EB INDUSTRIES

Electron Beam Welding

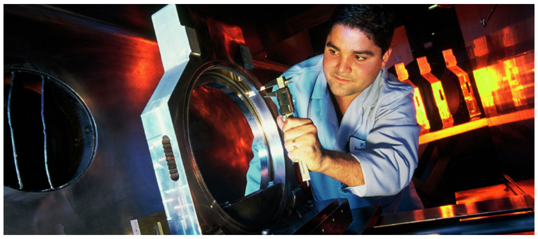
Engineers Design Guide

Electron beam welding represents an advanced, precision fusion welding process. Electron beams are generated by using an electron gun, which accelerates electrons to very high speeds using electrical fields. This concentrated beam is directed onto the materials to be joined, where its energy is absorbed and converted into heat. This localized heating melts the metals, enabling them to fuse together seamlessly. Electron beam welding is typically conducted in a vacuum to prevent contamination and ensure optimal weld quality.

Due to the high precision and energy density of electron beams, the process is highly automated and computer-controlled. Specialized fixturing is commonly employed to secure workpieces in place, with computer numerical control (CNC) systems guiding the movement of components during welding.

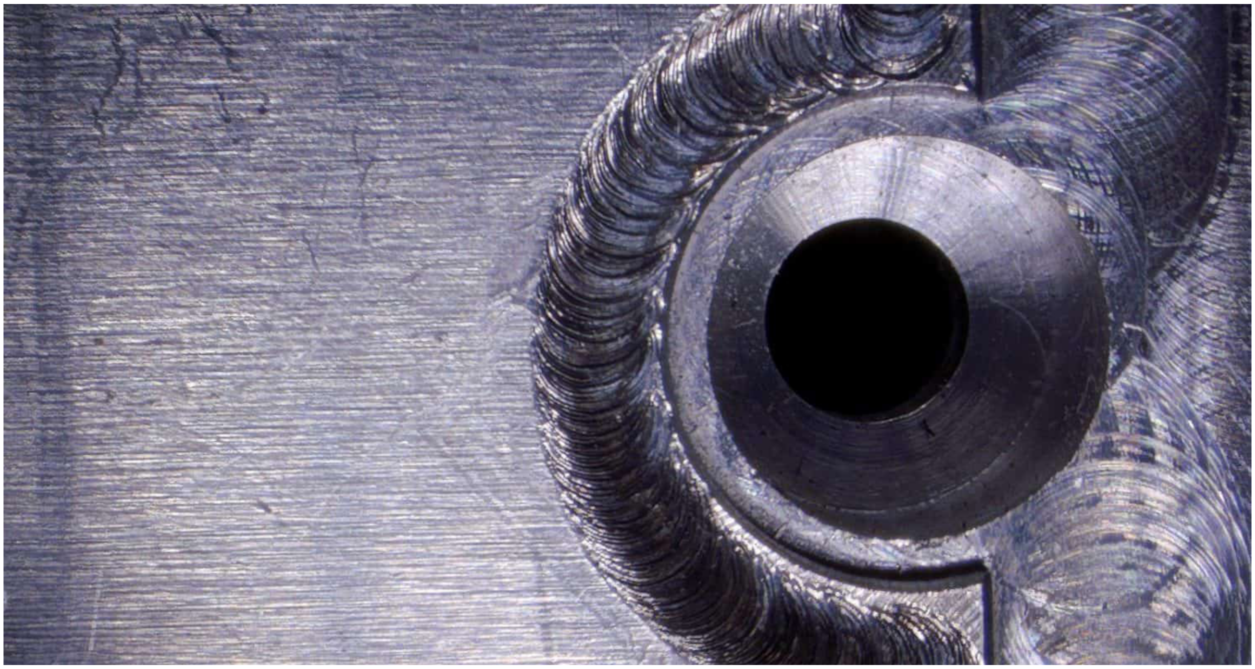
While electron beam welding equipment can be costly, requires meticulous maintenance and must be operated by skilled technicians, the technology offers exceptional advantages. Welds produced are characterized by their precision, strength and purity, making them ideal for applications demanding high-quality joins. Electron beam welding also allows for precise repeatability, ensuring consistency in weld performance across various materials and applications. For many industries and materials, electron beam welding stands out compared to other techniques as a superior choice for achieving reliable and durable welds.

Not surprisingly, technical problems arise from time to time, particularly when applying electron beam welding for the first time. Electron beam welding is a reliable and quality process for joining metals. By avoiding several common pitfalls :



- The selection of a material specification or condition unsuitable for welding
- Incorrect joint design
- Incorrect machining preparation
- Assembly of parts in a contaminated condition

This Design Guide will discuss a variety of electron beam welding 'best practice' guidelines. At EB Industries, our approach as welding technical experts is particularly effective at pre-emptive planning to avoid these typical design and process roadblocks, particularly when we're involved in part and process design at an early stage in the project.



EB Weldable Materials and Material Combinations

When designing a component as a welded fabrication, it may be necessary to compromise between opting for the ideal mechanical properties of a material and choosing another alloy that has better welding properties. A grade of steel normally used for a cast component, for example, would not be the obvious choice for a welded fabrication.

These notes outline the factors that determine the weldability of some of the metals most commonly employed in EBW applications, but are intended as a guide rather than a complete listing of all weldable material specifications. If in any doubt, therefore, 'consult the welder before cutting metal!'

Steels

Most steel and steel alloys are EB weldable. Depending on the carbon content of the steel, there might be some additional preparations required, such as preheating or strain relief during the welding process, etc. Free machining/free cutting grades are generally not suitable for EB welding as lead and sulfur additions to the material act as contaminants and negatively affect weld quality.

Stainless steel weldability depends on the series: some, like 304 SS or 17-4 PH SS, weld very easily, others are very difficult to weld. Some high carbon steels, like 316 SS, tend to be crack prone, which can result in unsatisfactory welds.

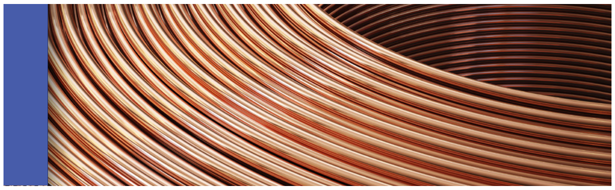
Precipitation Hardened (PH) stainless steel (austenitic stainless) are generally weldable, as are most stainless alloys with chromium, nickel and copper. Additionally, materials like Hastelloy and Chromoly steel are EB weldable.

Case-hardened steel components are weldable provided the case is removed mechanically from the area to be welded.

Aluminum and Aluminum Alloys

Generally, aluminum is weldable with an electron beam, but like stainless steel, weldability depends on the particular series. Low and medium strength grades weld well, but the higher strength alloys tend to be crack prone, due to higher copper content. Alloys like 6061 aluminum don't weld well to themselves, so they require a filler material, typically 4047 aluminum, to complete the welding.

Copper



Copper and beryllium copper alloys generally weld well under an electron beam—much more easily than under a laser. Copper can be prone to cracking and porosity, so we typically recommend pure copper 101 compared to less pure copper alloys, like 110.

Titanium

Titanium welds beautifully with an electron beam. In fact, electron beam welding is recommended for titanium welding applications.

Exotic Metals

Magnesium alloys, nickel-based alloys, Tantalum, Monel, Kovar, Inconel, Molybdenum and Zirconium are all EB weldable. Tungsten is very difficult to weld using any technique.

For a more complete and detailed list of weldable materials please go to https://www.ebindustries.com/weldable-materials/

Dissimilar Metals

If two dissimilar metals can be welded together at all, electron beam welding is usually the way to do it. Copper welds to nickel with few issues under an electron beam. Aluminum, due to its low melting temperature, is very difficult to weld to other materials. Nickel-based alloys, such as Monel and Inconel, can be welded to some steels.

Weld Types and Joint Design Parameters

An electron beam welder is capable of welding in two different modes: keyhole, or full penetration, and conduction, or partial penetration. Each mode produces welds with different characteristics.

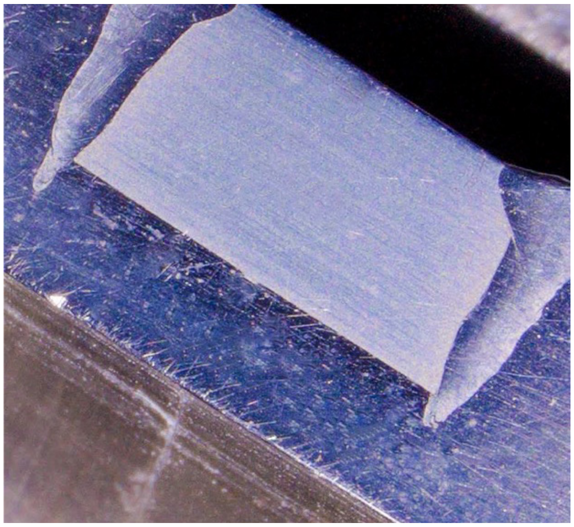
Keyhole Mode/Full Penetration Welds

A keyhole mode weld has a deep, narrow profile with an aspect ratio greater than 1.5. The "keyhole" refers to a literal hole in the material, caused by its vaporization, which allows the energy beam to penetrate even more deeply.

The advantages of keyhole weld joints:

- High joint strength
- Ease of inspection - the depth of the weld can be visually gauged
- Contract more symmetrically during solidification than conduction/partial penetration welds
- Tend to have fewer defects than conduction/partial penetration welds

Keyhole mode welds are incredibly strong and are indicated for deep penetration and structural welds. At EB Industries we use keyhole mode welding for applications like turbine blades, valves going into space, tank bearings, etc.



Conduction Mode/ Partial Penetration Welds

Some EB weld design applications require conduction mode/partial penetration welds. This is mainly because welds are often used to assemble end pieces or covers to a main body that contains sensitive electronic and non-metallic parts. The width of a conduction weld is always greater than its depth, making the process well suited to joining thin-wall materials and spot welding.

A conduction mode weld is achieved using lower power and a relatively low energy density. The resulting weld is shallow and wide, almost bowl shaped. Conduction mode welding simply heats the parts until the materials melt, flow together and solidify.

The fitting thickness is depending on the conception needs; however it must be greater than the maximum weld penetration.

Weld Shrinkage

Regardless of the welding mode, joint designs must account for shrinkage. If the design does not allow uniform shrinkage of the weld metal, cracks can form, especially in high yield strength materials.

The amount of shrinkage relates to the weld cross-section as follows:

Transverse shrinkage = $k\ A/t$
Where: K = empirical factor between 0.1 and 0.17, usually 0.1 A = weld cross-sectional area (fused area) t = weld thickness.

A simplified calculation for a keyhole mode butt weld is Transverse shrinkage = $k \times$ average width of the weld.

The above equations are useful for quick calculations and estimates for single pass welding, which is generally how an electron beam weld is applied. Obviously, more complex situations and more critical applications, require, more detailed examination of shrinkage factors.

In longitudinal welds, transverse shrinkage will reduce the width across the joint. The same applies for circumferential welds, and additionally, the diameter will be reduced.

Good weld design takes into account shrinkage such that welds are mechanically sound and, if necessary, aesthetically appropriate to the use of the part. Proper prototyping of parts is the best way to ensure that weld shrinkage doesn't become problematic in the finished parts.

The machining preparation for EBW is very straight-forward; the basic requirement is for the joint to simulate 'solid' metal in the path of the electron beam.

The need for closely fitting joints becomes clearer when it is realized that no filler material is used in beam welding (except for special applications) and consequently, it is essential to have good fit conditions.

Types of Welded Joints

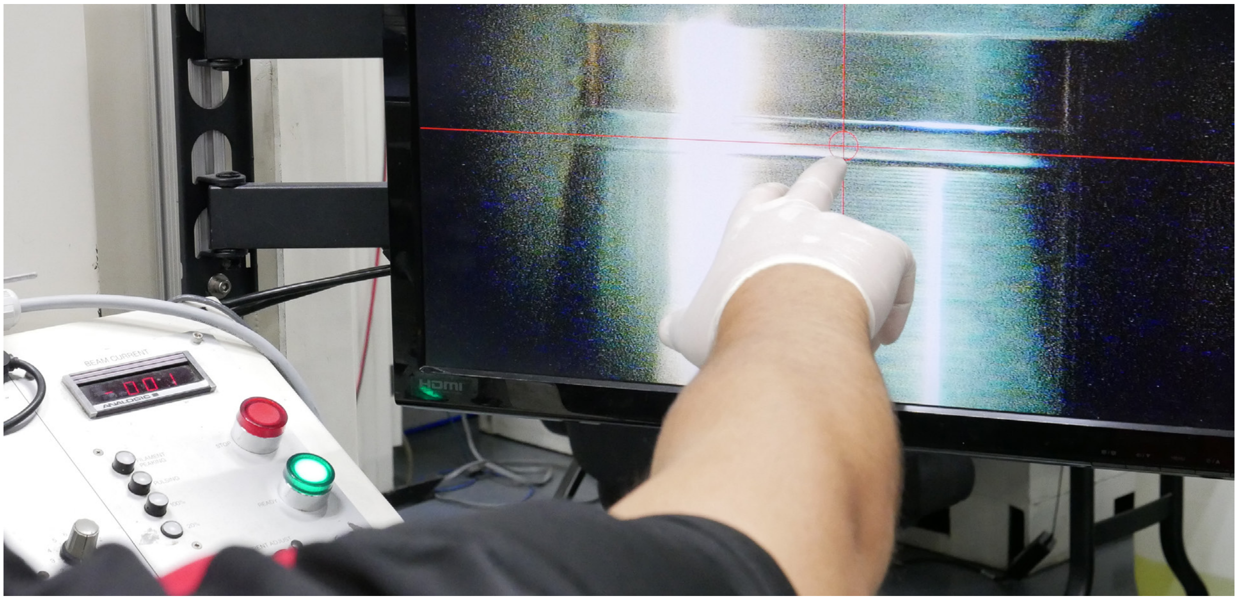
- **Butt Weld**
  - A fit-up tolerance of 5% of the material thickness is desirable.
  - Sheared edges are acceptable provided they are straight and square
  - Misalignment and out-of-flatness of parts should be less than 10-15% of the material thickness
- **Lap Weld (burn-through or seam weld)**
  - Spaces between pieces to be Lap welded severely limit weld penetration and/or feed speed
  - For round welds in titanium, no gap can be tolerated
- **Fillet Weld**
  - Square edges and good fit-up are necessary

Cleaning and Machining

Parts to be electron beam welded must be very clean and free of debris from machining, hydrocarbons or oxidation contaminants.

Most design changes required to make a part more weldable are basic machining operations, such as turning, milling, leaving extra material, etc.

- Machined parts should not be rumbled or vibro-deburred
- Clean parts and joints using solvents, then clean using a like-material wire brush. Wire brushing prior to solvent cleaning typically embeds hydrocarbons and other contaminants into the part, rendering the solvents far less effective
- Do not use shop rags that may be contaminated with oil residue to clean parts. Use clean cloths, such as Kimwipes, when cleaning surfaces with solvents
- If debris must be blown off a part, use a bottled gas; we prefer nitrogen or argon. Compressed shop air is acceptable but introduces safety risks
- Always use new or recently cleaned stainless steel brushes to clean the weld joint. Older, dirty brushes may contain oils and other contaminates. Brushes used to clean one metal should not be used to clean a different metal as flakes can be carried on the brush bristles, causing contamination
- Be sure to thoroughly clean and wire brush any etched metal surface. Residual contaminants and by-products from the etching process can alter the chemical composition of the weld pool
- Clean all wire brushes and scraping/filing/cutting tools frequently. Ferrous components need to be degaussed to avoid deflection of the electron beam by stray magnetism
- Avoid chamfering as this can create an air trap within the joint and result in weld porosity defects



Traditional Electron Beam Welding Inspection Methods

EB Welding is essentially a machine-controlled process in which precise parameters can be determined at the development stage and logged for future use in the production of the component.

The EB welding process is a vacuum remelt of parent materials, resulting in parts that are thoroughly clean and correctly fitted.

Hence, provided that the weld development is designed to accurately simulate the physical geometry and material specification of the actual component, the results achieved on the test pieces will be repeatable within very close tolerances on the production components.

Non-destructive testing of EB welds is a subject in its own right, but a brief summary of the principal NDT methods used should be included:

1 Visual Inspection

All welds are visually inspected using 10x or greater magnification as necessary. Surface defects e.g. cracks, mis-alignment, under penetration or undercutting can usually be detected by this method.

2 Penetrant Crack Detection

Normally the water washable fluorescent dye technique is used to identify possible surface defects that may not be readily seen by visual examination.

3 Radiography

Where the component joint geometry permits, an X-ray examination technique can identify sub-surface defects that would be hidden from the visual.

4 Penetrant Inspection Methods

In particular, internal porosity and crack defects can be identified and recorded on film. Radiography is, however, a relatively expensive NDT technique and for this reason is sometimes used on a sample basis, typically 10% of the batch of components welded.

5 Ultrasonic Testing

Subject to component geometry, ultrasonic testing can provide a cost effective and reliable method for detecting internal weld defects. Results can be assessed against a go/no-go setting and printed to provide a permanent record.

6 Pressure or Vacuum Leak Testing

These provide, again subject to component configuration, a performance test of individual components.

7 Batch Control Test Pieces

Test pieces directly simulating the component weld and material condition can be used for quality control and can be run either before, after or during the production batch. They provide the opportunity for NDT as well as macro and micro section examination.

8 Process Control Specification

There are several governing bodies, such as the American Welding Society (AWS) and SAE Aerospace, that dictate the requirements for welded assemblies. The specification to use depends on the end use of the assembly.

About EB Industries

EB Industries is a full-service provider of electron beam welding, laser welding and laser hermetic sealing services as well as a contract manufacturing company with a large network for value added processes. We have been a pioneer in precision welding for more than five decades and today are known for precision, service and reliability by OEM, Tier 1 and Tier 2 manufacturers in aerospace, medical, semiconductor, electronics and other critical industries.

EB Industries has continually met the unique requirements of component fabrication companies by helping customers design, develop and produce welded components. EB Industries also provides and manages additional services to produce complete assemblies. We are certified to AS9100D, ISO 9001:2015, ISO 13485:2016 as well as NADCAP certified for welding. Our reputation for fast delivery, low weld failure rates and informed, straightforward customer relationships is unmatched in the welding services industry. In 2019, we were awarded a perfect 100 NPS (Net Promoter Score) for customer experience.