A Comparison of Welding Methods and Their Use on Magnetized Assemblies

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This paper was a collaborative effort between Dexter Magnetic Technologies, the industry leader in engineered magnetic solutions, and EB Industries, LLC, the premier experts in high-quality engineered welding.

Abstract

Metal Inert Gas (MIG) and Tungsten Inert Gas (TIG) welding are versatile and widely used methods for joining metals. However, in industries requiring extreme precision, minimal distortion, and high-quality welds, Electron Beam Welding (EBW) and Laser Beam Welding (LBW) stand out as superior options. This abstract compares MIG/TIG with EBW/LBW in terms of precision, heat input, speed, and quality. While MIG and TIG are accessible and versatile, EBW and LBW provide unmatched precision, low heat input, and high speed, making them essential in aerospace, automotive, and electronics sectors.

In magnetized assemblies, these welding methods are crucial for maintaining magnetic integrity. Preventing demagnetization during the welding process is vital to preserving the functionality of highly engineered magnetic products. Collaboration between skilled welders and magnetics engineers ensures that the correct design and process requirements are met for successful production. (American Welding Society [AWS] Standards, n.d.).

Introduction:

MIG and TIG welding have been widely used for decades due to their versatility, ease of use, and ability to produce high-quality welds. However, with the advancement of technology, Electron Beam Welding (EBW) and Laser Beam Welding (LBW) have emerged as cutting-edge welding methods offering superior precision and performance in certain applications.

Tungsten Inert Gas (TIG) Welding

Tungsten Inert Gas (TIG) welding, is an arc welding process that produces the weld with a non-consumable tungsten electrode.

PHOTO OF TIG WELDING

Examples where TIG would be used are:

1. In food and medical equipment where complete fusion and good surface finish is required to prevent contamination.
2. Tubing for high vacuum systems
3. High-purity gas systems
4. Jet and rocket engines
5. Industrial systems
6. Aircraft exhaust systems

Metal Inert Gas (MIG) Welding

Metal inert gas (MIG) welding is a welding process in which an electric arc forms between a consumable MIG wire electrode and the workpiece metal(s), which heats the workpiece metal(s), causing them to fuse (melt and join). Along with the wire electrode, a shielding gas feeds through the welding gun, which shields the process from atmospheric contamination. The process can be semi-automatic or automatic.

Examples where MIG would be used:

• 1-phase MIG welders can be used for small maintenance work, general repairs, and light fabrications in home garages, body shops, farms, and ranches.

• MIG welding is used for automotive parts and repairs.

• MIG welding is common in industries like boat and shipbuilding, chemical refineries, and heavy construction for building materials and bridges.

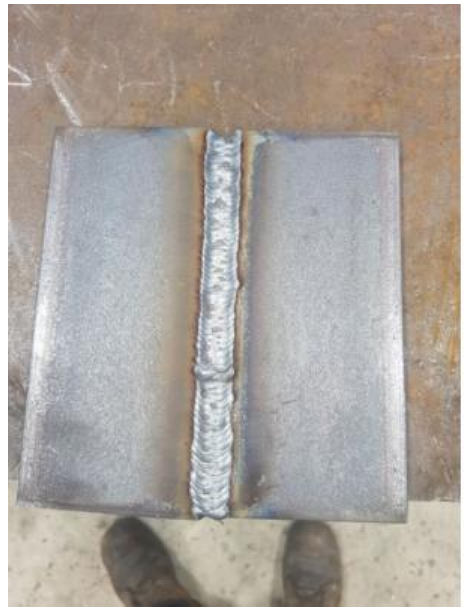


PHOTO OF MIG WELDING

Electron Beam Welding (EBW)

Electron Beam Welding (EBW) is a highly precise welding technique that utilizes a focused beam of high velocity electrons to join materials. The process occurs in a vacuum, which prevents the electron beam from scattering and ensures a concentrated energy transfer to the workpiece. This concentrated energy melts the material, creating a strong, high-quality weld with minimal distortion.

Examples where EBW would be used:

1. Aerospace industry where precision and strength are critical

2. Medical devices in the production of medical implants and surgical instruments

3. Technology to weld delicate components in microelectronics

Laser Beam Welding (LBW)

LBW is a welding process that uses a concentrated laser beam to join materials. The laser provides a high-energy light source that is focused into a small area, generating intense heat that melts and fuses the material. LBW is known for its precision, high speed, and ability to create deep, narrow welds with minimal distortion.

Examples of where LBW would be used:

1. Medical device manufacturing of medical devices, such as surgical instruments and implants

2. Automotive industry where minimal heat affected zones is valuable

3. Manufacturing processes where speed and consistency are crucial

Comparison of MIG/TIG Welding and EBW/LBW:

Precision:

MIG/TIG Welding: While MIG and TIG welding can achieve precise welds with skilled operators, their precision is limited compared to EBW and LBW due to factors such as electrode size and arc characteristics. Both processes can be automated or can be performed manually.

EBW/LBW: EBW and LBW offer exceptional precision, allowing for precise control over the heat input and weld bead placement. This precision is particularly advantageous in industries such as aerospace and electronics, where tight tolerances are critical.

Heat Input:

MIG/TIG Welding: MIG and TIG welding involve the application of heat directly to the workpiece, resulting in significant heat input and a larger heat-affected zone (HAZ).

EBW/LBW: EBW and LBW generate heat through focused energy beams, resulting in minimal heat input and a narrow HAZ. This reduces the risk of distortion, warping, and metallurgical changes in the base material.

Speed:

MIG/TIG Welding: MIG and TIG welding are relatively slower processes compared to EBW and LBW, especially when welding thick materials or performing multiple passes.

EBW/LBW: EBW and LBW offer higher welding speeds due to their ability to deliver concentrated energy to the workpiece, resulting in rapid fusion and shorter cycle times.

Versatility:

MIG/TIG Welding: MIG and TIG welding are versatile processes suitable for a wide range of materials, including ferrous and non-ferrous metals, alloys, and thin sheets.

EBW/LBW: EBW and LBW are highly versatile and can weld a variety of materials, including metals, plastics, ceramics, and composites. They are particularly wellsuited for joining dissimilar materials with different thermal properties.

Quality:

MIG/TIG Welding: MIG and TIG welding can produce high-quality welds when performed by skilled operators. However, the risk of defects such as porosity, lack of fusion, and spatter is higher compared to EBW and LBW.

EBW/LBW: EBW and LBW produce welds with exceptional quality, characterized by minimal defects, high strength, and excellent mechanical properties. Their precise control over the welding process ensures consistent and reliable welds.

Additional Benefits Summary of EBW/LBW:

Electron Beam Welding (EBW):

Precision & Minimal HAZ: Provides precise, narrow welds with minimal distortion.

Material Versatility: Capable of welding various materials without pre/post-weld treatments.

High Welding Speed: Rapid welding with deep penetration, performed in a vacuum to eliminate contamination.

Laser Beam Welding (LBW):

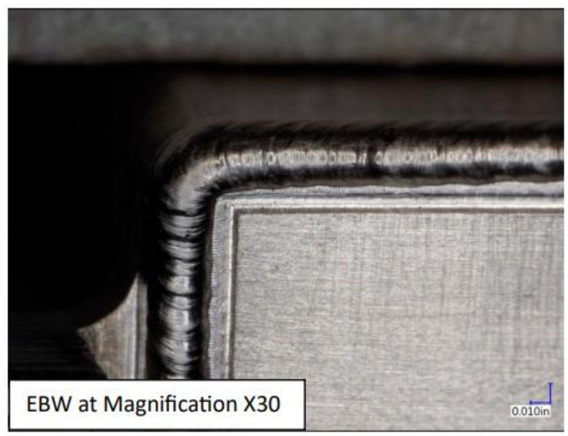
Precision & Minimal HAZ: Allows accurate welding with minimal distortion.

Material Versatility: Suitable for welding metals, plastics, ceramics, and composites.

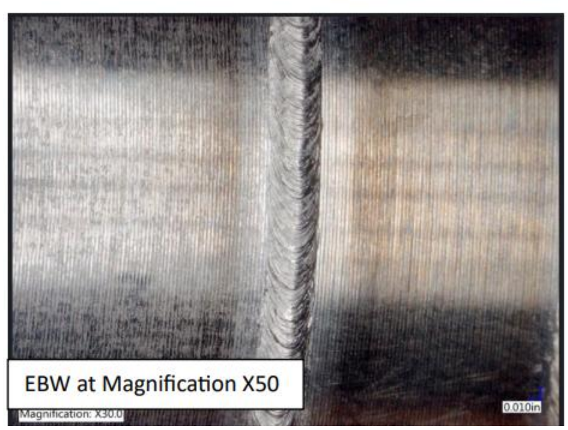
High Welding Speed & Non-contact Process: Fast, precise welding with no physical contact, reducing contamination risk.

Overall, EBW and LBW offer a combination of precision, speed, versatility, and quality that make them highly desirable for a variety of industrial applications, including aerospace, defense, automotive, electronics, medical devices, and microelectronics. Their ability to produce high-integrity welds with minimal heat input and distortion makes them indispensable tools for joining magnetized assemblies and other critical components where precision and reliability are paramount.

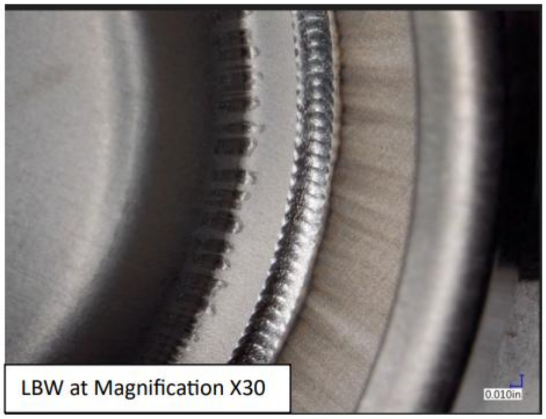
Image Examples of EBW/LBW:



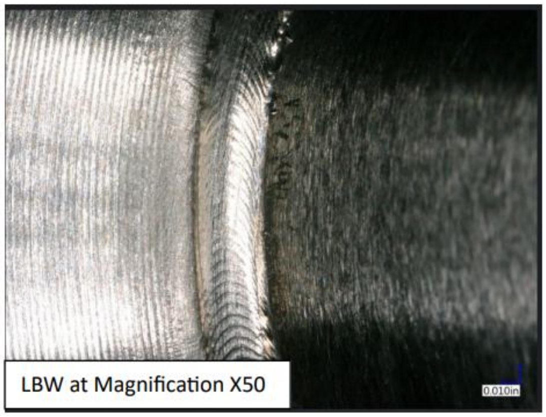
EBW at Magnification X30



EBW at Magnification X50



LBW at Magnification X30



LBW at Magnification X50

Why Use Welding on Magnetized

Assemblies? Welded magnetic assemblies are used in many industries and applications including semi-conductor manufacturing, medical devices for surgical or implantable products, aerospace, defense motors, and more. So why the appeal? Working with rare earth magnets requires an increased need for protection and retention. While rare earth magnets provide a high energy density to the small packages they can come in, they are also caustic, brittle, and are typically assembled with constant repulsion or attraction forces in undesired directions. Therefore, welding a magnetic assembly in place will provide the following top design elements:

- Prevent corrosion caused by the application environment.
- Mechanically retain the magnet assembly in place during end use.
- Protect the magnets from impact damage.
- Reduce magnetic particulate and FOD from the system it operates in.
- Maintain magnetic performance, even when internally cracked or damaged.

Some environments may be naturally corrosive to most materials, such as machinery used at subsea levels on the ocean floor. Other applications are placed in environments designed for high performance and results, such as the hydrogen environment in which semiconductor manufacturing can take place. In this unique instance, Neodymium Iron Boron (NdFeB) rare earth magnets experience hydrogen decrepitation. Without a hermetic seal, these NdFeB assemblies will crumble and turn to powder due to hydrogen embrittlement.

In some cases, hermetically sealing the magnet in an enclosure protects the magnet from the environment; in other cases, it protects the environment from the magnet.

As previously mentioned, some magnets are assembled into an array that purposely creates high forces of attraction and/or repulsion which increases performance of the device.

This means there is a high risk to the system, and possibly the operators, in an instance where the magnetic assembly suddenly disassembles. Welding an assembly to contain these forces is one form of mechanical retention that can be reliable and protective.

By covering the magnets or magnetic assemblies, you can also protect them from impact damage. Due to the powdered metal manufacturing processes that rare earth metals require, they are naturally more prone to cracking and chipping. In turn, this also prevents the release of FOD and magnetic particulate into your higher-level assembly or system. When magnetic particles detach from an energized magnet, they remain magnetized and will attract to other ferrous materials in the product.

Moreover, if a magnet were to get damaged while contained in a welded assembly, mechanically retaining the parts in place assures continued equivalent performance. As long as the magnets cannot shift or twist, the magnetic circuit remains intact and operates as it would prior to the crack/breakage.

Challenges of Welding a Magnetized Assembly:

There are many hidden technical challenges that can present themselves when welding magnetized assemblies without proper experience and design knowledge. This is critical both for the magnetic design as well as the method of welding. Due to unique magnetic configurations to provide enhanced performance, magnetizing after assembly welding is typically not an option. The main considerations for welding challenges will include the heating effects, interaction with the magnetic field, and unwanted interaction at the weld location.

Heat Effects:

There are many effects heat can have when welding magnetized assemblies, regardless of the method of welding chosen. To start, all rare earth magnets are susceptible to demagnetization due to higher temperatures. The temperatures of welding can reach much higher than these recommended limits. Below are some general ranges for welding temperatures that can be seen:

Welding Type	Temperature Range (°C)
MIG Welding	~3,000-12,000
TIG Welding	~3,000-14,000
Electron Beam Welding	~5,500-25,000
Laser Beam Welding	~3,000-15,000

However, it’s important to note that the temperature of these different types of welding, do not necessarily reflect the heat input into the work piece. Arc welding surpasses high energy beam welding when it comes to heat input. The heat affected zone (HAZ) is much smaller in high energy beam welding methods. This is important to analyze before welding a magnetized assembly. Yet, demagnetization of the assembly is not only defined by the temperature it experiences. There is a compounding effect that occurs between interacting magnets in the magnetic circuit, the physical geometry and structure of the circuit, materials used (ferrous and non-ferrous), and temperature. This multi-variable analysis can be predicted through specialized Boundary Element Analysis (BEA) software when run by skilled Magnetics Engineers. These engineers can use these analyses to identify the right balance between magnetic performance and resistance to demagnetization.

The two main rare earth magnets with the highest energy outputs are Samarium Cobalt (SmCo) and Neodymium Iron Boron (NdFeB). NdFeB magnets outperform SmCo magnets as their theoretical maximum energy product is higher, as well as their manufacturable maximum output. On the other hand, SmCo is much better at resistance to demagnetization. Design considerations must be made to protect the magnet of choice and/or even choose the magnet that best withstands the welding process. When preparing for the welding method, using lower heat can decrease the risk of demagnetization, but also leads to a lower penetration depth.

The last major consideration for heating a magnetized assembly when welding is the coefficient of thermal expansion (CTE) of the magnets versus their mating/housing components. Magnets, due to their anisotropic structure, have a different CTE parallel to the magnetic orientation than they do perpendicular to the magnetic orientation. What makes this more challenging is that different raw magnet material suppliers can have slightly different manufacturing methods that create inconsistencies in these values from vendor to vendor.

Interaction with the Magnetic Field:

The next consideration of welding magnetized assemblies is the location of the weld zone in physical relation to the magnetic field. While this can also be considered to reduce the heat effects, it should also be strongly considered when performing arc welding because of the interaction between the arc and magnetic field.

When electric current flows through a conductor, it generates a magnetic field. One of the fundamentals of magnetism is that flux lines repel each other and never cross. The electrical arc created during arc welding is the closing of an electrical circuit that creates high resistance in the area to be welded, therefore converting electrical energy into thermal energy. When the arc is created, a magnetic field is also formed. Therefore, existing magnetic fields near the arc cause the flux lines from the arc and work piece to repel each other when they get too close. This distorts the arc from its intended path, leading to the phenomenon called arc blow. Arc blow can lead to arc deflection, arc instability, and electrode sticking. Each of these reduce weld quality and increase weld difficulty. Welders can sometimes reduce interactions of the two magnetic fields to complete a weld successfully, but the safest and most reliable alternative is using a high energy beam welding method where this effect does not occur.

What makes high energy beam welding methods even more attractive, is the distance that can be increased between the welding equipment and the work piece, thus increasing safety for the welder, the welding equipment, and the work piece. Both arc welding and high energy beam welding methods can be automated, but MIG/TIG welding equipment must still be within a smaller specific distance from the work piece to create an arc. Whether manual or automated, even the arc welding torch can contain ferrous metals that attract to the work piece if held too closely. Electron beam and laser beam welding methods have the advantage of being held further away.

Please note that it's the concern of the distance from the torch to the magnetic field, and not necessarily the distance from the torch to the magnet. Due to magnetic assembly circuit design, you cannot solely rely on an explicit physical distance between the torch and magnet. You have to understand the shape, size, and density of the whole magnetic field. For example, where the torch attracts with hundreds of pounds of force on one side of a magnetic assembly, it could very easily be removed with 15 lbs of force on the opposite side, even if equidistant from the magnets on both sides. Being that magnetic fields influence MIG, TIG and electron beam welding, laser welding is the preferred method of welding charged magnet enclosures.

Unwanted Weld Site Interaction

Most magnetic assemblies are assembled together using adhesive. While mechanical retention is always recommended, until it can be mechanically held in place, industrial strength adhesives are used to position the entire array of magnets. Recall that high performance assemblies typically involve magnetic attraction and repulsion leading to unwanted movement and displacement of the components until they are held in place by something such as an epoxy, acrylic, or another appropriate adhesive. This poses a challenge when you have a magnetic assembly that must then be welded. Contamination of the weld site due to adhesives creates low quality and unreliable welds that do not meet the intended specification. With high-strength industrial adhesives, it is imperative that the adhesive is fully cleaned from the weld site prior to a full cure.

In addition, due to the heat that is produced by welding, a designer must always also consider the integrity of the glue at such temperatures. If the glue lets loose before the mechanical retention is finalized, you pose a danger to the equipment, work piece, and operator if the magnets try to free themselves. There is also concern of the outgassing caused at higher temperatures. If glue must be used in a welded magnetic assembly, cleanliness of the weld site as well as selection of a low out gassing adhesive must be considered.

All methods can be used on demagnetized enclosures however electron beam welding and laser welding are preferred due to the reduced heat effect on the magnets. In some cases, heatsinking may also be required to further reduce the welding heat impact on the magnet(s). This would depend on the thermal mass of the enclosure, the distance from the weld to the magnet, the weld penetration required, the material of the enclosure and the type of magnetic material.

Additional Design Considerations for Welding Magnetized Assemblies:

There are many considerations when designing magnetic assemblies that will eventually be welded. Some of the prior technical challenges can pose areas for design improvements. You may consider the material of the magnet or the magnetic circuit itself. You may need to consider the CTE of the magnets as well as their surrounding and mating components. In this case, there may be enough variance that requires a compliant layer to take on the expanding forces that occur during heating. In other cases, including sufficient gap in the interior of the assembly to account for the material expansion may be adequate. Or even, changes may be made in the allowable welding temperature to accommodate the material limits. Either way, temperature tolerance stack ups are essential to confirming the assembly will not experience irreversible damage during the manufacturing process.

Some designs are large enough that they allow for relocation of the weld site further away from the magnetic field. Yet, in some cases, this is not feasible and large assemblies can sometimes have very powerful magnetic fields. On much smaller applications, you would consider very thin containment walls which are advantageous to magnetic field performance. High energy beam welding methods can allow for walls seen as thin as 0.010 inches. Because a magnetic field decays with the inverse square of distance, the closer components can be brought to a small magnetic assembly, the higher your performance will be. Thick walls in small assemblies will reduce performance drastically, and in some cases, cause the design to become unusable.

Another consideration with assemblies is the manufacturing expectation that many components, produced at different ranges of their tolerance, will create an assembly stack up range that varies greater than any individual component would. Due to the complexity of magnetic assemblies with many components, a designer must consider the weld joint and how easy it will be to maintain the correct gapping between the two welded materials. To account for this, the designer can work with the welders to identify if filler material is needed to account for the gap that may occur.

When welding dissimilar metals, there is also collaboration needed in material selection. Welders will want metals that will interact to produce a quality, reliable, and functioning weld. However, magnetics engineers will design with specialized materials, typically a mix of ferrous and non-ferrous, for varying reasons. Sometimes, interactions of these dissimilar materials can lead to weld cracks, porosity, and many other welding challenges, making it hard to successfully complete a welding procedure qualification.

One additional advantage of electron beam welding is the process requires a high vacuum (1 x10^-3 torr or higher). Trapping a vacuum inside the enclosure may be advantageous, depending on the application, to provide an inert inner-assembly environment.

The process of laser hermetic sealing (LHS) which is laser welding in a controlled environment glove box offers additional advantages over other processes in that the part can pre vacuum baked and back filled with a variety of gases (typically; nitrogen or argon with a trace amount of helium for leak detection) to reduce the moisture content inside the enclosure.

Finally, after the weld is produced and the assembly is fully sealed and/or contained, there are post-welding design consideration that higher-level systems must take into account. In some cases, welded assemblies are then machined. For example, a permanent magnet rotor may be welded closed with a sleeve and end caps, but the wall thickness must be reduced as much as possible. This thinner wall reduces the eddy currents but remains thick enough to act as a mechanical retention. In some cases, the thicker wall will allow for increased heat distribution in the work piece and is later machined down to achieve extremely high runout tolerances. Due to potential warpage from welding, this may be critical for fitment in higher-level assemblies. The surface finish of the final work piece may also be a consideration. It’s best to leave the surface finish polishing until the last step to ensure consistency, even around the weld joints.

In the most sensitive applications, even the physical appearance of a weld can be cause for rejection. What may be used in oil and gas rigs may not require high quality surface finishes, but products used in surgical operation rooms should likely need to be sleek and polished to increase cleanliness and visual appearance. Visual appearance in applications, like medical, can even be a visual indication of product reliability and capability. As a patient, one could imagine seeing a room with shiny clean equipment that’s aesthetically pleasing versus dull and dirty equipment that looks rough and worn, and easily predict which doctor's office would be chosen. Therefore, it's always critical to specify the standards your product requires in regard to aesthetics as this can be the most subjective part of the inspection process. Discoloration of the weld, weld alignment or symmetry, surface irregularities, undercutting, etc. can all have varying levels of concern to different customers.

Conclusion:

In conclusion, while MIG and TIG welding remain popular choices for many welding applications due to their versatility and accessibility, Electron Beam Welding (EBW) and Laser Beam Welding (LBW) offer superior precision, minimal heat input, high speed, versatility, and quality. Manufacturers should carefully evaluate their specific requirements and consider factors such as material type, thickness, joint design, and production volume when selecting the most suitable welding process. By choosing the right welding method, manufacturers can achieve optimal weld quality, efficiency, and cost-effectiveness in their operations.

However, the real challenges arise when manufacturing magnetized assemblies. Typically, because welding is a later step in the production processes, a lot of time and money has already been spent on the product being developed. If the assembly is scrapped at high rates because of improper design and process preparation, the costs will be much higher. Regardless of the welding method used, it's wise to collaborate with skilled welders and magnetic engineers to prevent product, equipment, and most importantly, people safety risks.

References:

American Welding Society (AWS) Standards. (n.d.). Welding Handbook (9th ed., Vol. 2: Welding Processes, Part 1).

Manufacturer specifications and guidelines for welding equipment and materials.