals forming a V shape. This increases the space for a welder to fit in their tools such that they can fill in the filler metal easily. The shaded region shows the fusion zone, which is where the base metal is melted and filler metal is placed. The filler metal extends all the way through the metal, with the root slightly jutting out. The extra metal on the surface of the welded joints can be shaved off using grinders or other cutting tools, to create a smoothened surface. The area shown in the diagram above is called the Heat Affected Zone (HAZ).

[6] https://constructionmanuals.tpub.com/14250/css/Parts-of-Welds-49.htm

In cryogenic applications, where maintaining insulation is vital, welding ensures a complete durable seal while joining metals. Further, because of the flexibility that welding offers it allows unique connections at varied angles which standard screws or soldering techniques cannot offer.

Types of welding for cryogenic applications

There are many different types of welding, and each use a different methodology and work on different metals. Some are more suitable for cryogenic applications than others.

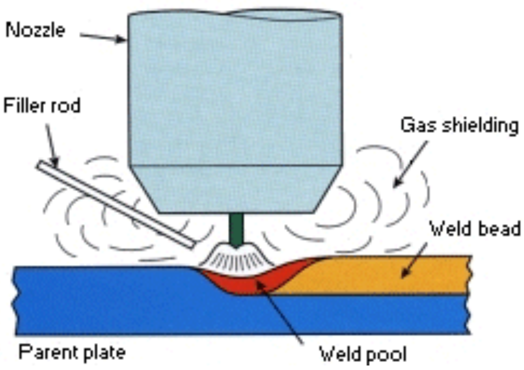
One of the most common types of welding is arc welding. Here, heat is provided to the metal using an electric arc. An electric arc is produced when air is ionised due to electric current and there is a visible discharge of plasma between two electric poles.[7]

Figure 2: An electric arc[8]

This arc can generate extremely intense concentrated heat, which is enough to melt the base and filler metals, and thus be used for welding. To form such an arc, the handheld electrode provides one electric pole and the workpiece forms the other pole.

Gas Tungsten Arc Welding (GTAW)

GTAW is probably the most common welding process. It is also called Tungsten Inert Gas (TIG) welding. It is a manual welding process where highly trained welders use a welding gun and a separate rod of filler metal.



[7] "Electric Arc - Meaning, Causes, Advantages and Disadvantages," VEDANTU, accessed April 2024, https://www.vedantu.com/physics/electric-arc.
[8] "Electric Arc," Wikipedia, May 19, 2020, https://en.wikipedia.org/wiki/Electric_arc.

Figure 3: TIG Welding[9]

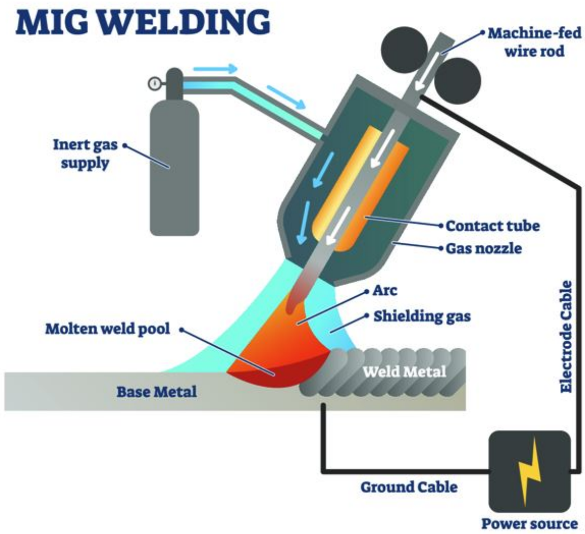
The most notable feature of this type of welding is the use of inert gases like argon. The base metals are surrounded with argon completely, with minimal exposure to the natural atmosphere. This is done by adding argon through an additional tank and even through the weld gun. The argon is labelled in the diagram above as 'Gas shielding'. Using such an inert gas is important to prevent the metal from oxidising in the high temperatures that it will be exposed to.

GTAW requires the use of accurate handiwork, with welders having to use both hands. In one hand, they hold the weld gun (or 'Nozzle' in the diagram). This has a rod inside it made of tungsten. Tungsten is used because it has an extremely high melting point of 3422 °C and can withstand the high temperatures used in welding. The weld gun creates a strong voltage difference between itself and the base metals, which ionises the surrounding argon, generating an electric arc which heats the tungsten rod within it to 1700+ °C, enough to melt the base metal. In the other hand, the welder holds the filler rod, which is brought near the weld gun. By manoeuvring their hands around the joint, welders can use the nozzle to melt the metals and quickly fill the gap with the filler metal.

Once the welding process is complete and the entire groove has been filled with filler metal, the welder can allow the weldment to cool. The HAZ is now a blackish-brown colour and after cooling, welders can use a wire brush to clean the joint and bring back the original sheen to the metal.

Gas Metal Arc Welding (GMAW)

GMAW, also called Metal Inert Gas (MIG) welding is a form of arc welding wherein an electric arc is created between an electrode and the workpiece. Unlike GTAW, the wire itself serves as both the heat source and the filler metal. It is a consumable electrode.



[9] https://www.twi-global.com/technical-knowledge/job-knowledge/tungsten-inert-gas-tig-or-gta-welding-006

Figure 4: MIG Welding[10]

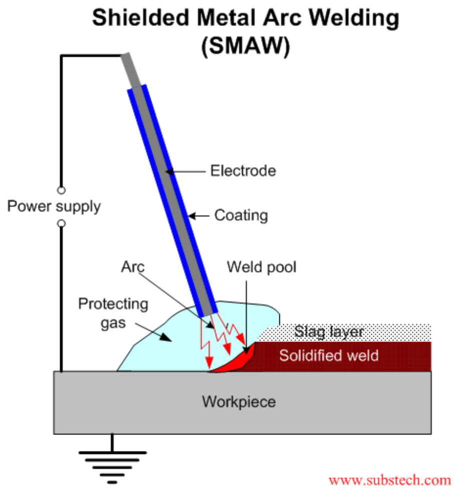
The weld gun provides a shielding gas, argon/helium, which prevents oxidation. The arc melts the electrode and the base metal, allowing them to fuse together. After the groove is filled, the weld gun is moved away and the weldment cools.

Varying the voltage provided to the electrode can vary how filler metal is transferred. For more precise control, the electrode can be supplied with lesser voltage keeping the size of the 'weld ball' (the piece of filler metal that comes out of the electrode) very small.[11] To weld faster but less accurately voltage level could be increased such that thicker beads of metal drop into the workpiece. This prevents lack of fusion but increases spatter (covered later) and is used in thicker materials. Increasing the voltage level causes much greater temperatures which could deform the metal's microstructure.[12] Where metal deformation isn't a major issue, but spatter is a bigger issue, the voltage can be increased even further to cause spraying of the filler metal, making a more aesthetically pleasing weld that can penetrate even thicker materials.

Lastly, GMAW welding can be entirely automated, saving labour costs and time, while improving consistency. However, setting up automated GMAW welding is extremely costly and does not work on custom/niche weld joints.

Shielded Metal Arc Welding (SMAW)

SMAW, also called stick welding also uses a consumable electrode. However, instead of using an inert shielding gas like argon/helium, the electrode is flux-coated. A flux coating is a layer of chemical on the electrode which transforms into a substance that protects against atmospheric contamination.[13]



[10] "MIG Welding Explained," Fractory, April 19, 2022, https://fractory.com/mig-welding-explained/.
[11] "MIG Welding Explained," Fractory, April 19, 2022, https://fractory.com/mig-welding-explained/.
[12] Ibid.
[13] "What Is a Flux Coating? - Definition from Corrosionpedia," Corrosionpedia, July 24, 2017, https://www.corrosionpedia.com/definition/1418/flux-coating.

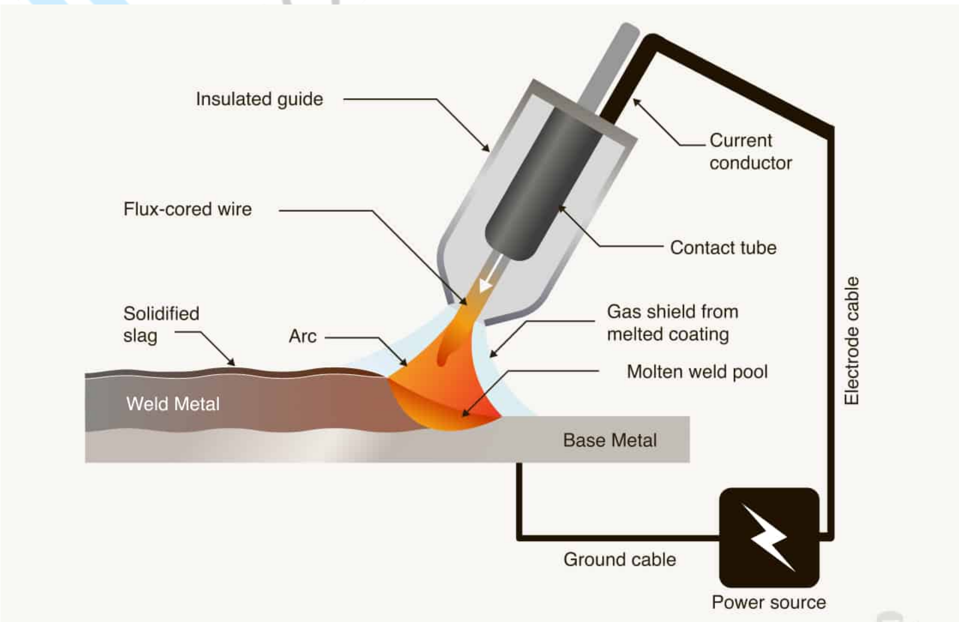
Figure 5: Process of SMAW[14]

Just like GMAW, the electrode creates an electric arc as it comes into contact with the workpiece. The arc creates an immense amount of heat melting the electrode and the base metal allowing them to fuse. However, as this temperature increases rapidly, the flux coating around the electrode is also consumed forming shielding gas and slag around the weld area. This slag and shielding gas protect the weldment from oxidation or any other reaction with atmospheric gases. Upon cooling the slag remains in beads on top of the filler metal and can eventually be removed using a chipping hammer and wire brush.[15]

In SMAW, we can use different types of electrodes which contain different compositions of flux. High levels of cellulose allow for faster welding and larger, stronger welds but also creates a lot more hydrogen gas which can fill up small gaps in the weld and cause porosity. Flux could also comprise high amounts of titanium oxide, which reduces spatter and helps with moving the weld gun more consistently. It also creates a more viscous slag which can be removed easily. Flux could also be more basic in nature with high quantities of calcium chloride or calcium carbonate. This is useful for welds that need to be resistant to cracking but have slag that is harder to remove. Thus, we see that different types of flux have varied advantages and disadvantages and based on their application can be suitably picked.

Flux Cored Arc Welding (FCAW)

FCAW is an improvement on SMAW. It too uses a consumable electrode with flux.



[14] "Shielded Metal Arc Welding (SMAW)," SubsTech, n.d., https://www.substech.com/dokuwiki/doku.php?id=shielded_metal_arc_welding_smaw.
[15] "Shielded Metal Arc Welding (SMAW) Explained | Stick Welding," Fractory, August 4, 2022, https://fractory.com/shielded-metal-arc-welding/.

Figure 6: FCAW[16]

The electrode creates an arc when in contact with the base metal, resulting in the flux transforming into slag and gas. In FCAW however, the flux is not a coating but present in the wire itself, along with the weld metal. The flux also emits more toxic fumes to shield the weld area compared to SMAW or GMAW.[17]

Submerged Arc Welding (SAW)

Another type of arc welding, SAW uses a solid powdered flux as shielding. The arc is "submerged" under the flux and is not visible while welding.

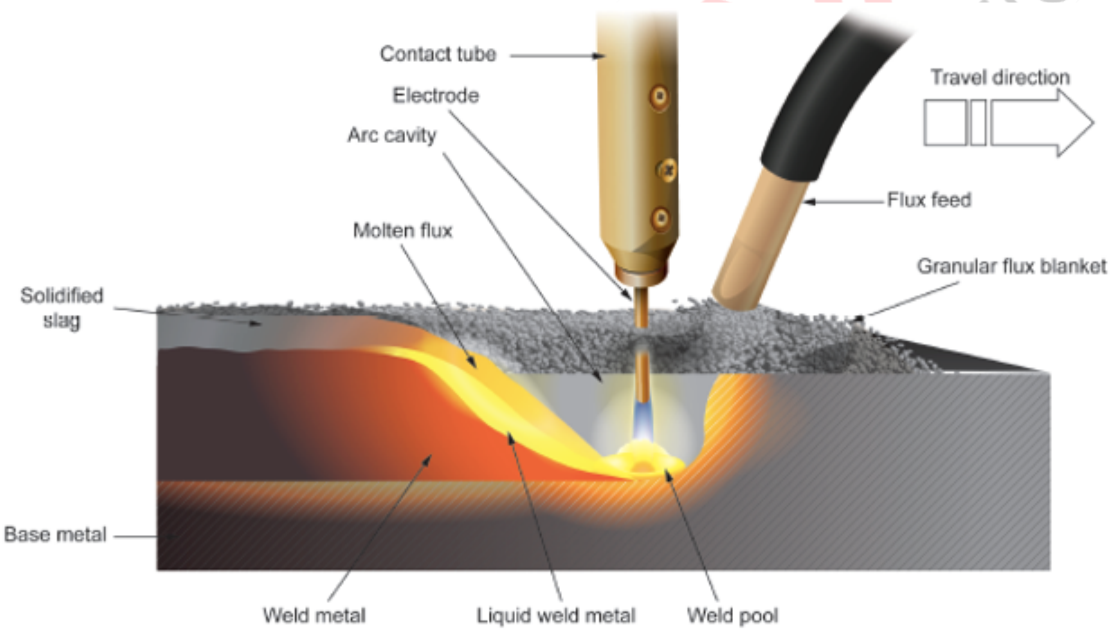


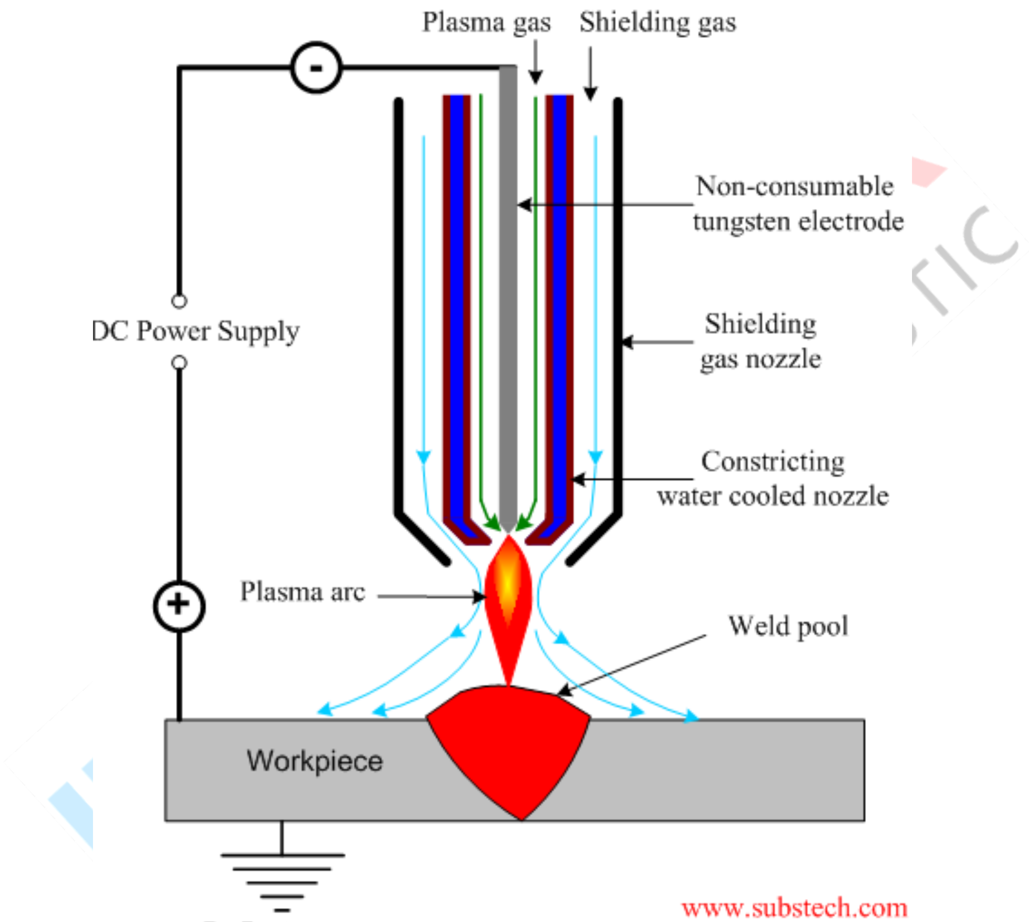
Figure 7: SAW[18]

Because the arc is not visible while welding, it is difficult for manual welding to take place and SAW is usually automated. Automation standardises the welding procedure allowing for a more powerful arc and faster deposition of filler metal. Because the arc is submerged, there is very little weld spatter and the welding process is safe to observe from the naked eye. Additionally, unused flux can be easily recovered, unlike in other welding processes where flux is consumed.[19]

Plasma Arc Welding

[16] James, "Flux Core Welding: Process & Tips," Weld Guru, 2019, https://weldguru.com/flux-core-welding/.
[17] "Flux-Cored Arc Welding (FCAW) Explained," Fractory, August 16, 2022, https://fractory.com/flux-cored-arc-welding-explained/.
[18] "What Is Submerged Arc Welding (SAW)?," CWB Group, n.d., https://www.cwbgroup.org/association/how-it-works/what-submerged-arc-welding-saw.
[19] Ibid.

As the name suggests, this type of welding uses plasma in the welding process. Like GTAW, this process too uses a tungsten electrode. However, in Plasma Arc Welding, the tungsten electrode is placed deeper inside the nozzle, rather than being directly exposed to the outside. The nozzle has a very narrow opening, through which inert gas is directly expelled. The arc is generated within the nozzle itself, unlike GTAW where it is



generated outside. These modifications increase the plasma gas flow rate and the strength of the arc, allowing the weld to be deeper into the metal.[20]

Figure 8: Plasma Arc Welding[21]

Plasma arc welding torches get much hotter than GTAW, reaching 13000 °C.[22] To prevent the tungsten nozzle from melting, the welding gun is also constantly cooled by water.

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[20] "Plasma Arc Welding (PAW) Explained," Fractory, November 28, 2022, https://fractory.com/plasma-arc-welding-paw-explained/.

[21] "Plasma Arc Welding (PAW)," SubsTech, n.d., https://www.substech.com/dokuwiki/doku.php?id=plasma_arc_welding_paw.

[22] "What Is Plasma Arc Welding? | Skill-Lync," YouTube, accessed April 2024, https://www.youtube.com/watch?v=5sDGpncKhzk.

Plasma welding, albeit more expensive, is also more precise and allows for an extremely narrow HAZ. And while it can operate on lower currents, it is extremely noisy (> 100 dB) and uses very delicate equipment.[23]

Electron Beam Welding

This is a unique welding method that does not use an electric arc to generate heat.

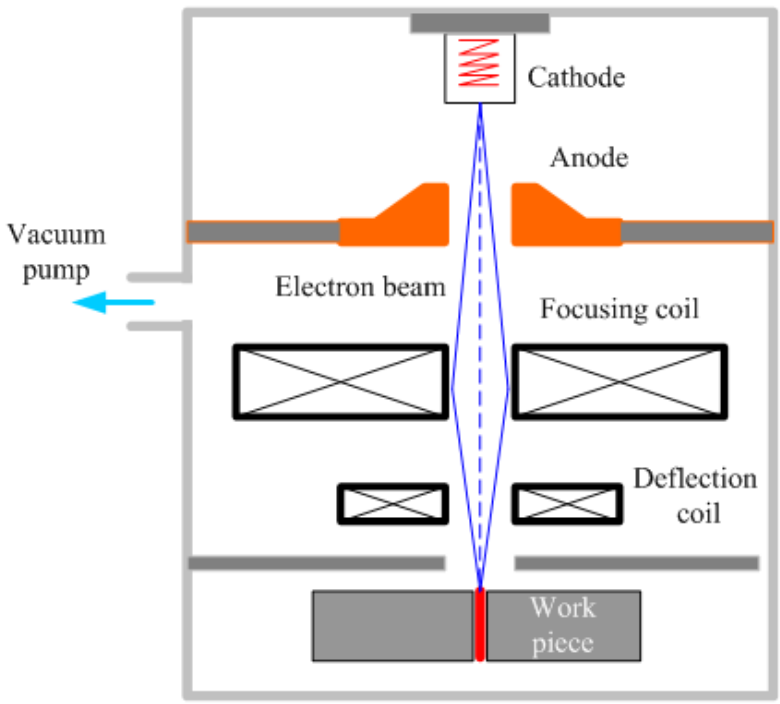


Figure 9: Electron Beam Welding[24]

Here electrons are accelerated out by an electron gun at extremely high speeds, using electric fields.[25] Using magnetic coils the electron beam is deflected and focused onto the workpiece. Such a large force on the workpiece generates heat which melts the base metals and allows them to immediately fuse together.

Because concentrated beams of electrons are being used, this particular type of welding requires the presence of a vacuum environment. Gas molecules can interfere with electrons and cause them to scatter.

Electron beam welding is an excessively automated process due to a high risk of human error and injury. The workpiece is moved around automatically within a larger welding chamber. This type of welding does not require any filler metal and still creates very

[23] "Plasma Arc Welding (PAW) Explained," Fractory, November 28, 2022, https://fractory.com/plasma-arc-welding-paw-explained/.
[24] "Electron Beam Welding (EBW)," SubsTech, n.d., https://www.substech.com/dokuwiki/doku.php?id=electron_beam_welding_ebw.
[25] "What Is Electron Beam Welding? Process Definition and Advantages," TWI Global, n.d., https://www.twi-global.com/technical-knowledge/faqs/faq-what-is-electron-beam-welding.

strong joints. The use of automation allows it to be easily replicable and helps with standardising welded joints. Additionally, it is of course far more expensive than other forms of welding and requires a lot of maintenance.[26]

Oxy-Fuel Welding

Oxy-Fuel welding is a simpler process that generates heat using oxygen and a fuel gas.

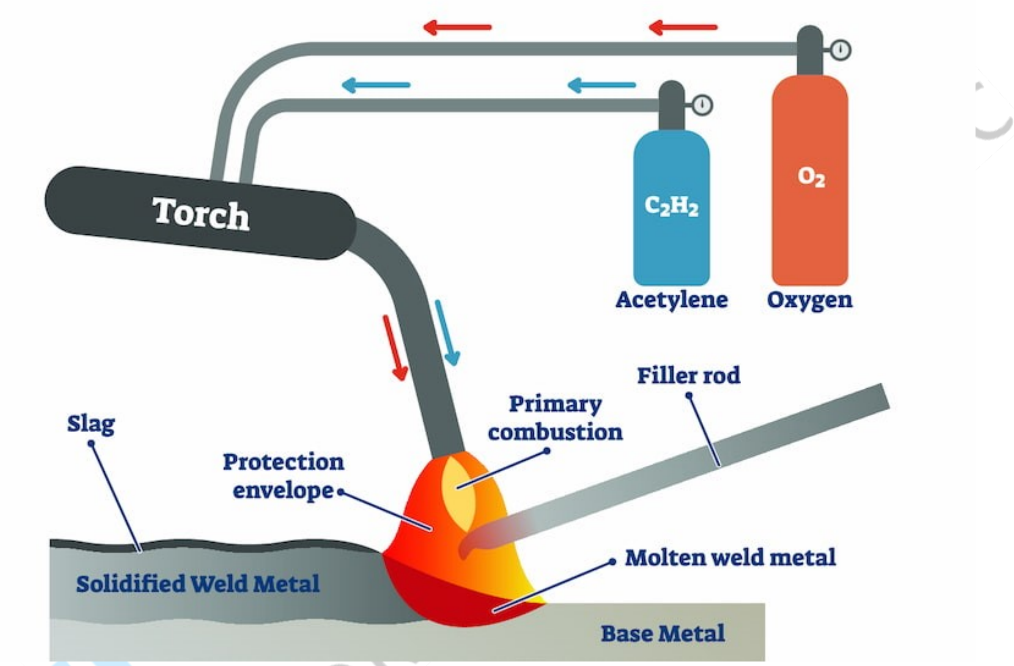


Figure 10: Oxy-Fuel Welding[27]

While the diagram above shows acetylene, these fuels could be gasoline, hydrogen, alkanes, etc too.[28] Because no electric arc is used, the temperatures that gas welding can heat the metals up to is lesser, resulting in it being effective only for thinner welds. Additionally, the use of highly combustible substances makes fire safety a key concern.

The type of flame used in the welding process affects the joint. The strength of the flame can be controlled by the amount of oxygen: more oxygen leads to stronger flame and higher temperatures which could cause the metal to deform or change properties. A weaker flame with lower temperature could result in ineffective welding.[29]

This simple and straightforward technique does not require electricity and is much cheaper than other welding techniques, making it an obvious choice for beginner

[26] Ibid.
[27] Siim Sild, "Oxy-Acetylene Welding Explained | Gas Welding," Fractory, December 27, 2022, https://fractory.com/gas-welding-explained/.
[28] "Gas Welding: Definition, Types, Applications, and Advantages," XO Metry, n.d., https://www.xometry.com/resources/sheet/what-is-gas-welding/.
[29] Siim Sild, "Oxy-Acetylene Welding Explained | Gas Welding," Fractory, December 27, 2022, https://fractory.com/gas-welding-explained/.

welders. In industry, it is very rare to see gas welding in action because arc welding is far more effective.

Possible defects in welding

There are numerous defects that can take place while welding. Over time, welders are trained to minimise these welding defects to ensure strong, reliable and permanent welds.

Lack of Penetration: This occurs when the filler metal doesn't completely reach the bottom/root of the joint. To avoid such a defect, the welder must ensure that their gun reaches the bottom of the joint, but if unable they can also change the groove shape to a double-V.

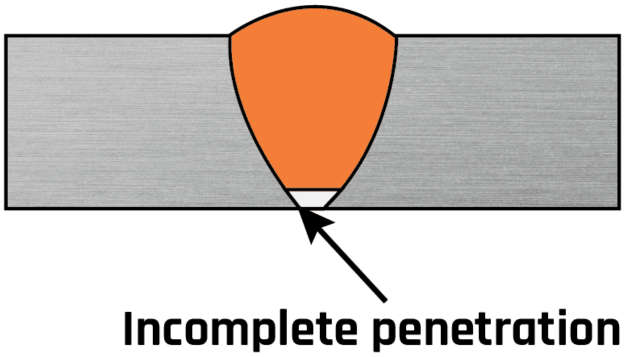


Figure 11: Joint with lack of penetration[30]

Lack of Fusion: As the name suggests, this is when the two parent metal pieces are not completely joined due to gaps in the weld. If this happens, the joint must be taken apart and rewelded.

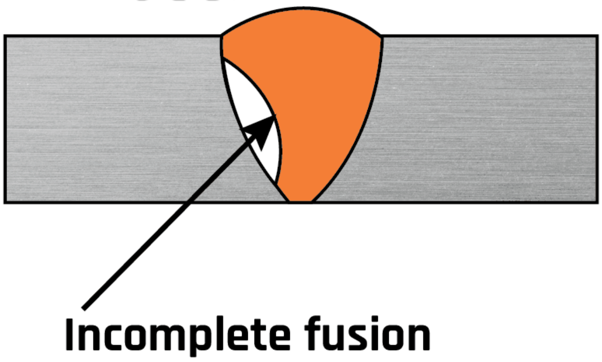


Figure 12: Joint with lack of fusion[31]

Undercutting: When the base metal gets cut and isn't entirely filled up with filler metal, the joint is said to have an undercutting. This can be fixed by simply adding more filler metal to the weldment.

[30] Graham Fry, "The 7 Most Common Welding Defects, Causes & Remedies - Australian Welding Institute," https://welding.org.au/, n.d., https://welding.org.au/articles/the-seven-most-common-welding-defects-causes-and-remedies/.
[31] Graham Fry, "The 7 Most Common Welding Defects, Causes & Remedies - Australian Welding Institute," https://welding.org.au/, n.d., https://welding.org.au/articles/the-seven-most-common-welding-defects-causes-and-remedies/.

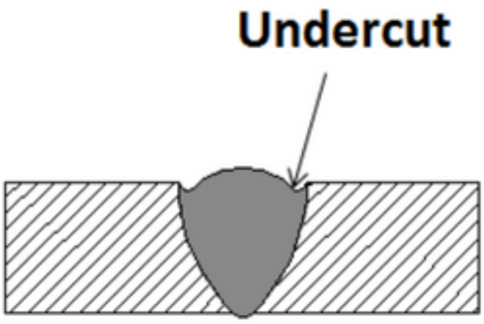


Figure 13: Joint with undercutting[32]

Spatter: Occasionally, droplets of molten metal, usually the filler metal, can drop near the joint if the welder isn't careful. Upon cooling these droplets form small beads like seen below called spatter. Using smoothening tools this spatter can be removed off the joint.

Figure 14: Spatter around a welded joint[33]

Tungsten/Slag Inclusion: During the welding process, if tungsten overheats it could also melt and drop into the weld. Similarly slag, which is used for atmospheric shielding could also drop into the weld. This weakens the joint and it needs to be cut apart and rewelded.

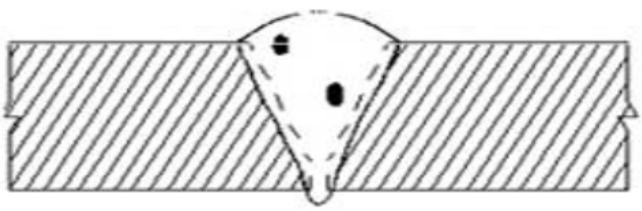


Figure 15: Tungsten inclusion in a welded joint[34]

[32] "What Is an Undercut in Welding?," SSimder, accessed April 2024, https://www.ssimder.com/blogs/ssimderwelder/what-is-an-undercut-in-welding.
[33] "What Is Weld Spatter? (a Complete Guide)," TWI Global, n.d., https://www.twi-global.com/technical-knowledge/faqs/what-is-weld-spatter.
[34] "Nondestructive Evaluation Techniques : Radiography," www.nde-ed.org, n.d., https://www.nde-ed.org/NDETechniques/Radiography/TechCalibrations/RadiographInterp.xhtml.

Cracks: An obvious defect in welding is if there are cracks in the joint. This could occur due to too much expansion/contraction of the metal upon heating/cooling. Cracks can further be classified based on how they form.

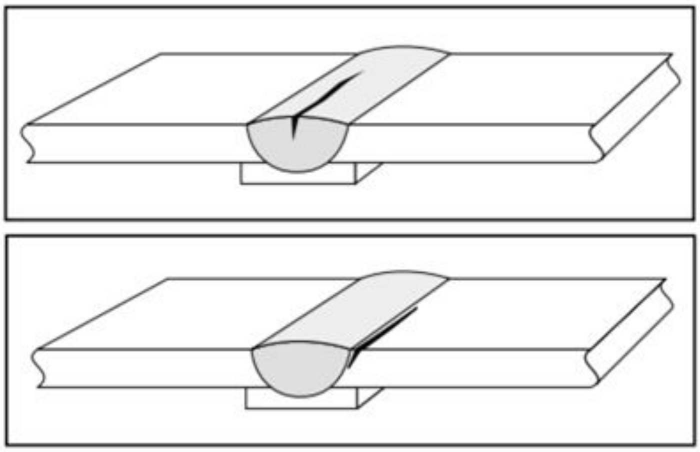


Figure 16: Cracks in welded joints[35]

Porosity: This is when small gas pockets form in the middle of the weld, resulting in the joint having holes in it. Porosity is acceptable to a threshold but in excess can result in a weak joint that can be come apart easily.

Figure 17: Holes due to porosity in a weld joint[36]

Overlap: When the face of the weld i.e. the part on the wider end of the groove, overextends onto the base metal, we see an overlap defect. Using smoothening tools this can be easily removed.

[35] "Understanding Why Your Welds Crack – Part 2," WELDING ANSWERS, August 28, 2019, https://weldinganswers.com/understanding-why-your-welds-crack-part-2/.

[36] "Weld Porosity," LinkedIn, accessed April 2024, https://www.linkedin.com/pulse/weld-porosity-pmet-pittsburg-mining-environmenta/.

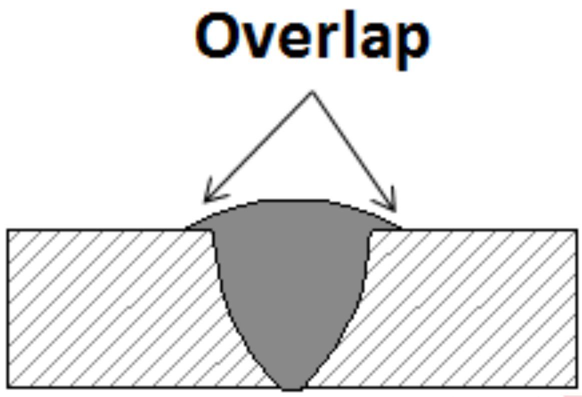


Figure 18: Overlap in a joint[37]

Warpage: If the base metals undergo excess heat and pressure they might deform entirely due to expansion and contraction. This causes them to bend in unwanted ways. To ensure this doesn't happen welders must be cognizant that the heat they supply is localised and doesn't affect the rest of the metal.

Figure 19: Warpage after welding[38]

Burn Through: This occurs when the filler metal gets so hot it burns a hole through the entire metal. This is especially common when welding thinner plates.

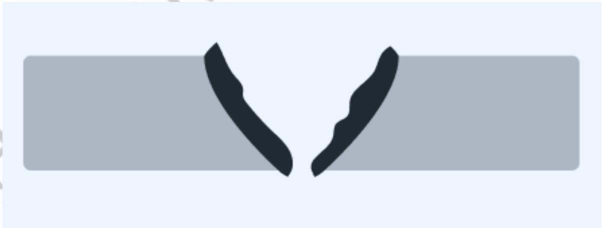


Figure 20: Burn through in a joint[39]

[37] Blackstone Advanced Technologies, "Overlap Welding: What Is It?," blog.blackadvtech.com, n.d., https://blog.blackadvtech.com/overlap-welding-what-is-it.

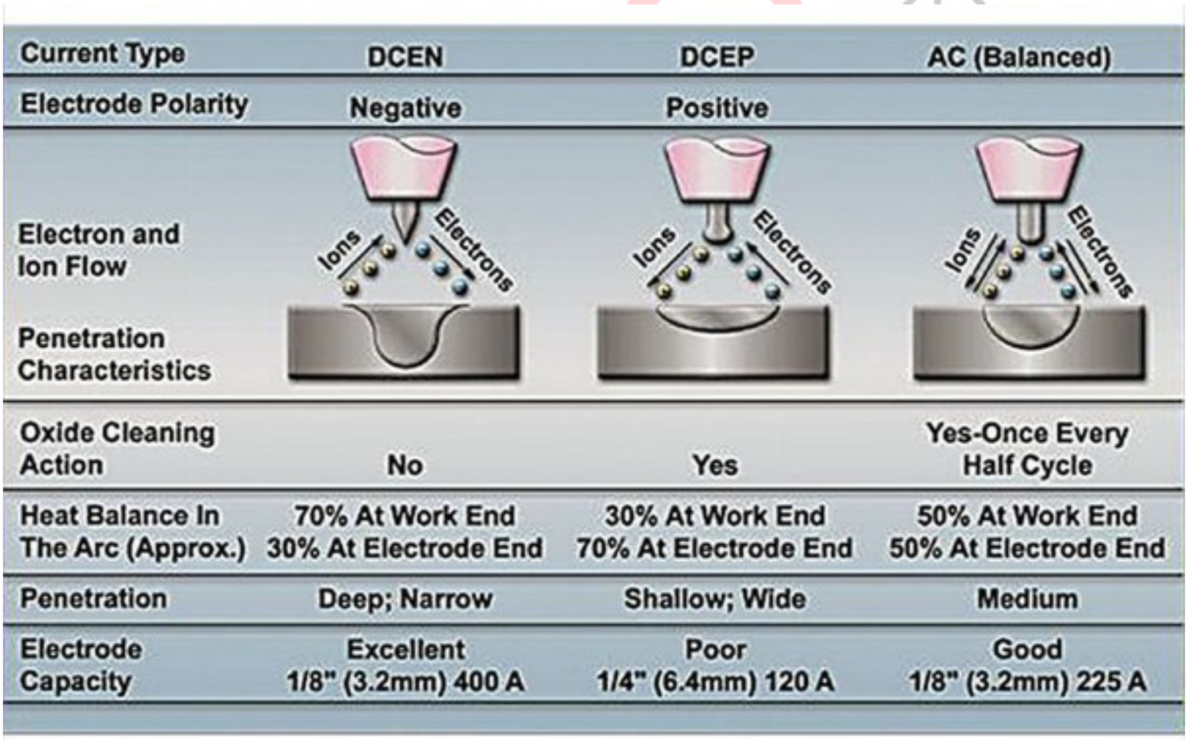
[38] "The 10 Common Weld Defects You Should Know.," sentin, April 7, 2020, https://sentin.ai/en/10-common-weld-defect-imperfections-discontinuities/.

[39] Siim Sild, "Welding Defects - Types, Causes, Prevention," Fractory, October 10, 2022, https://fractory.com/welding-defects-types-causes-prevention/.

Variables that cause welding defects

There are various variables that affect the quality of the weld. Apart from the quality of metal used and the welder’s skill, which are key factors, lots of other factors play a role in achieving the necessary mechanical and chemical properties for the weld.

Electrode Polarity: In arc welding, when an electric circuit is formed, either the electrode is negative and the workpiece is positive, or vice versa. When the electrode is negative, it is referred to as a DCEN current (Direct Current Electrode Negative). Similarly, the other way around is DCEP. A larger proportion of the heat is generated near the positively charged pole (~70%). In most welding methods, DCEN is used to ensure more heat at the workpiece, which results in a deeper weld penetration. Some welding methods like SMAW and GMAW use the reverse DCEP polarity. Additionally, AC current can also be used.



Current Type	DCEN	DCEP	AC (Balanced)
Electrode Polarity	Negative	Positive	
Electron and Ion Flow / Penetration Characteristics	Ions / Electrons	Ions / Electrons	Ions / Electrons
Oxide Cleaning Action	No	Yes	Yes-Once Every Half Cycle
Heat Balance In The Arc (Approx.)	70% At Work End 30% At Electrode End	30% At Work End 70% At Electrode End	50% At Work End 50% At Electrode End
Penetration	Deep; Narrow	Shallow; Wide	Medium
Electrode Capacity	Excellent 1/8" (3.2mm) 400 A	Poor 1/4" (6.4mm) 120 A	Good 1/8" (3.2mm) 225 A

Figure 21: Effects of polarity on welding[40]

Gas Flow Rate: In GTAW and other forms of welding that use an inert gas, the rate at which the gas flows onto the workpiece is referred to as the gas flow rate. Usually, the gas flow rate is higher if the nozzle is bigger. Typically, argon flows out at a rate between 7 to 16 litres per minute and helium at 14 to 24 litres per minute. Large flow rates cause turbulence in the welding area which can cause porosity.

[40] “How Can the Polarity Change on a DC Electricity Welding Machine?,” Quora, 2019, https://www.quora.com/How-can-the-polarity-change-on-a-DC-electricity-welding-machine.

Electrode extension: This is the length of electrode that pops out of the nozzle. For some welding methods the electrode is permanently inside like Plasma Arc Welding, but for others it protrudes outwards. A very long or very short extension result in an irregular arc which could cause defects like undercutting and lack of fusion because the weld area is not completely filled.

Current: The current supplied to the electrode is crucial to control how much filler metal is melted and thus the speed with which welding takes place. If too much filler metal is melted quickly and the welder is unable to keep up, too much metal could deposit resulting in very thick and irregular welds. Additionally, this could also cause burn through defects. A very low current can make the arc unstable and not continuous causing inconsistent welding.

Welding speed: The speed with which a welder or welding machine operates influences the quality of weld. If the welder moved the torch too quickly, there isn't enough melting of base metal and not enough penetration takes place. It could also cause excessive spatter. The width of the weld is also narrower and thus not strong enough. A very low welding speed increases the heat on the base metals, resulting in possible warpage and other chemical damage to the HAZ.

Comparison and Evaluation of Welding Methods

Each form of welding has its advantages and disadvantages and are thus used in different applications.

Here is a summary of the different welding processes.

Welding Method	Fast	Ease of learning	Cost	Versatility/ Precision	Chance of Defect	Welder skill
GTAW	✓	✓	✓✓	✓✓✓✓	✓	✓✓✓✓
GMAW	✓✓✓	✓✓✓✓	✓✓✓	✓✓	✓✓	✓
SMAW	✓✓	✓✓	✓	✓✓✓	✓✓✓✓	✓✓✓
FCAW	✓✓	✓✓✓	✓✓✓✓	✓✓✓	✓✓	✓✓
SAW	✓	✓✓✓✓	✓✓	✓✓	✓✓	✓
Plasma Arc	✓✓	✓✓	✓✓✓✓	✓✓✓	✓✓	✓✓✓
Electron Beam	✓✓✓	✓✓	✓✓✓✓	✓✓✓	✓	✓✓✓
Oxy-fuel	✓✓	✓✓✓✓	✓	✓	✓✓✓	✓

For cryo-scientific applications, versatility and precision are extremely important, given that the welding is very rarely standardised and depends on the customer's requirements. Additionally, high defect rates can quickly increase costs and it is important to have low defect rates. These two parameters immediately eliminate GMAW, SMAW, SAW and Oxy-fuel welding. The third most important parameter is cost. FCAW, Plasma Arc Welding and Electron Beam welding are all too expensive. This leaves GTAW as the only potential welding method. In INOX, GTAW is the primary welding method and is used for almost all products.

Similarly, we can analyse the requirements of other welding applications and choose the best welding method. Each method has its merits and demerits, and all are applicable for different tasks.

Testing Welded Joints

To ensure a joint is properly welded and there are no defects there are various ways to test it. It is important that these tests are non-destructive. Every single joint is labelled and tested to ensure it meets criteria specified in international standards published by ASME or CEN.

Dye Penetrant Test

To test whether a joint has any gaps/holes in it on a surface/sub-surface level (2-3 mm below surface), we can use a dye penetrant test.

To do a dye penetrant test the following is carried out on the joint:

1. Clean the joint with acetone well to ensure there is no impurity.
2. Use a brush to paint the red dye onto the joint. The dye can alternatively be sprayed as well.

Figure 22: Me conducting a dye penetrant test

3. Wait 10 minutes for the dye to penetrate through the metal.

4. Use acetone to clean the excess dye off the metal, such that the surface is spotless.
5. Spray a detector solution to force the dye out of the gaps.
6. Observe any red marks on the joint due to the dye.

Such dye penetrant tests can reveal porosity, cracks or incomplete fusion. If unsure what the issue is, a more advanced radiation test can be performed.

Figure 23: Gaps detected on the joint at the red mark

There are numerous advantages of the dye penetrant test. It is easy to perform even on complicated joints. It is also much faster and far less expensive because there is no camera or advanced equipment needed. And lastly, since the defect is visible on the surface, interpreting the test results is much simpler.[41]

A major disadvantage of dye penetrant testing is that it only works on a surface level. To detect defects deeper into the metal, we must use another form of non-destructive testing. Further, dirty surfaces with paint, rust or oil are difficult to examine.

Radiographic Testing

This form of non-destructive testing uses X-rays to understand the internal characteristics of the weld and identify any defects. It is a form of volumetric testing which is able to detect defects not just on the surface but through the entire volume of the weld.

To perform radiation testing, a film is placed behind the weld joint being tested. Either on the side of the source or of the film, an IQI (Image Quality Indicator) sheet is placed. This has markings on it which can be seen in the final output and can be used to assess if the image was taken appropriately or not. From a source, radioactive isotopes produce X-rays which pass through the joint. Because the joint is made of metal some of the radiation gets absorbed, resulting in the image being visible on the film. Images of the joint are taken from different angles to ensure we obtain a complete view.

[41] "Dye Penetrant: A Guide," Flyability, n.d., https://www.flyability.com/dye-penetrant.

After the images are captured, the films are sent for development. Using chemical solutions, the film is shaded with different intensities of monochromatic colour to be able to view the welded joint. It can be analysed under a bright light to see defects.

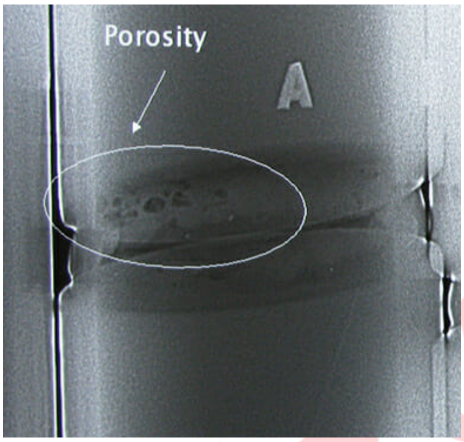


Figure 24: Porosity as seen in a Radiography Test[42]

The image above is of a joint taken through radiographic testing. We see porosity around the joint.

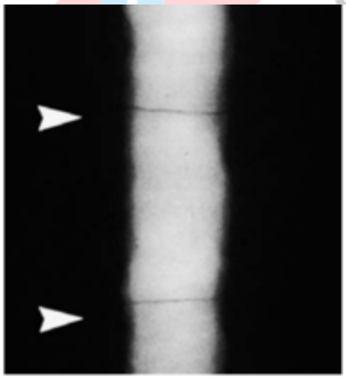


Figure 25: Cracks in a welded tube[43]

This image above shows cracks in the weld joint.

These images show how valuable radiographic testing can be in identifying defects. These defects would not be visible by eye or by dye penetrant testing.

However, radiographic testing does have disadvantages. It has a significant safety hazard because of the radiation that is produced which can be extremely harmful for humans. To prevent this radiation from reaching anywhere else in the unit, the radiography testing equipment is surrounded by very thick metal shielding. Additionally, it can be difficult to find a place for the film, especially on curved joints or joints placed in hard-to-reach places.

[42] "Radiographic Weld Inspections," Applied Technical Services, n.d., https://atslab.com/nondestructive-testing/radiographic-weld-inspections/.

[43] "Radiographic Inspection (X-Ray Testing)," Orange Coast Testing Inc., n.d., https://www.orangecoasttesting.com/radiographic.

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Figure 26: With the people who taught/mentored me at Inox India Ltd.

Bibliography

Applied Technical Services. “Radiographic Weld Inspections,” n.d. https://atslab.com/nondestructive-testing/radiographic-weld-inspections/.

Corrosionpedia. “What Is a Flux Coating? - Definition from Corrosionpedia,” July 24, 2017. https://www.corrosionpedia.com/definition/1418/flux-coating.

CWB Group. “What Is Submerged Arc Welding (SAW)?,” n.d. https://www.cwbgroup.org/association/how-it-works/what-submerged-arc-welding-saw.

Demaco Cryogenics. “Bekijk al Onze Projecten in de Industrie,” n.d. https://demaco-cryogenics.com/nl/industrieen/space/.

Demaco Cryogenics. “The Versatility of Cryogenics: 11 Cryogenic Applications.” Accessed April 2024. https://demaco-cryogenics.com/blog/the-versatility-of-cryogenics-11-cryogenic-applications/.

Flyability. “Dye Penetrant: A Guide,” n.d. https://www.flyability.com/dye-penetrant.

Fractory. “Flux-Cored Arc Welding (FCAW) Explained,” August 16, 2022. https://fractory.com/flux-cored-arc-welding-explained/.

Fractory. “MIG Welding Explained,” April 19, 2022. https://fractory.com/mig-welding-explained/.

Fractory. “Plasma Arc Welding (PAW) Explained,” November 28, 2022. https://fractory.com/plasma-arc-welding-paw-explained/.

Fractory. “Shielded Metal Arc Welding (SMAW) Explained | Stick Welding,” August 4, 2022. https://fractory.com/shielded-metal-arc-welding/.

Fry, Graham. “The 7 Most Common Welding Defects, Causes & Remedies - Australian Welding Institute.” https://welding.org.au/, n.d. https://welding.org.au/articles/the-seven-most-common-welding-defects-causes-and-remedies/.

INOX India Pvt. Ltd. “Food & Beverage Industry| INOXCVA.” Accessed April 2024. https://inoxcva.com/food-and-beverages.php.

James. “Flux Core Welding: Process & Tips.” Weld Guru, 2019. https://weldguru.com/flux-core-welding/.

LinkedIn. “Weld Porosity.” Accessed April 2024. https://www.linkedin.com/pulse/weld-porosity-pmet-pittsburg-mining-environmenta/.

Orange Coast Testing Inc. “Radiographic Inspection (X-Ray Testing),” n.d. https://www.orangecoasttesting.com/radiographic.

PetroWiki. “Liquified Natural Gas (LNG),” January 15, 2018. https://petrowiki.spe.org/Liquified_natural_gas_(LNG).

Quora. “How Can the Polarity Change on a DC Electricity Welding Machine?,” 2019. https://www.quora.com/How-can-the-polarity-change-on-a-DC-electricity-welding-machine.

sentin. “The 10 Common Weld Defects You Should Know.,” April 7, 2020. https://sentin.ai/en/10-common-weld-defect-imperfections-discontinuities/.

Sild, Siim. “Oxy-Acetylene Welding Explained | Gas Welding.” Fractory, December 27, 2022. https://fractory.com/gas-welding-explained/.

Sild, Siim. “Welding Defects - Types, Causes, Prevention.” Fractory, October 10, 2022. https://fractory.com/welding-defects-types-causes-prevention/.

Socratic.org. “What Kind of Temperature Is Produced at the Core of a Nuclear Fission or Fusion Reaction? | Socratic.” Accessed April 2024. https://socratic.org/questions/what-kind-of-temperature-is-produced-at-the-core-of-a-nuclear-fission-or-fusion-#.

SSimder. “What Is an Undercut in Welding?” Accessed April 2024. https://www.ssimder.com/blogs/ssimderwelder/what-is-an-undercut-in-welding.

SubsTech. “Electron Beam Welding (EBW),” n.d. https://www.substech.com/dokuwiki/doku.php?id=electron_beam_welding_ebw.

SubsTech. “Plasma Arc Welding (PAW),” n.d. https://www.substech.com/dokuwiki/doku.php?id=plasma_arc_welding_paw.

SubsTech. “Shielded Metal Arc Welding (SMAW),” n.d. https://www.substech.com/dokuwiki/doku.php?id=shielded_metal_arc_welding_smaw.

Technologies, Blackstone Advanced. “Overlap Welding: What Is It?” blog.blackadvtech.com, n.d. https://blog.blackadvtech.com/overlap-welding-what-is-it.

TWI Global. “What Is Electron Beam Welding? Process Definition and Advantages,” n.d. https://www.twi-global.com/technical-knowledge/faqs/faq-what-is-electron-beam-welding.

TWI Global. “What Is Weld Spatter? (a Complete Guide),” n.d. https://www.twi-global.com/technical-knowledge/faqs/what-is-weld-spatter.

VEDANTU. “Electric Arc - Meaning, Causes, Advantages and Disadvantages.” Accessed April 2024. https://www.vedantu.com/physics/electric-arc.

WELDING ANSWERS. “Understanding Why Your Welds Crack – Part 2,” August 28, 2019. https://weldinganswers.com/understanding-why-your-welds-crack-part-2/.

Wikipedia. “Electric Arc,” May 19, 2020. https://en.wikipedia.org/wiki/Electric_arc.

www.nde-ed.org. “Nondestructive Evaluation Techniques : Radiography,” n.d. https://www.nde-ed.org/NDETechniques/Radiography/TechCalibrations/RadiographInterp.xhtml.

XO Metry. “Gas Welding: Definition, Types, Applications, and Advantages,” n.d. https://www.xometry.com/resources/sheet/what-is-gas-welding/.

YouTube. “What Is Plasma Arc Welding? | Skill-Lync.” Accessed April 2024. https://www.youtube.com/watch?v=5sDGpncKhzk.