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Electron Beam Welding Process

Azeem Uddin Azeem Islam



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Outline



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- Electron Beam Welding Process
 - Heat generation and welding parameters.
 - Principles of electron beam welding process.
 - Equipment and accessories.
 - Process applications and limitations.

EBW – Introduction

– History of EBW

- In early 1950s in Germany and France.
- First EBW machine in 1950s
- 1960s, Carl Zeiss sells with high voltage (125 – 150 kV)
- 1970s, EBW became a prominent choice between nuclear and aerospace industries
- As of 2024, largest and most powerful EBW from Japan, 300kW at 600kV, it was able to penetrate 305 mm of steel



EBW – Introduction



- EBW is considered one of the cleanest welding processes, with fewer defects than conventional arc welding.
- Because of its high equipment cost, vacuum chamber, and facility requirements, EBW has been limited to high-production applications. To date, EBW has seen the highest usage in the automotive and aerospace industries.
- Electron beam welding (EBW) is a fusion welding process that uses high velocity stream of electrons focused on work piece surface to weld material by melting and vaporization (Kinetic energy to Heat energy)
- In electron-beam welding (EBW), electrons are accelerated to a velocity max. nearly three-fourths that of light (~50,000 – 200,000 km/sec).

EBW – Introduction



- How it works:
- An electron beam machine works in much the same way as a cathode ray tube in a television.
 - A cathode section generates an electron beam.
 - An anode section accelerates the beam.
 - The lens system converges and deflects the electron beam to the desired position.

– Operating principle:

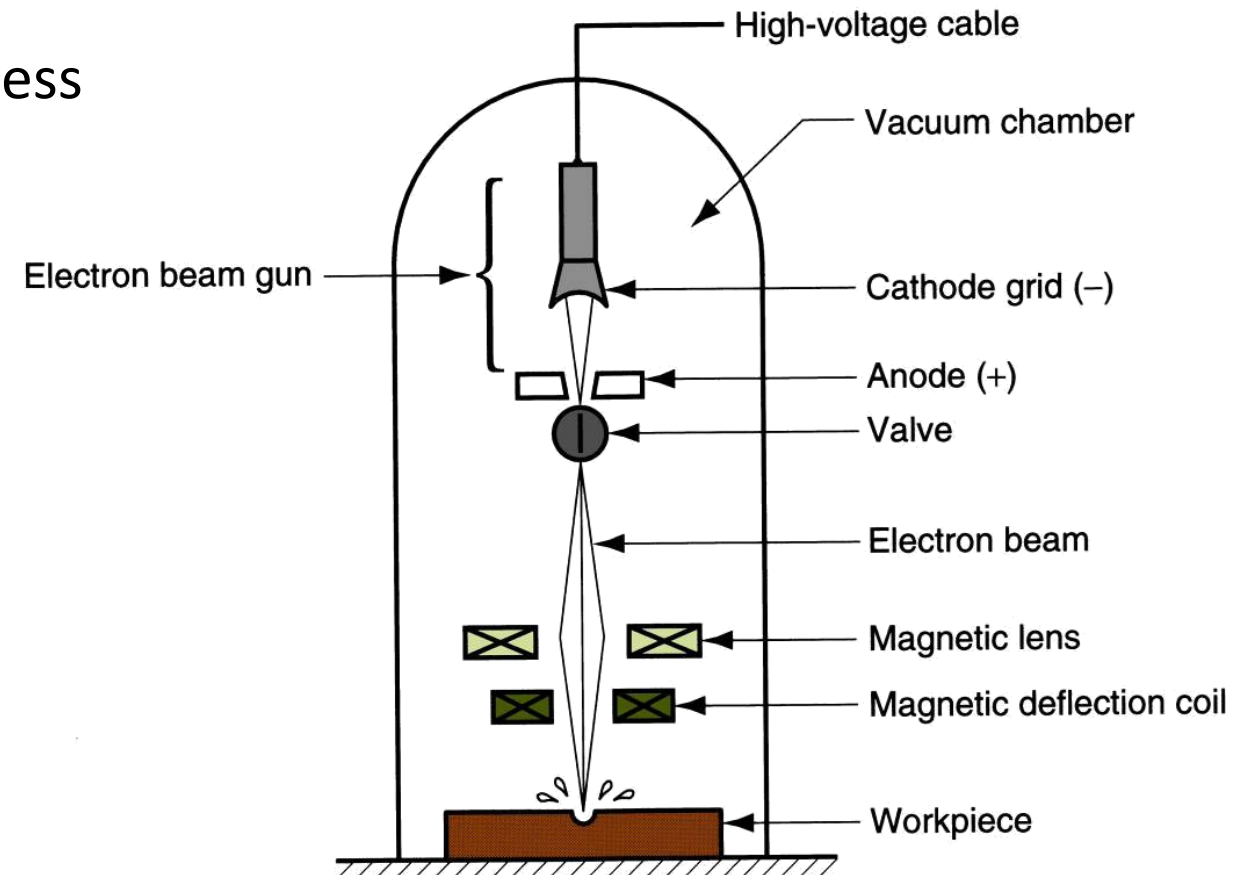
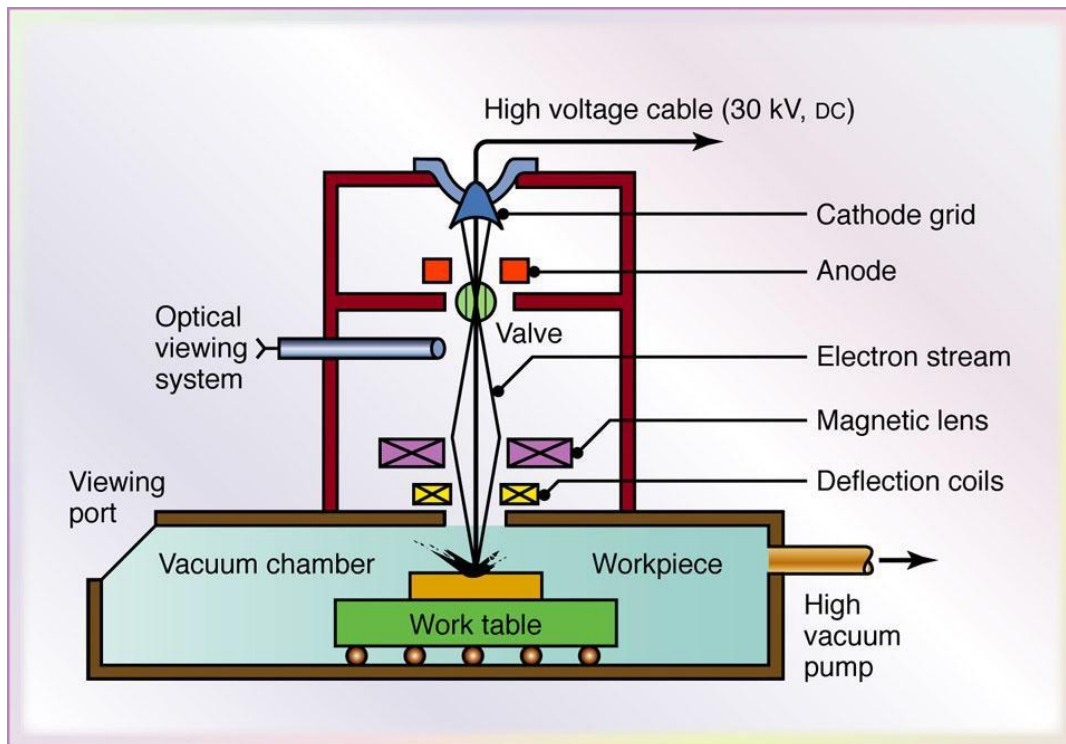
- A high velocity stream of electrons is directed against a precisely limited area of the work piece; on impact, the kinetic energy of the electrons is converted into thermal energy that melts and joins the materials to be weld.
- The process is performed in a vacuum chamber to reduce the scattering of electrons by gas molecules in the atmosphere.
- 20% to 80% the speed of light (10kV to 200kV)
- Basically, beam causes material interaction

– Process capabilities:

- A range of materials such as stainless steel, nickel and cobalt alloys, copper, aluminum, titanium, ceramic, leather and plastics can be processed by this method
- Thin and thick plates (0.1mm to up to 300mm).
- Sheet thickness 10mm.
- Aspect ratios as large as 5:1 to 25:1 (weld Depth:Width) can be achieved in most materials
- Weld area has fine crystalline structure
- Joint strength 15% to 25% better than conventional arc welding
- Enough power to vaporize metal ($10,000 \text{ kW/mm}^3$)

EBW – Introduction

- Equipment schematic:
 - Schematic illustration of the EBW process



EBW – Equipment



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- Operating Modes: Vacuum Capacity
 - High (1 to $1e-3$ torr or lower)
 - Medium ($1e-3$ to $2.5e-3$ torr)
 - Non-vacuum (760 torr or 1atm)
- Power Capacity
 - High (up to 200kV)
 - Low (30 to 60kV)
 - Non-vacuum always run at high voltage. High voltages maximize the working distance (usually length of beam travel in atmosphere).

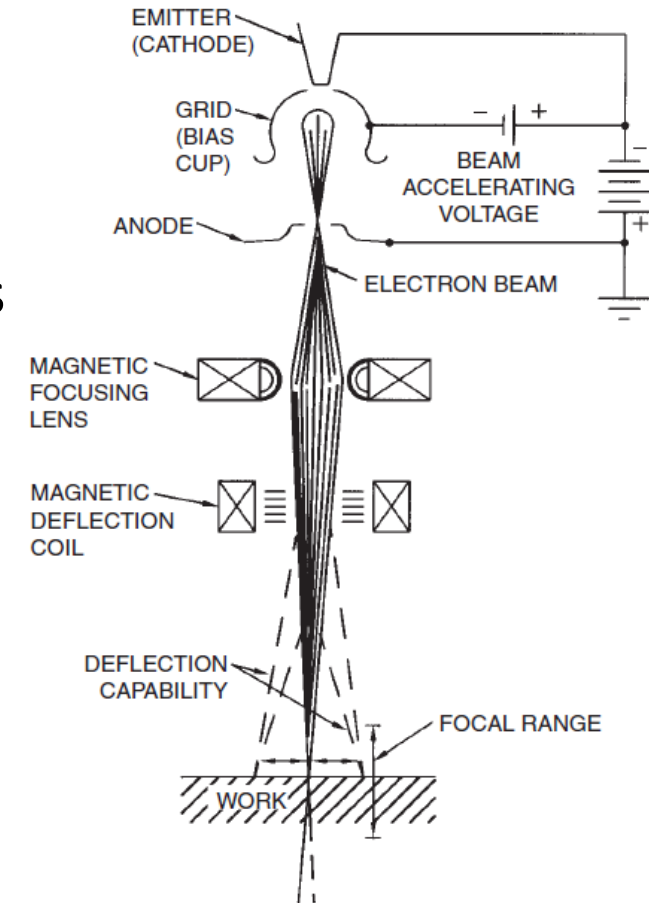
EBW – Equipment



- High-voltage beams can be focused to smaller spot sizes than low-voltage beams at equivalent power levels.
- Low-voltage systems employ compact electron beam guns which can be manipulated through multiple axes within the work chamber.

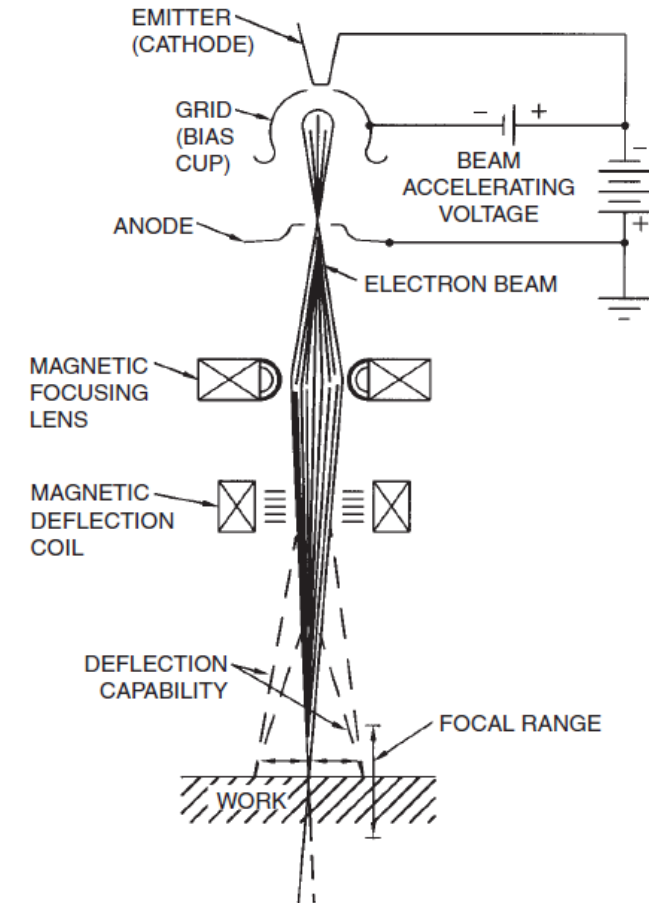
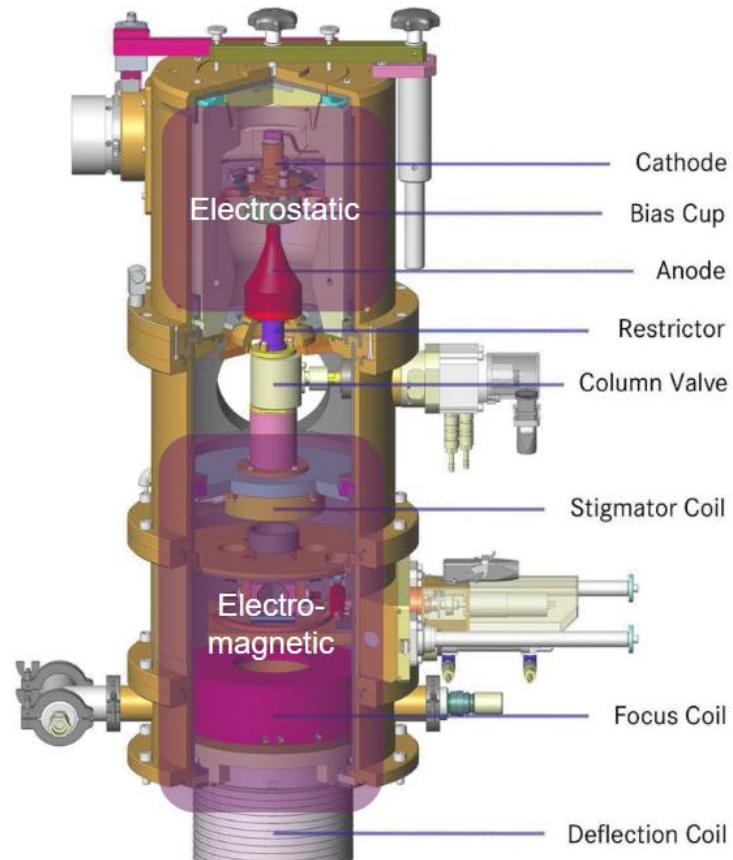
– Electron Gun

- The electron beam is formed inside of an electron gun, which has;
- Cathode – Hot tungsten filament emitting electrons Up to 2200-2500°C filament temperature
- Grid Cup – Element which is negatively biased with respect to the filament
- Anode – a neutral element through which the accelerated electron pass
- Magnetic coil focuses the beam (0.25-1mm)



EBW – Equipment

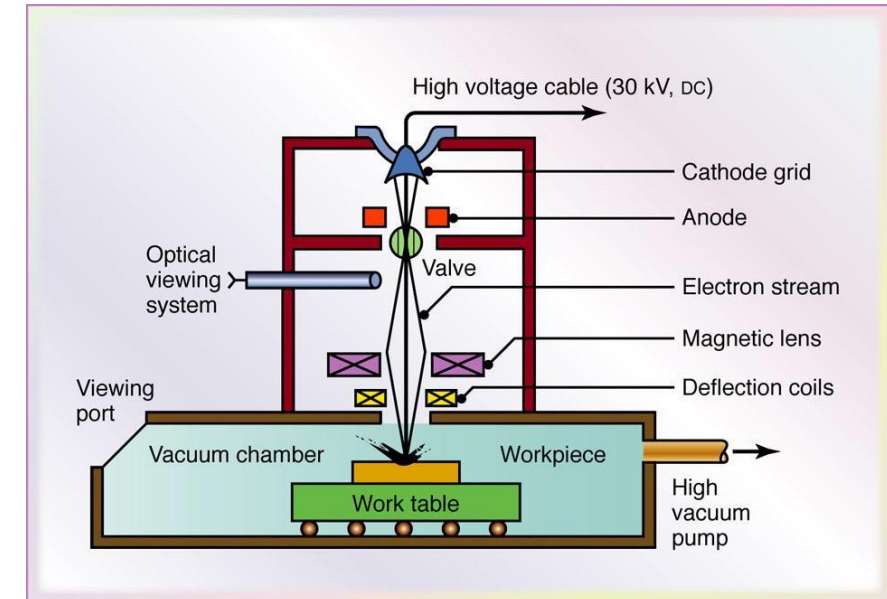
– Electron Gun



EBW – Equipment



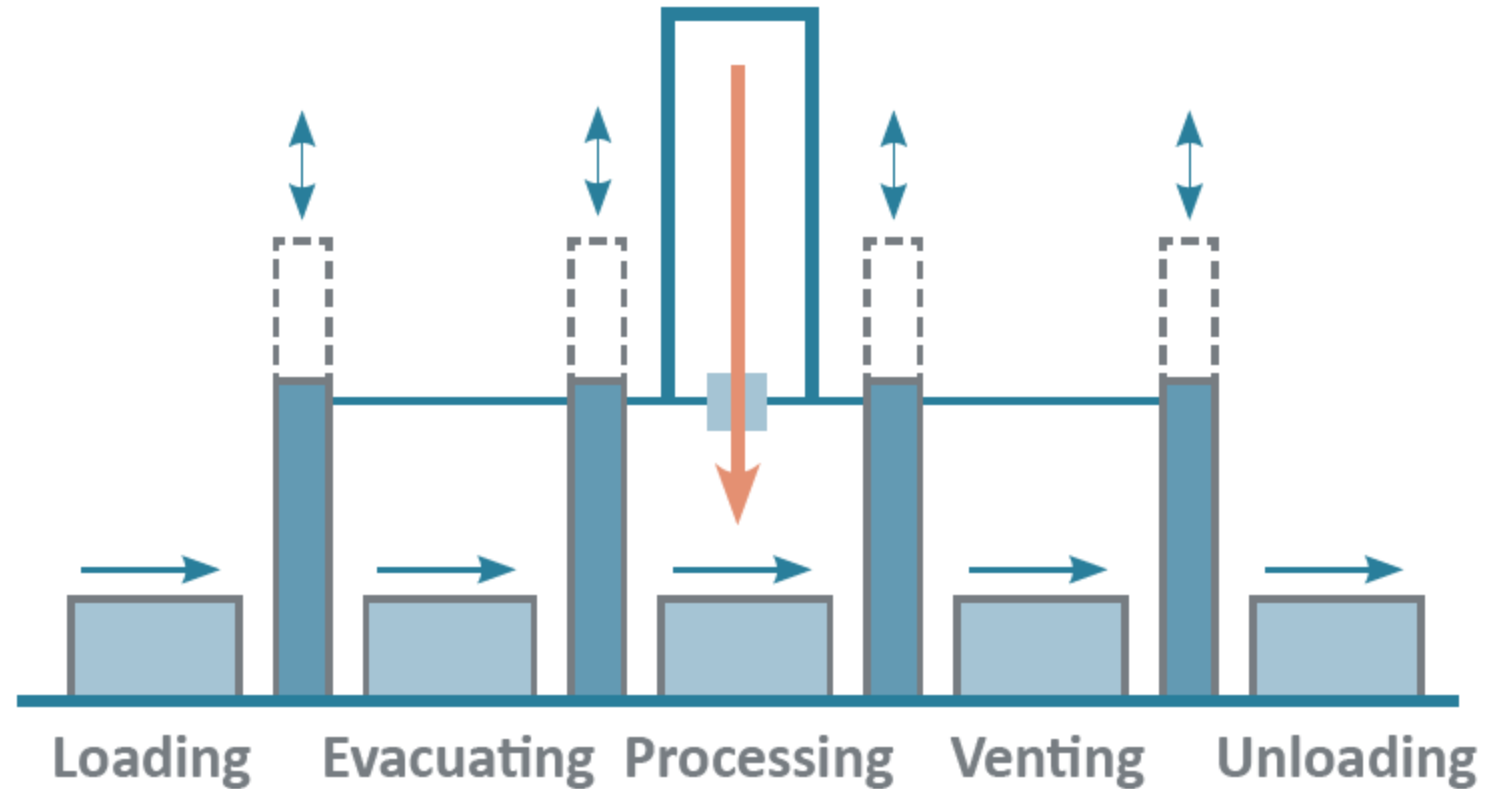
- Magnetic Lens
 - Used to focus the electron beam to any desired diameter to less than 0.00254 cm or ~ 0.03 mm at a precise location on the work piece
- Vacuum Chamber
 - It prevents collision of electrons with gas molecules which would scatter or diffuse the electron beam
 - It prevents the possibility of an arc discharge between the electrons
- Deflection coils
 - Focus the beam to move to predetermined locations
- Viewing system
 - Optical or video, magnified to monitor/inspect joint and weld, pre and post weld.



EBW – Equipment



- EBW vacuum to process finish



EBW – Equipment



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EBW – Equipment



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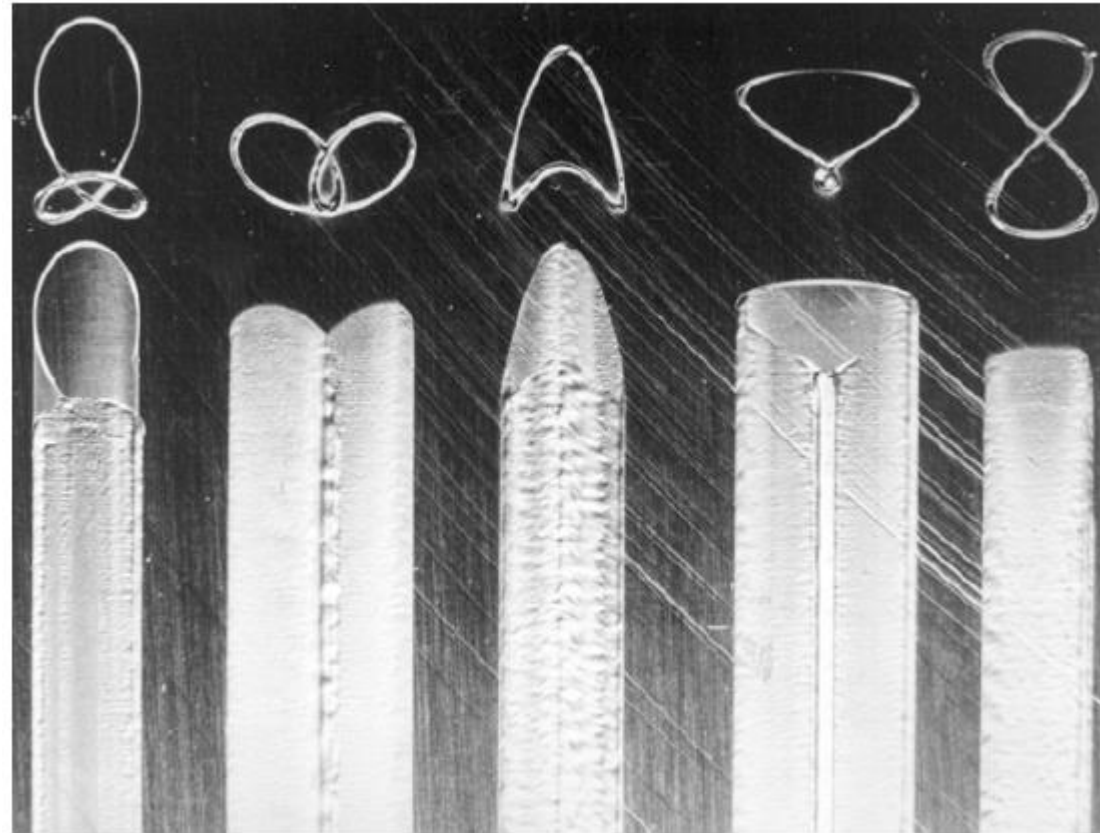


Electron beam rapid deflection

EBW – Equipment



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EBW – Equipment



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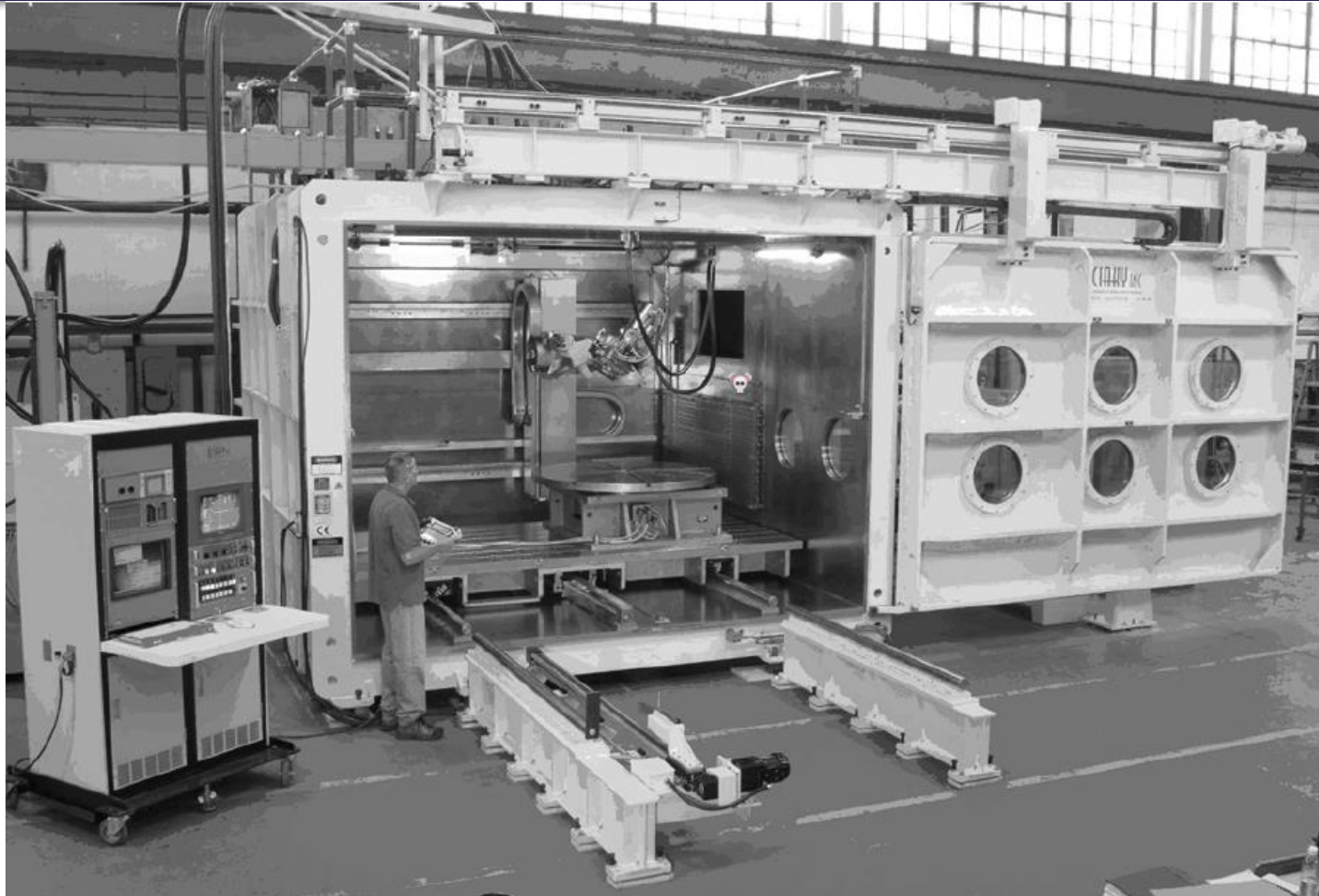
Credit: MULTHEM



EBW – Equipment



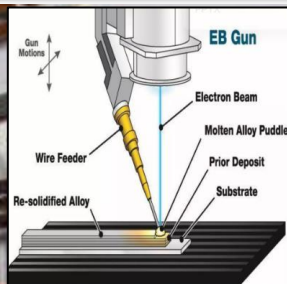
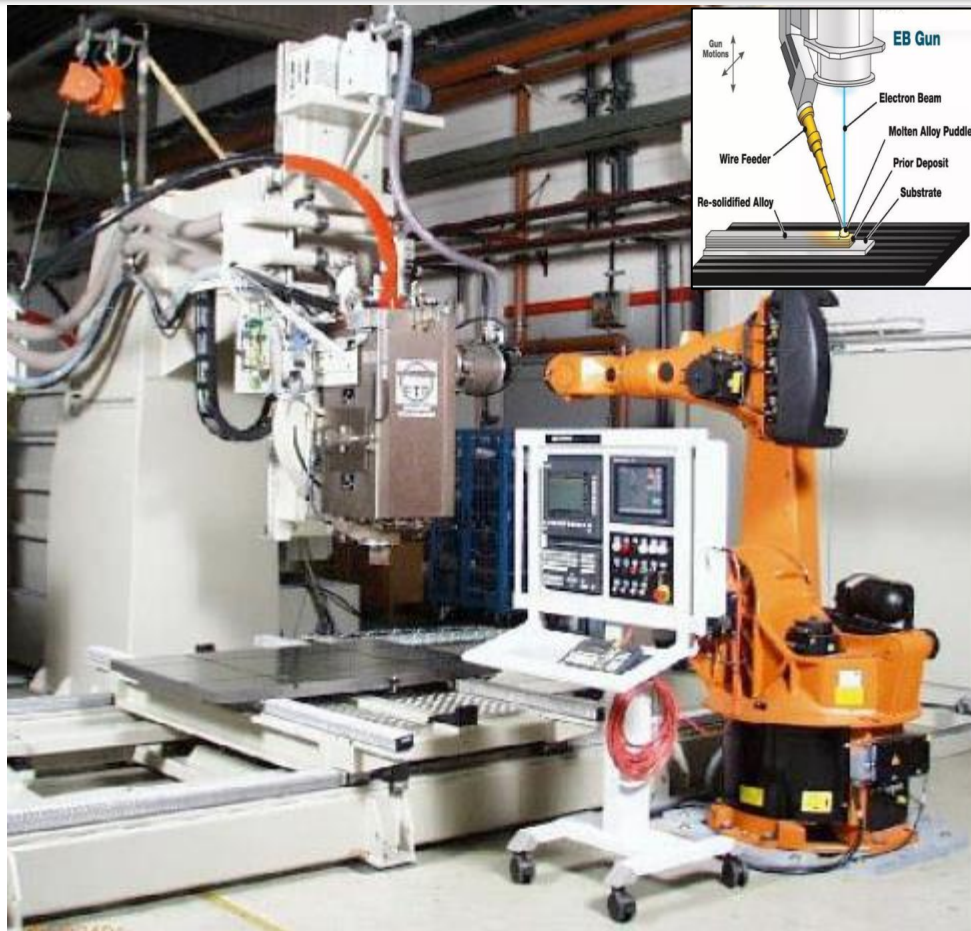
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EBW – Equipment

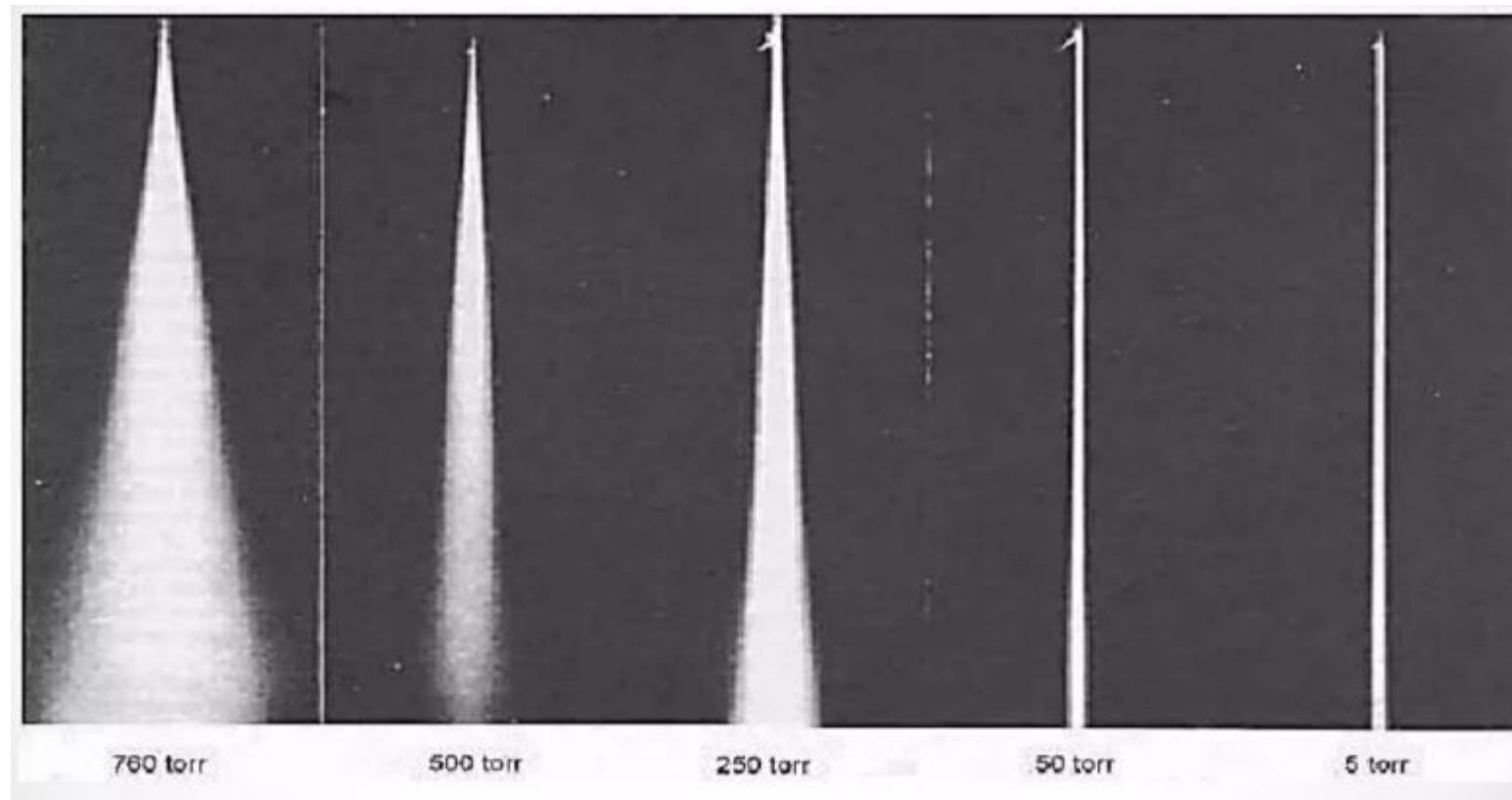


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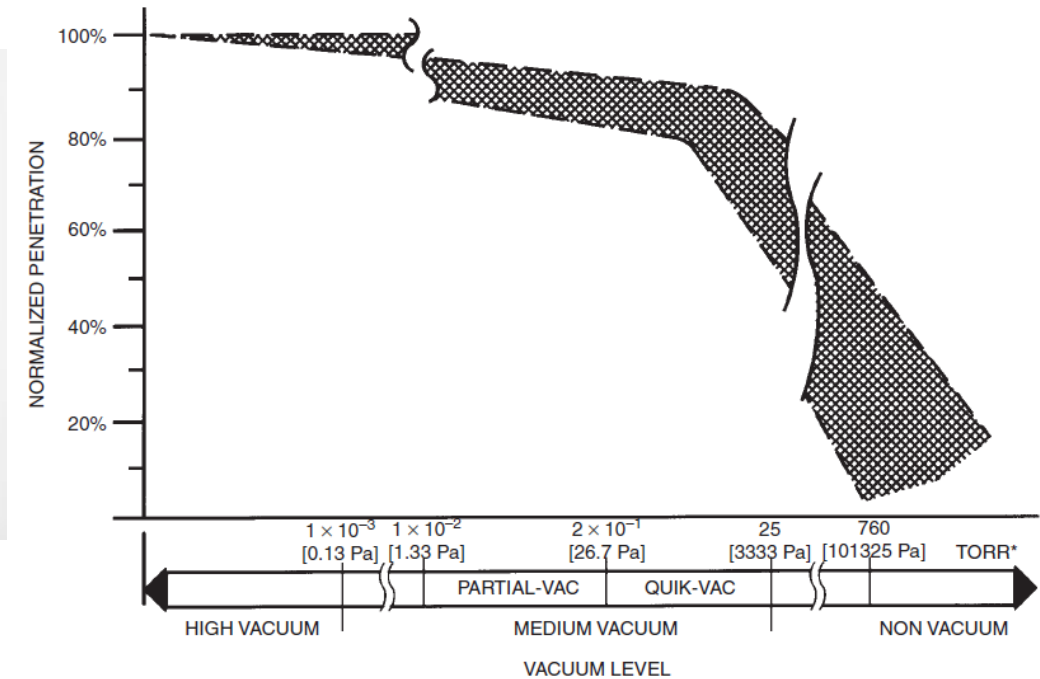
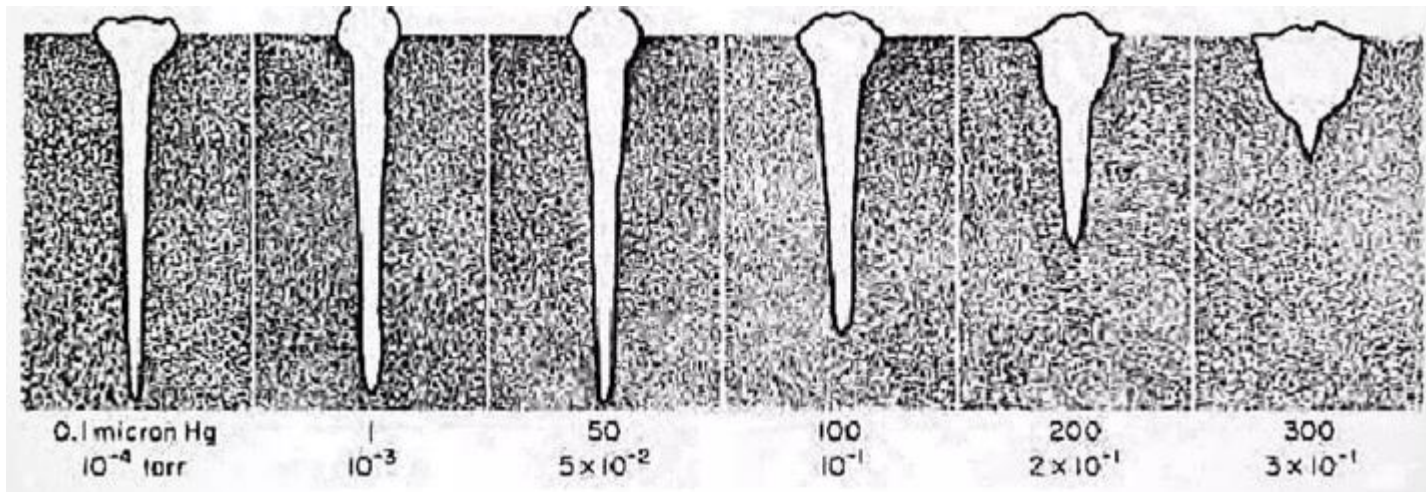
EBW – Equipment

- Beam vs Vacuum: Scatter due to collision with air molecules



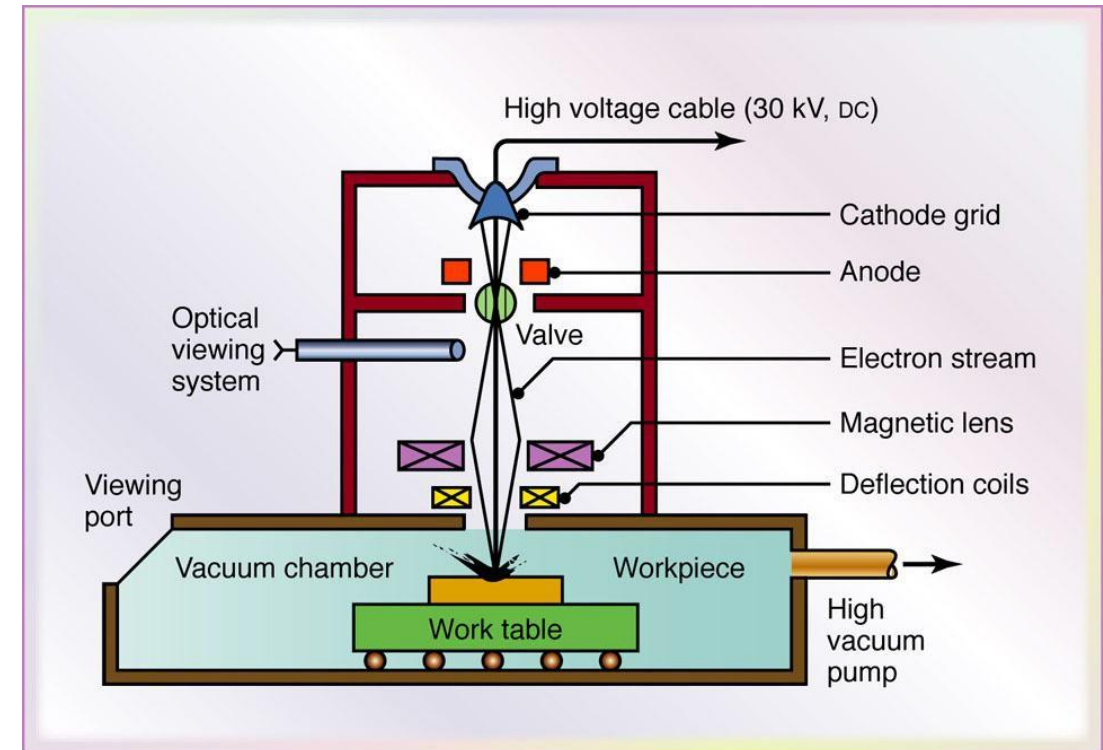
EBW – Equipment

– Penetration vs Vacuum:



EBW – Process parameters

- Processing material
- Beam voltage supply (V)
- Beam current (A)
- pulse duration (μs)
- Lens current
- Focusing length
- Beam deflection
- Safety characteristics



EBW – Process parameters

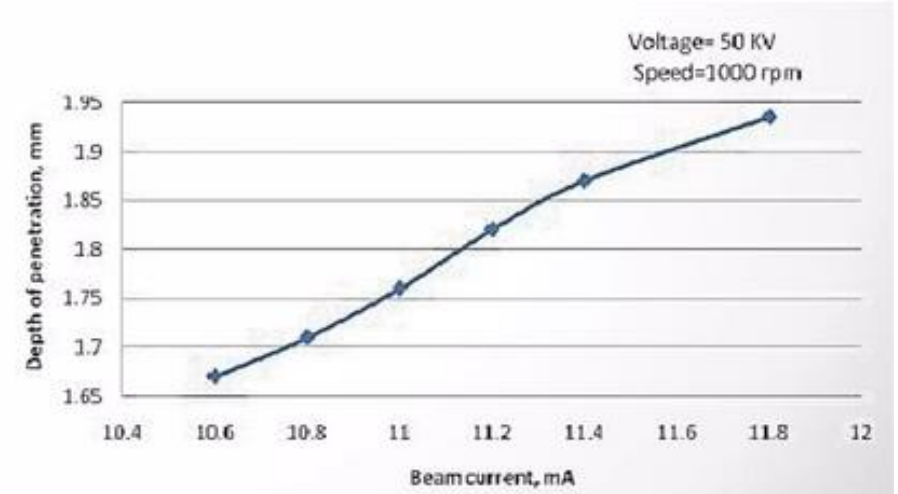


- Primary welding parameters
 - Beam voltage, Beam current, Travel speed, Focus coil current
- Secondary welding parameters
 - Vacuum level, Gun-to-work distance, Beam spot oscillation
- Energy efficiency
 - EBW has higher energy conversion efficiency than arc and laser welding. It can achieve the same penetration with lower energy input compared to arc and laser processes.
- Variables usually held constant
 - Material chemical composition, Cleaning method, Surface condition, Joint alignment, Fixturing, Heat sinking
- Process sensitivity and control
 - Even small changes in any parameter can significantly affect weld quality.
 - Strict process control is required for consistent performance.

EBW – Process parameters



- Beam Voltage
 - A value of potential difference, usually expressed in kilovolts (kV)
 - To accelerate and increase the energy (kinetic) of the electrons emitted through the electron gun in order to have high impact on workpiece. Increases density.
- Beam Current
 - Direct relation between penetration depth, measured in milliamperes (mA)
- Welding Speed
 - Inverse relation to penetration depth
- Beam Deflection
 - Generally, to modify the shape of the weld



EBW – Process parameters

– Beam focusing steps

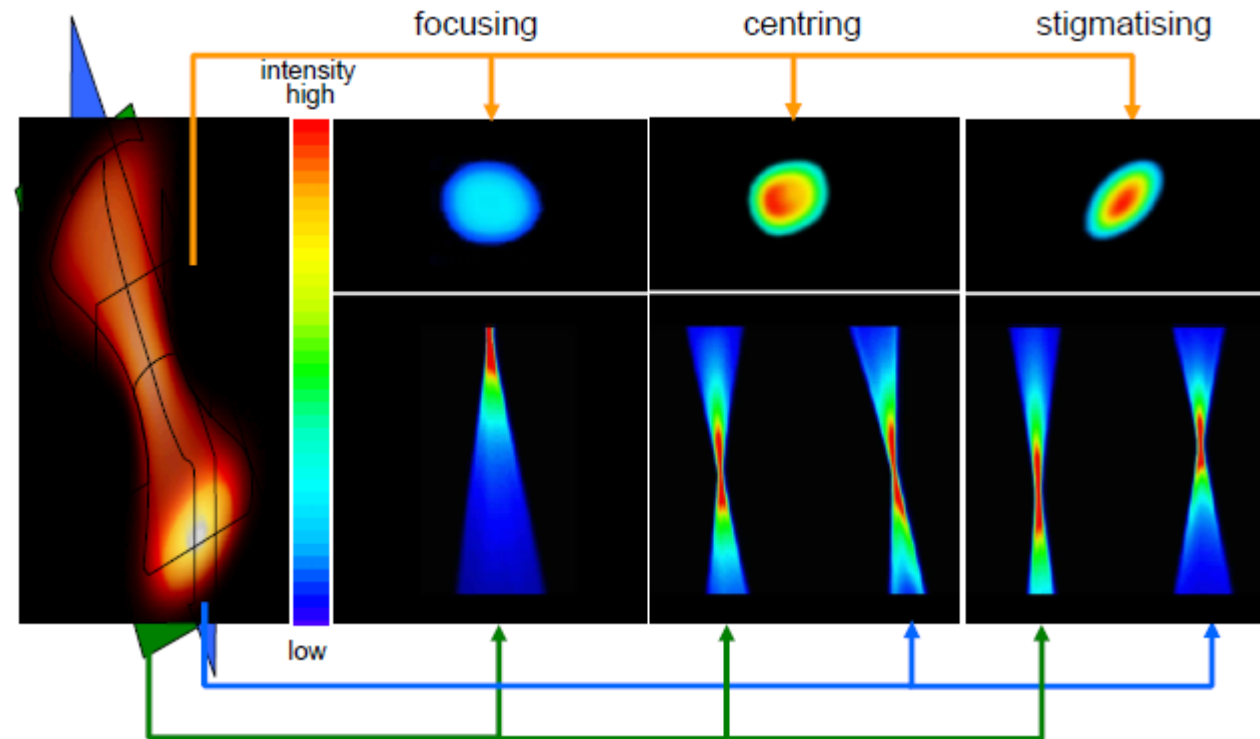
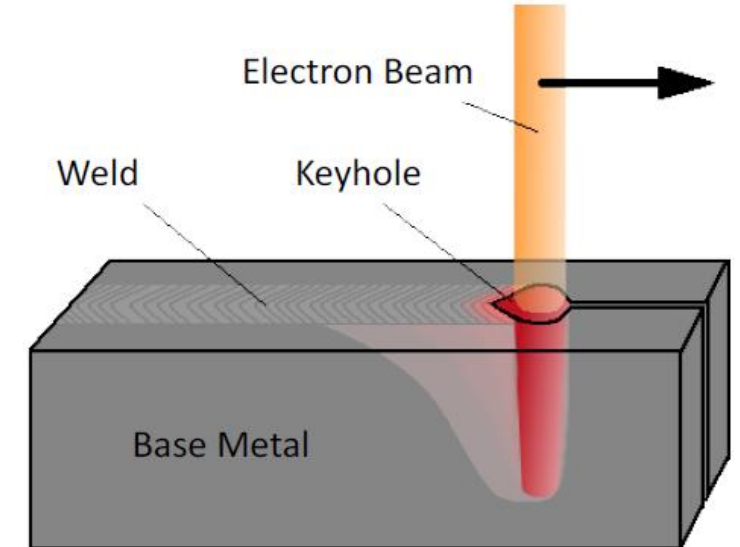


Illustration of beam focus, centering, and stigmatizing

EBW – Process parameters

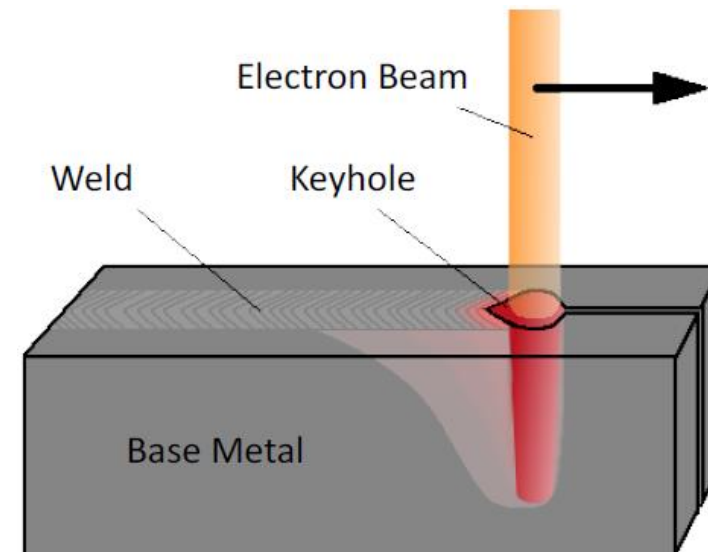
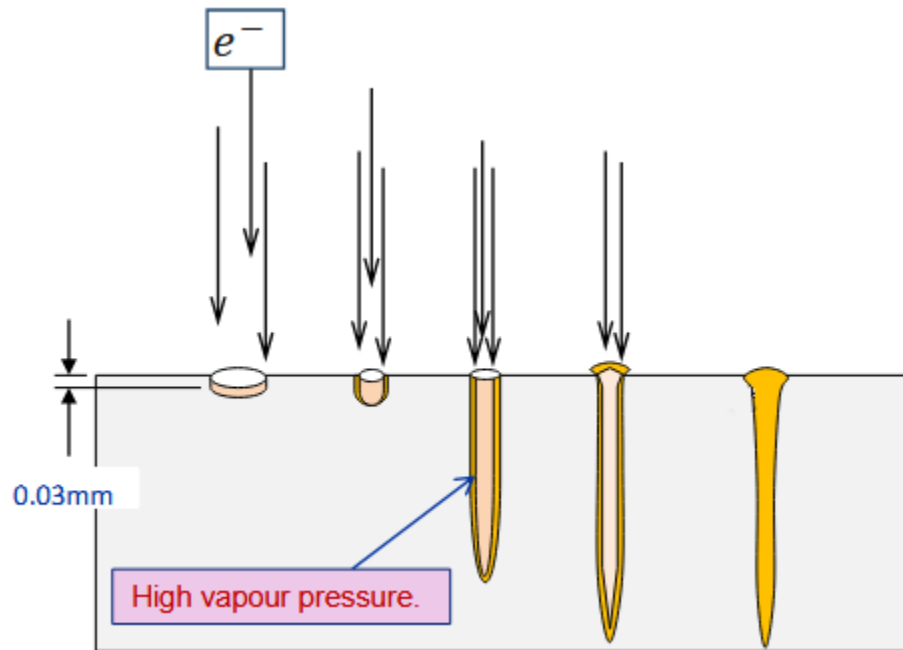
– Weld formation

- By focusing the EB, a tight spot can be placed on the weld joint, thus creating a condition called keyhole welding. In this mode, a vapor cavity is created in which metal is vaporized on the leading edge of the weld and deposited on the back surface
- The formation of the keyhole provides high power density EBW with the unique capability to produce deep, narrow welds and narrow heat-affected zones resulting in minimized distortion of weldments



EBW – Process parameters

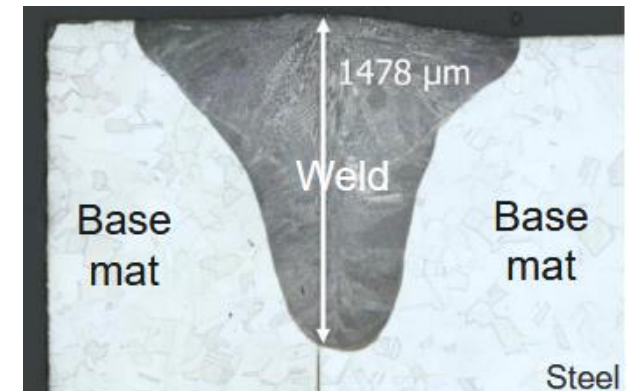
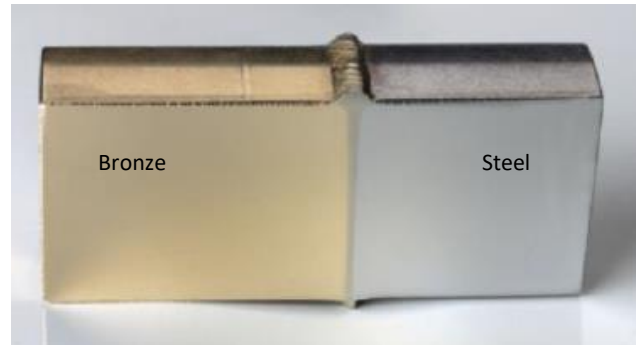
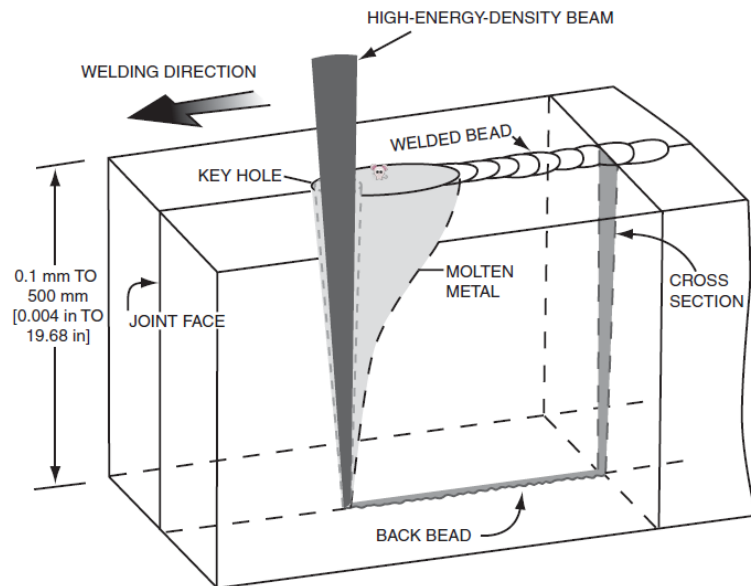
– Weld formation



EBW – Process parameters

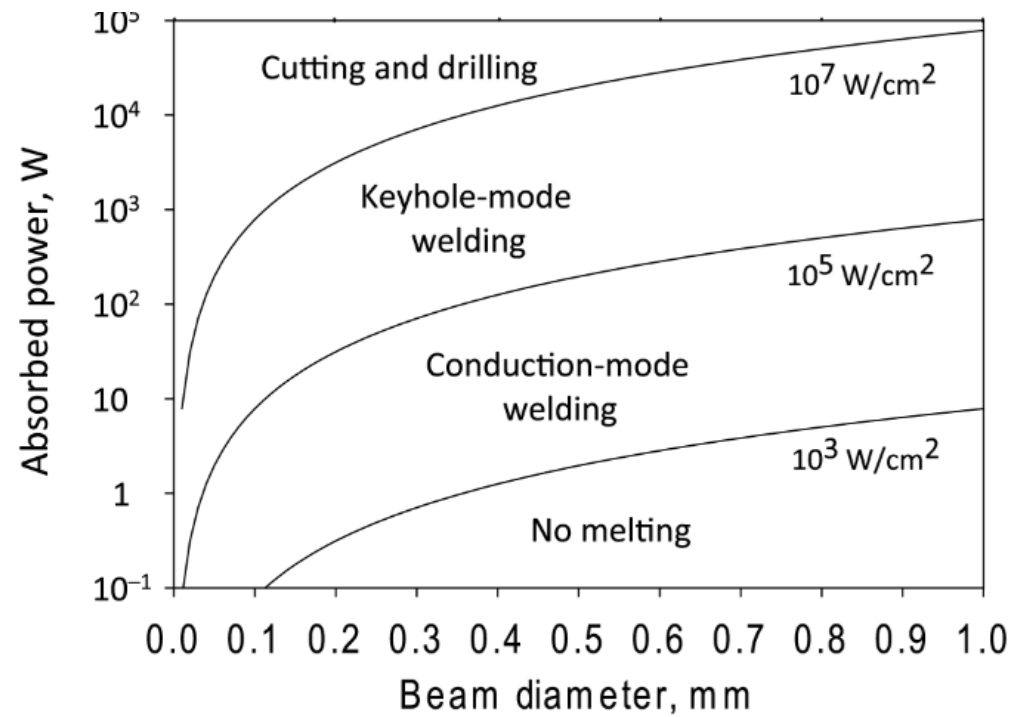
– Weld formation

- In contrast, lower energy density beam spots result in wider, shallower welds with aspect ratios typical of arc welds. This is called the conduction mode; this mode of welding has been utilized to provide very smooth bottom bead weld

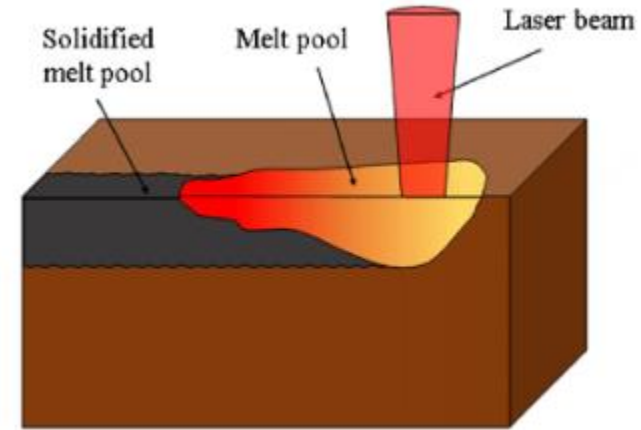


EBW – Process parameters

– Power vs Weld modes

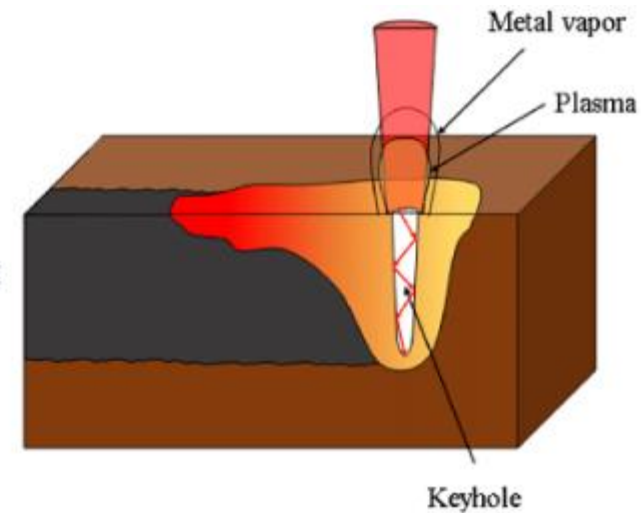


Aspect ratio:
 $\frac{\text{Width}}{\text{depth}} < 1$
Typ. 1/2



CONDUCTION MODE

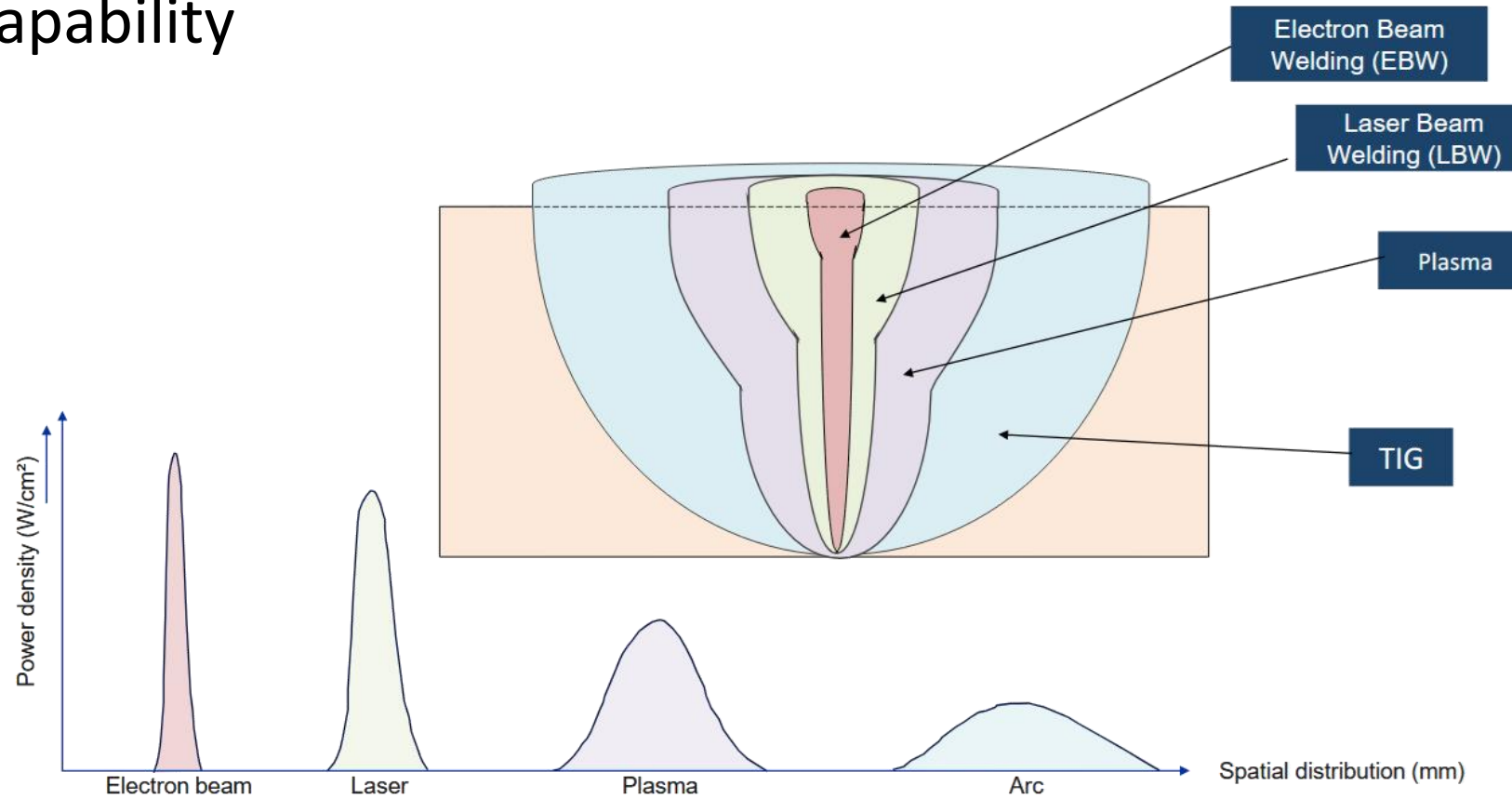
Aspect ratio:
 $\frac{\text{Width}}{\text{depth}} > 1$



KEYHOLE MODE

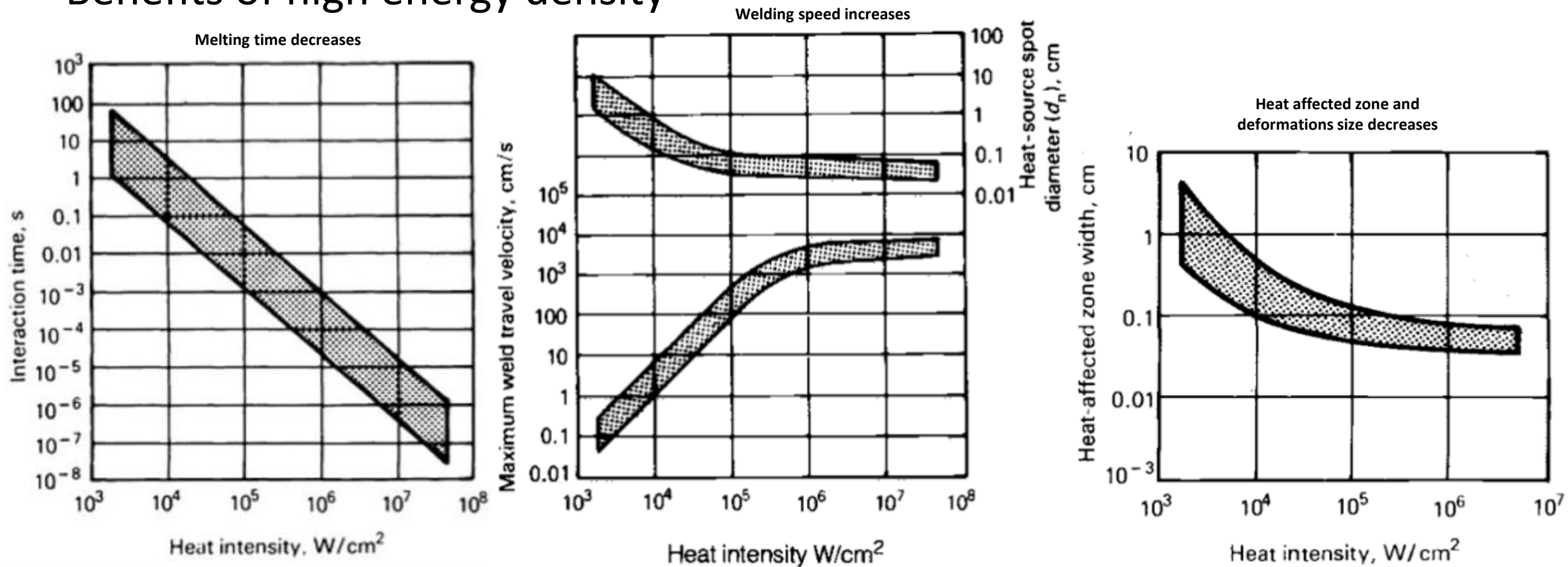
EBW – Process parameters

– Power capability



EBW – Process parameters

– Benefits of high energy density



EBW – Process parameters

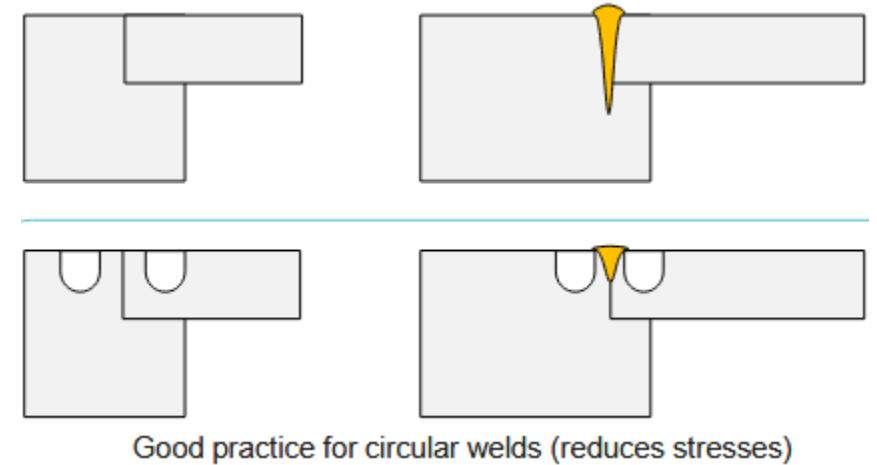
– Several Passes



EBW – Process parameters

– Important considerations – Partial Penetrations

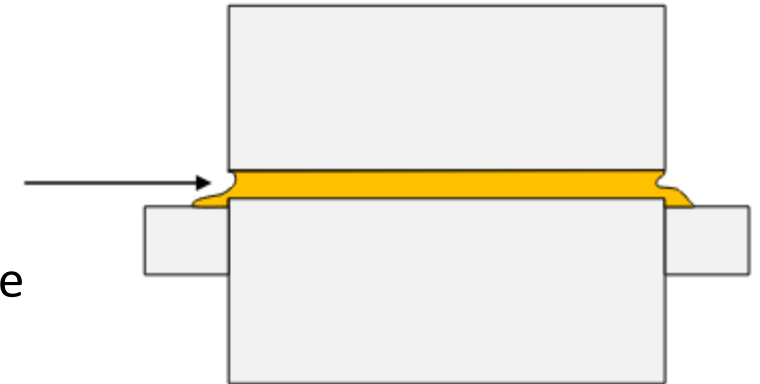
- Frequently used since the weld bead tends to have good geometries.
- Root defects called «spikes» are intrinsic to this type of welds when using sharp focus.
- Degassing of weld pool occurs only from one side, which can lead to a greater porosity rate.
- For thick plates (limit approximately around 60 mm) the horizontal position is recommended
- Where? welds are often used to assemble end pieces or covers to a main body that contains sensitive electronic and non-metallic parts.



EBW – Process parameters



- Important considerations – Full Penetrations
 - Degassing from both sides which limits porosity
 - No spikes
 - Weld positions
 - Vertical position, Penetrations $>30\text{mm}$ become difficult.
→ Geometrical imperfections: undercuts and shrinkage groove
 - Horizontal position is recommended for thick plates



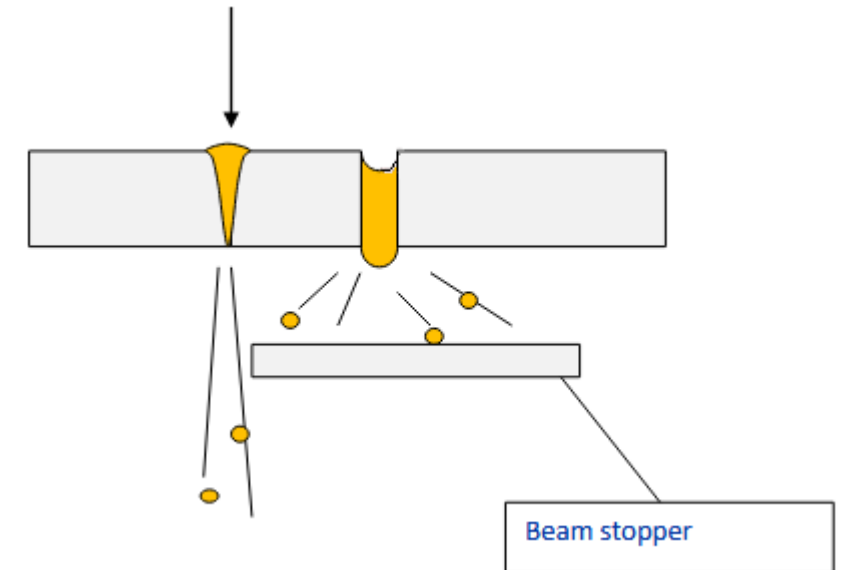
EBW – Process parameters



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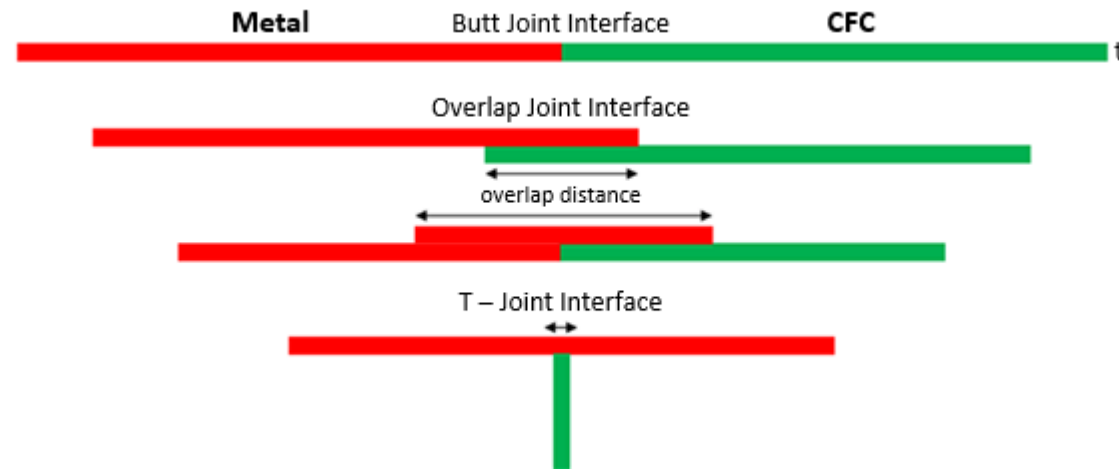
– Important considerations – Full Penetrations

- Beam stopper: in keyhole mode spattering is unavoidable in the root side.
- Severity of this phenomena increases with the thickness of the material.
- Beam stoppers are used to minimise this issue and protect the inner side of piece from beam
- Increase the strength of the joint
- Are easier to inspect than partial penetration welds
- Contract more symmetrically during solidification than partial penetration welds
- Tend to have fewer defects than partial penetration welds



EBW – Process parameters

- Joints types
 - Butt joints
 - Fillet Joints
 - Edge joints
 - Sheet joints



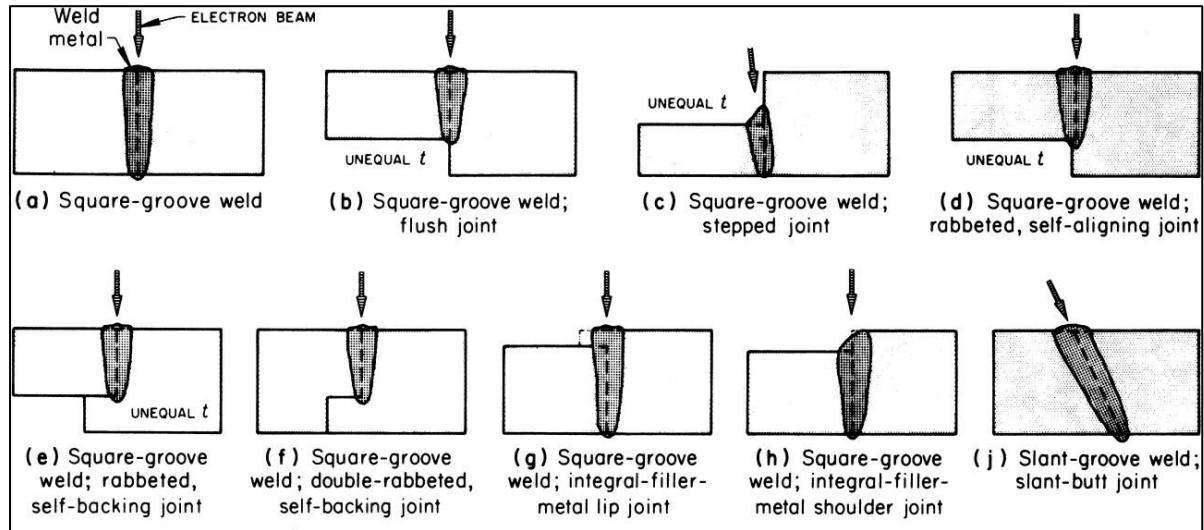
Credit: MULTHEM

EBW – Process parameters

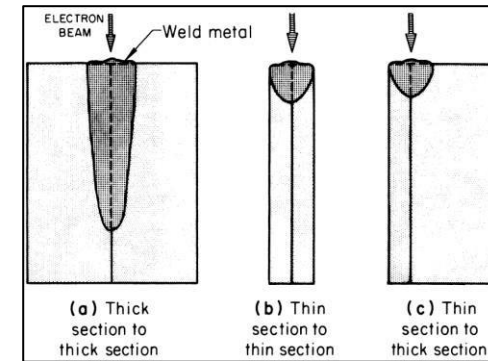


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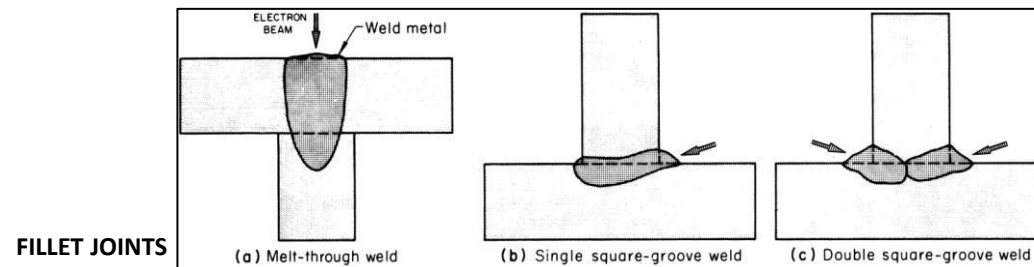
– Joints types



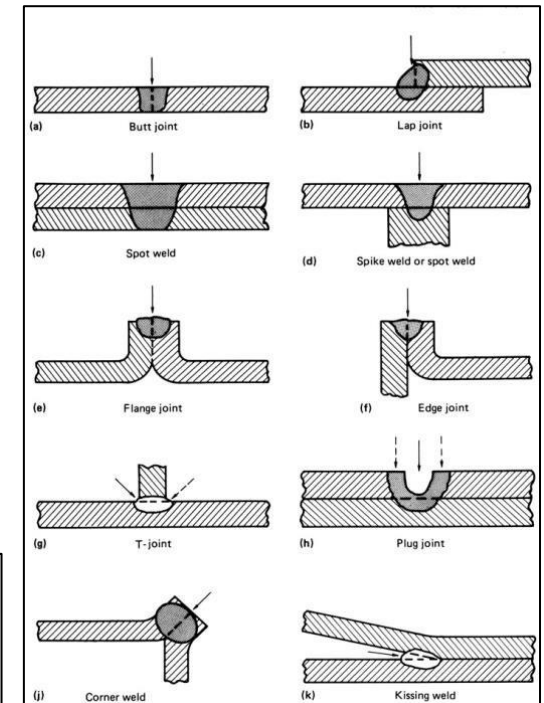
BUTT JOINTS



EDGE JOINTS



FILLET JOINTS



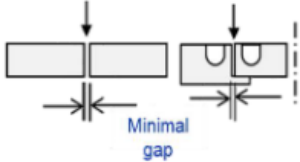
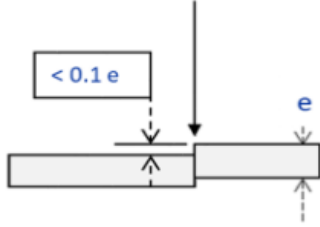
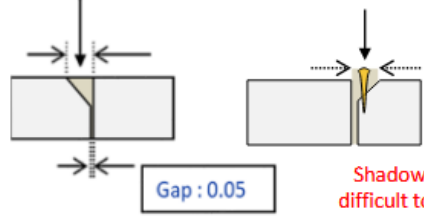
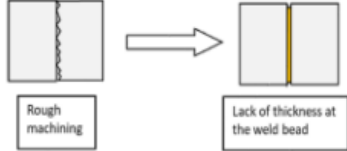
METAL SHEETS JOINTS

EBW – Process parameters



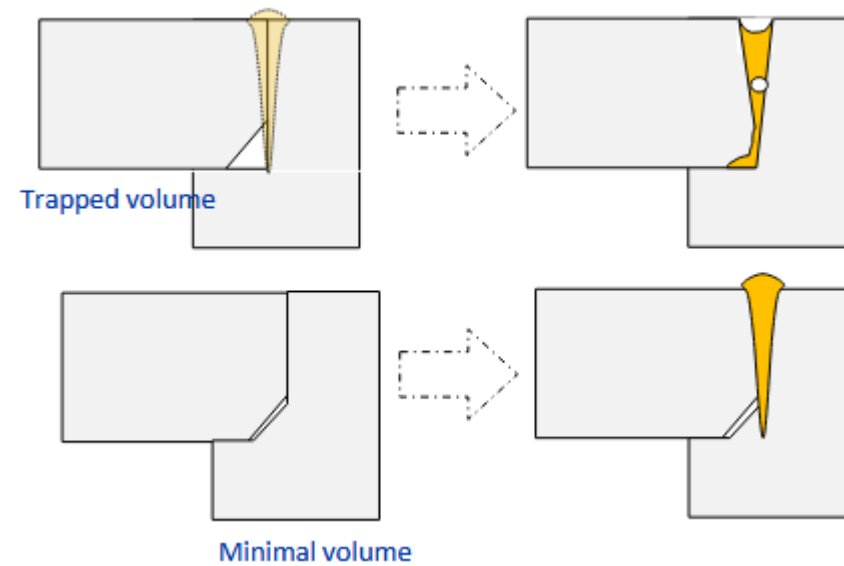
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– Interface issues

Gaps	Misalignment	Chamfers	Roughness
			
• <5% of the material thickness • Strategies for bridging larger gaps exists • Leads to concave welds!	• <10% of sheet thickness (depending on quality level ISO13919)	• Sharp angles pref. • High stresses in the head of the weld • Concave weld geometry • Shadow which makes it difficult to locate the joint	• Ra 1.6 / 3.2 μm is the required quality for the joint surface. • Consequences: • Shrinkage • Porosity rate • Residual stresses

EBW – Process parameters

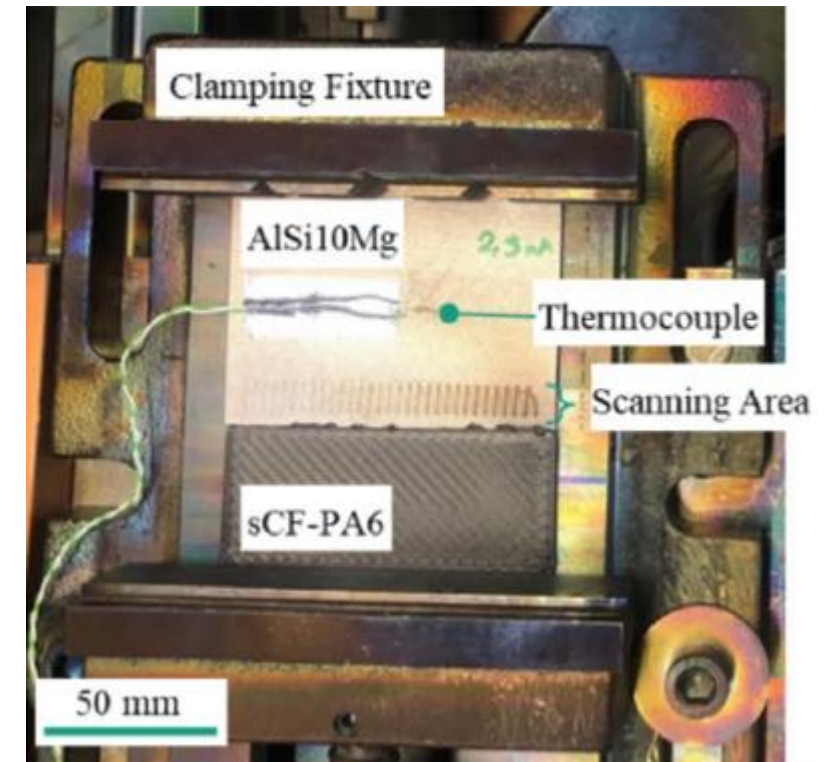
– Interface issues



EBW – Process parameters

– Clamping

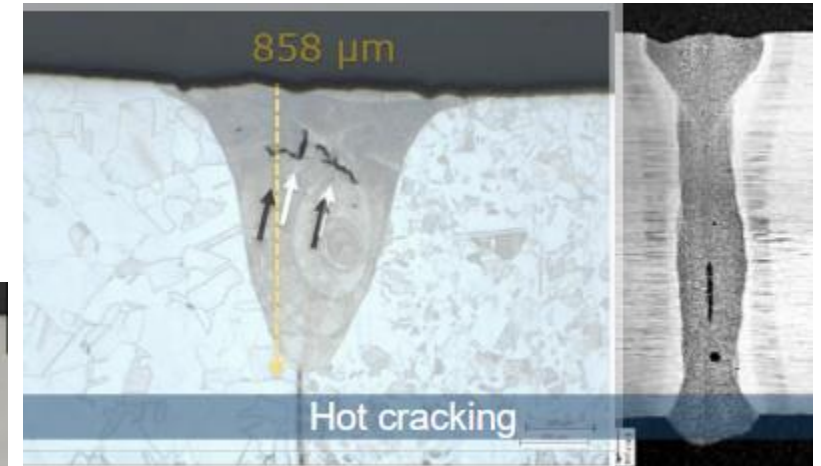
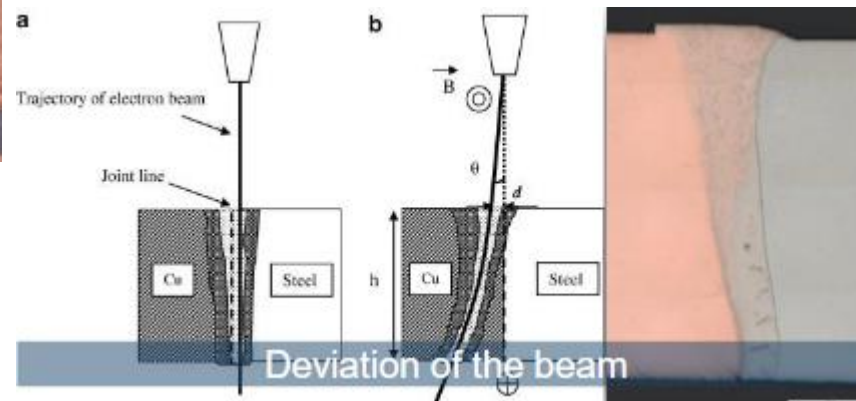
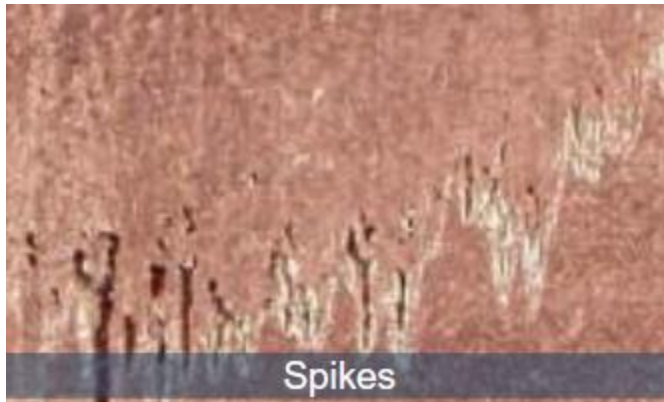
- All materials used for clamping and fixtures should be non- magnetic or de-magnetised prior to use in order to avoid any risk of the deflecting beam.



Credit: MULTHEM

EBW – Process

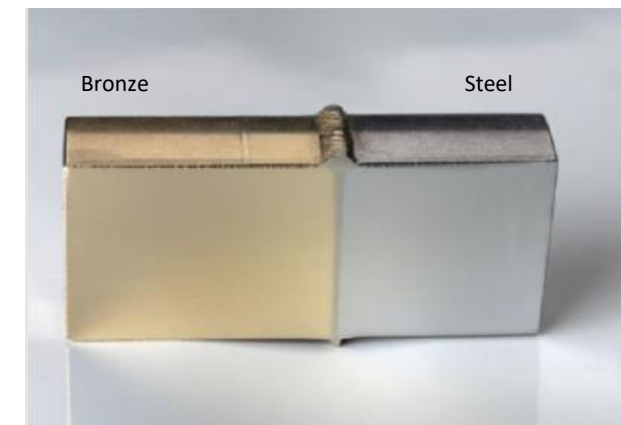
– Defects



EBW – Applications



- Most metals
- It is used to weld non-metallic materials and alloys.
- It is used to weld dissimilar metals
- Electron beam machining is being used extensively in the electronic, aerospace and automotive industries.
- Welding of cams
- Highly precise, very rare post-weld machining
- Suitable for large scale production



EBW – Applications



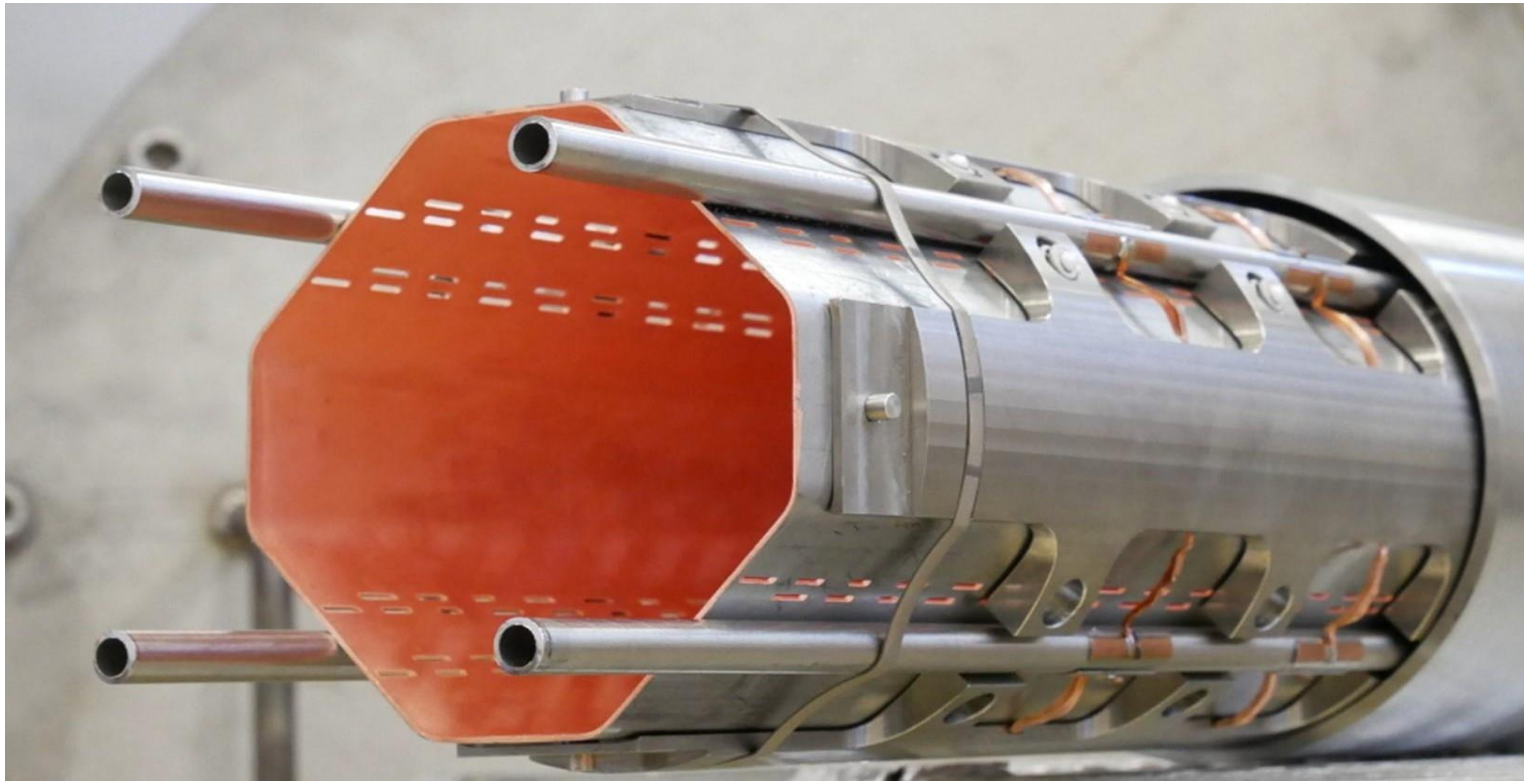
- Advantages for applications requiring
 - Single pass welding of thick joints
 - Precise control, speed (1-200"/min), strength (up to 95% for base material)
 - Hermetic seals of components retaining a vacuum
 - Low distortion
 - Low contamination in vacuum (no impurities)
 - Weld zone is narrow
 - Heat affected zone is narrow due to lower heat input per unit length
 - Dissimilar metal welds of some metals
 - Uses no filler metal
 - No shielding gas

– Materials

- Steel and alloys
 - Stainless steel is the most common material
 - Austenitic Stainless steels have a good general weldability. Care should be taken for hot cracking (due to impurities (S,P,B)).
 - Duplex steel (austenitic-ferritic): outgassing of N and Cr may reduce corrosion resistance
 - Pur Ni, Ni-Cu and Ni-Fe alloys can be advantageously welded by beam welding. In most cases without difficulty.

EBW – Applications

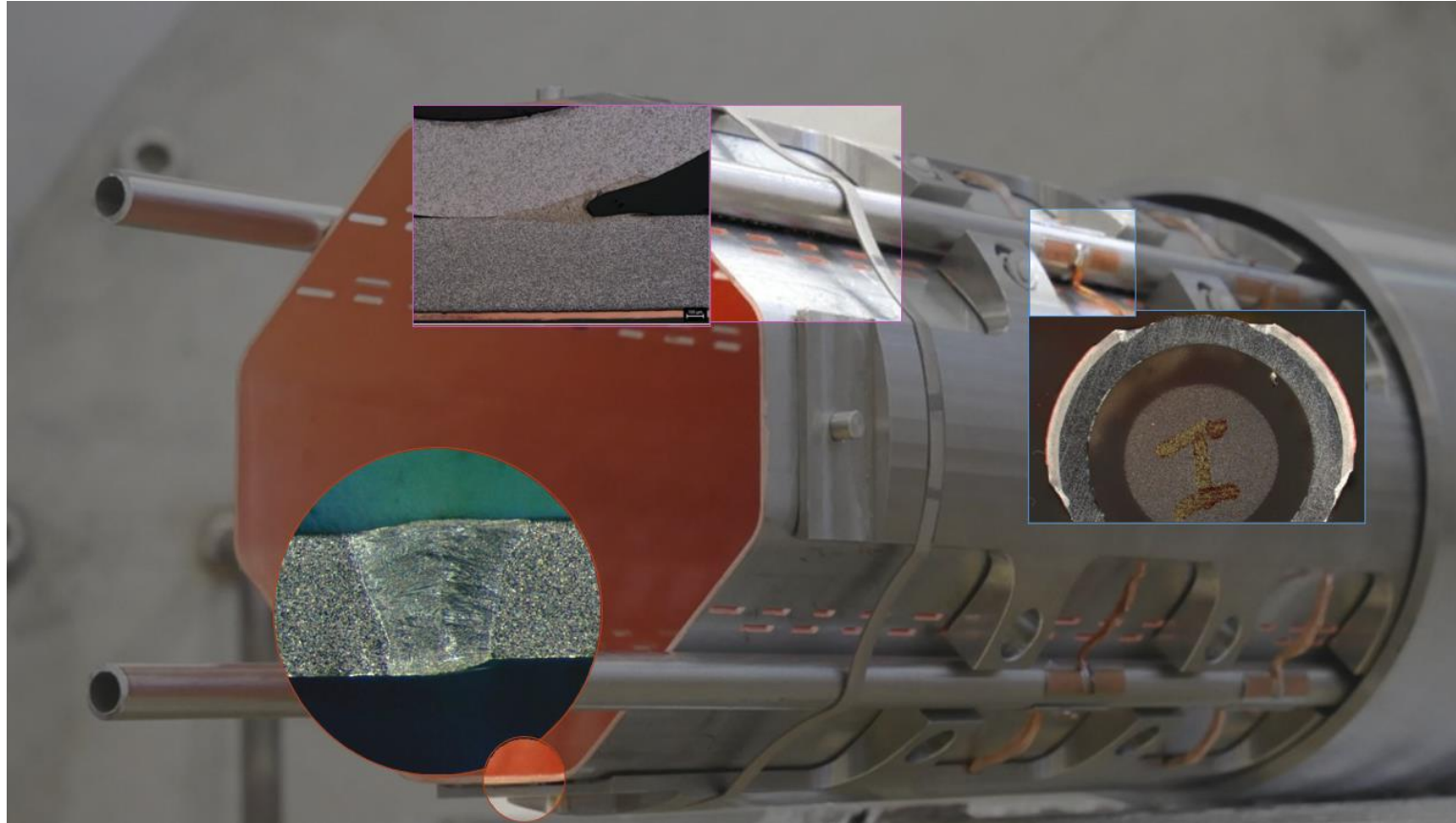
– Example



STEEL BEAM WELDING

EBW – Applications

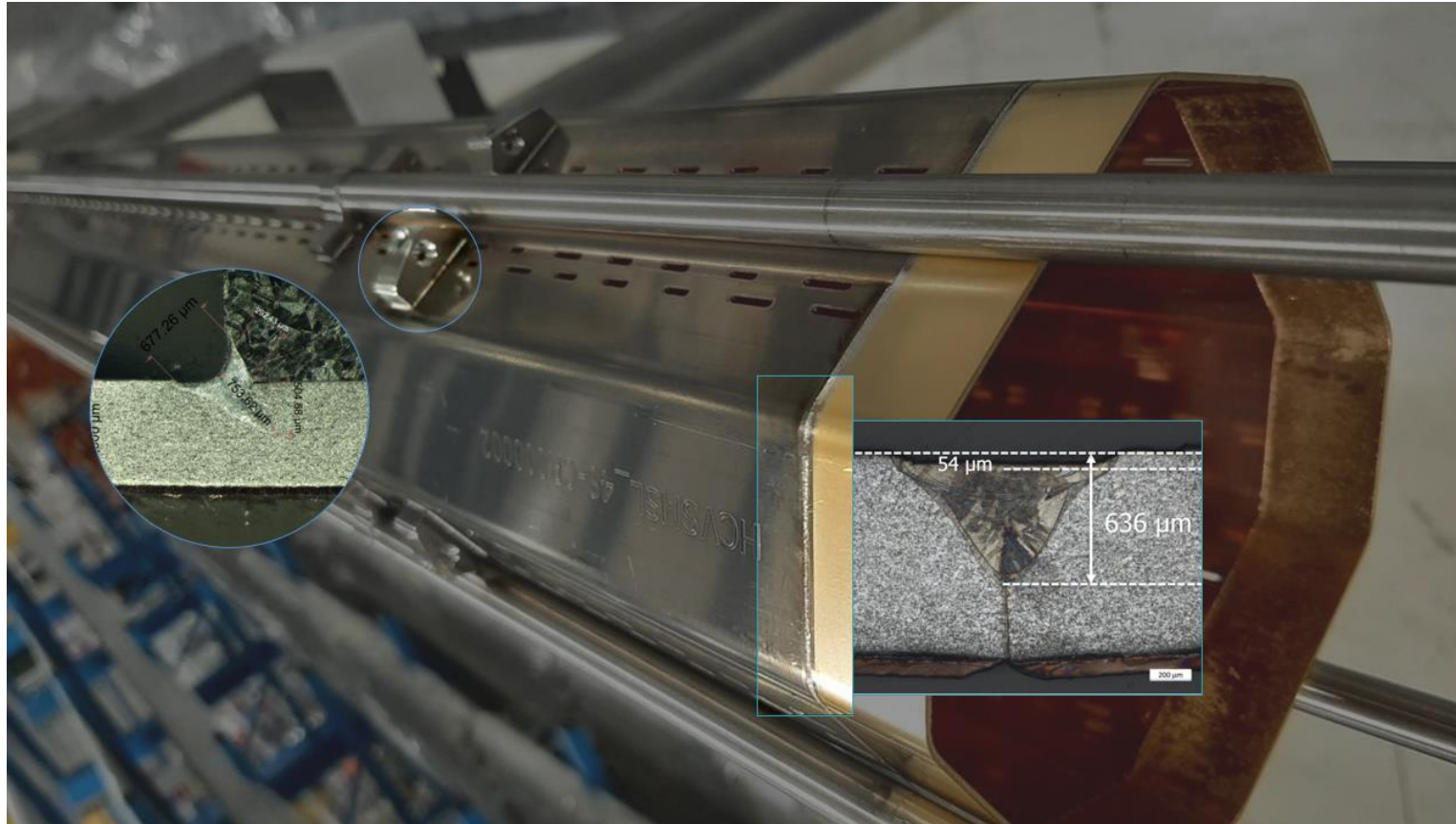
– Example



STEEL BEAM WELDING

EBW – Applications

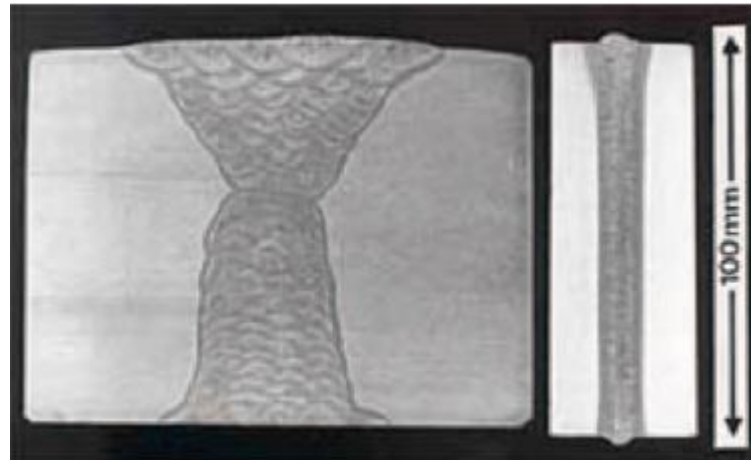
– Example



STEEL BEAM WELDING

EBW – Applications

– Example



MULTI PASS ARC WELD VS BEAM WELDING ON STEEL



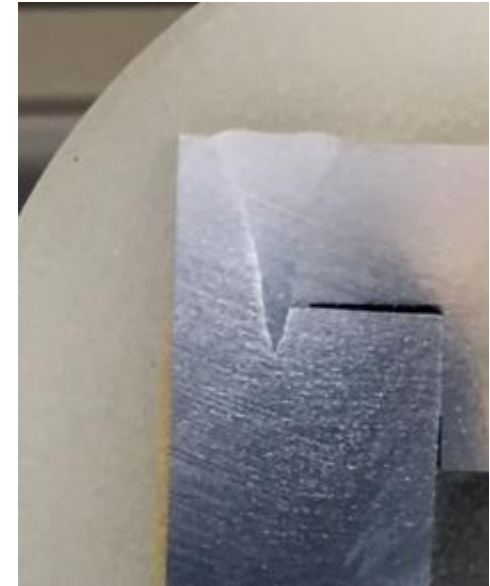
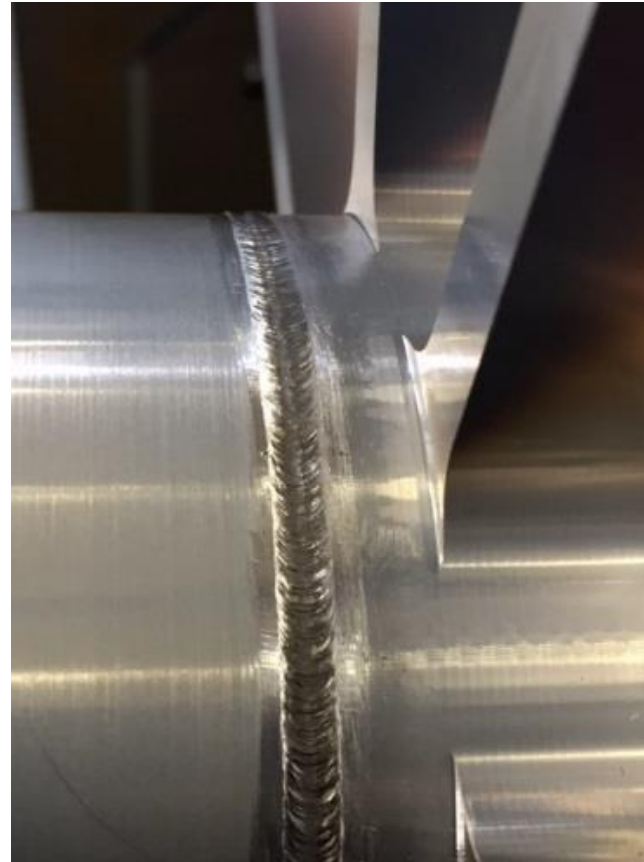
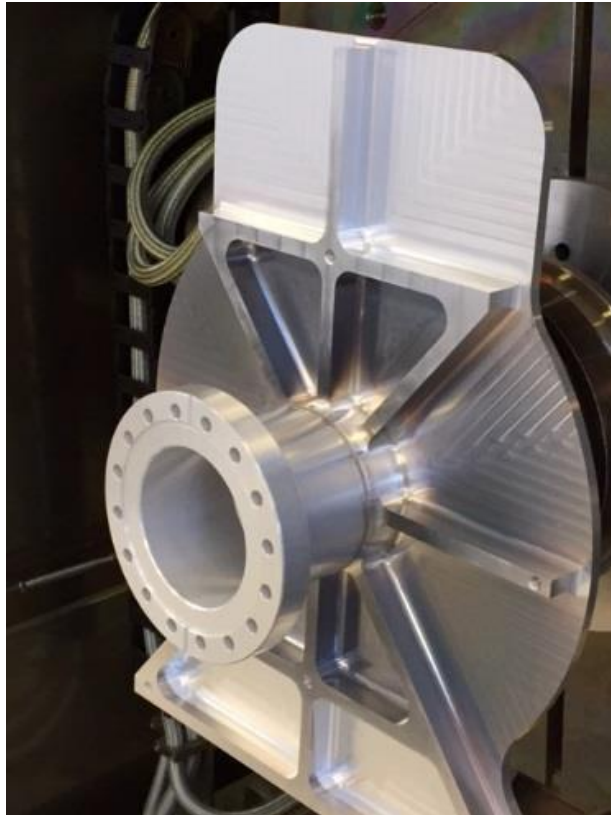
HIGH SPEED COLD SAW SEGEMENT EB WELDED WITH CARBON STEEL. SAVES 50% ON EXPENSIVE HIGH STEEL

– Materials

- Aluminum and alloys
 - Electrons destroy the alumina layer easily (compared to arc processes). Depths of penetration up to 200 mm with a good aspect ratio are obtained with EBW.
 - Series 5000 (Al-Mg): good weldability (risk of porosity in EBW due to Mg degassing under vacuum).
 - Series 2000 (Al-Cu), Series 4000 (Al-Si) and series 6000 (Al-Mg-Si): attention must be paid to the risk of hot cracking.
 - For castings, porosity rate is very high (high H₂ content). Welding under vacuum not recommended.

EBW – Applications

– Example



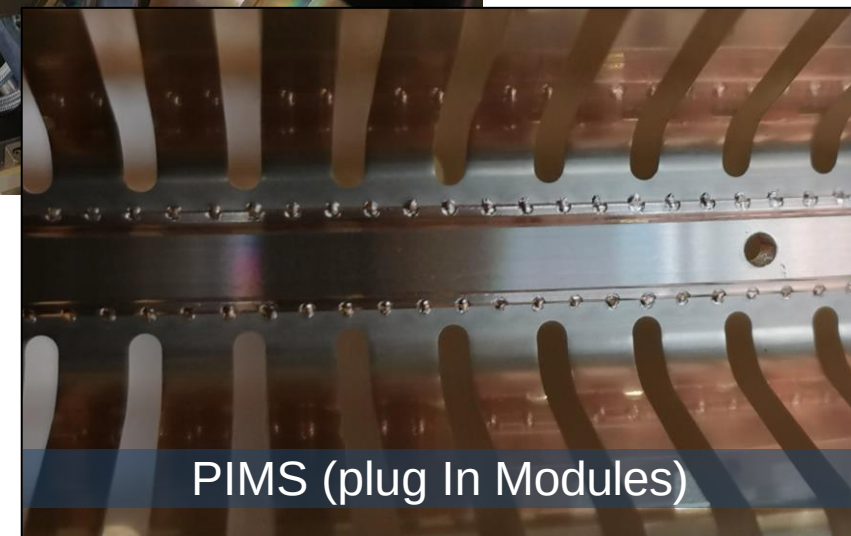
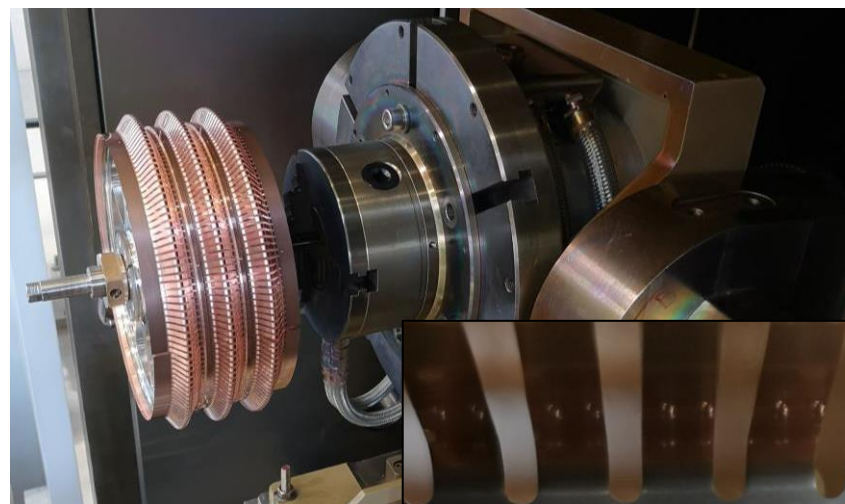
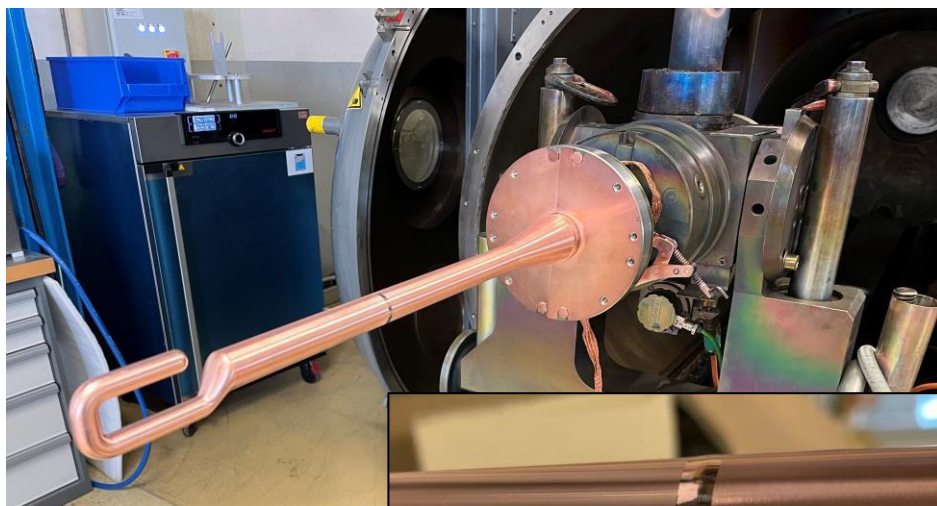
ALUMINUM WELDING

– Materials

- Copper and alloys
 - Most of copper alloys are weldable by EBW. Except for brass, Zn boiling point 910°C
 - For OF and OFE copper (Oxygen 0.001% max) weldability is good. The physical properties of copper limit the depth of penetration.
 - *Oxygen Free / Electronic (99.99%)
- High thermal conductivity and thermal expansion coefficient lead sometimes to important welding shrinkage depending on the heat input. Fitting needs to be tight to homogenize heat distribution.
- The depth of penetration is very sensible to this heat pumping effect.

EBW – Applications

– Example



PIMS (plug In Modules)

COPPER WELDING

– Materials

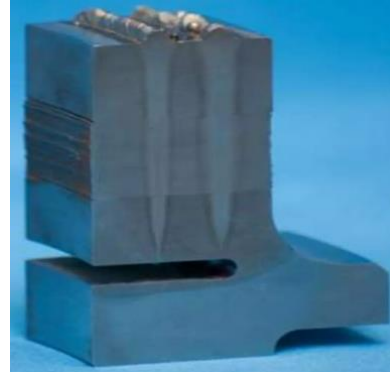
- Some other materials
 - Ti and its alloys have a good weldability by EBW. Welding under vacuum is preferred.
 - Nb has a very good weldability, with special attention to the quality of vacuum. Welded by EB ($P < 5 \times 10^{-5}$ mbar).
W, Mo and its alloys are also weldable, but with very low ductility of the joint.
- Dissimilar materials
 - E.g., Cu and Ni
 - Metal and polymers (e.g., steel, aluminum)
 - Leveraging high intensity and precise position of the beam

EBW – Applications

– Examples



Automotive shafts, clutches, gears



EB welded front bearing housing for Trent 700



Fan Blade Repair with
EBW



Compressor Rotor
Repair with EBW

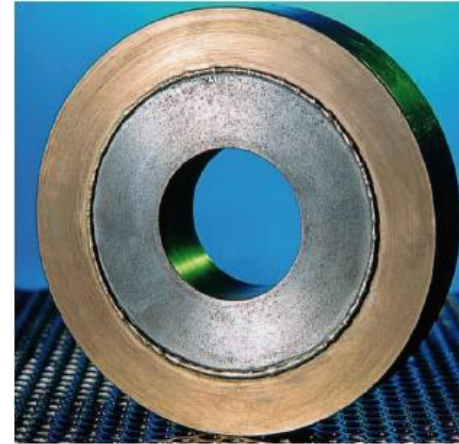


Universal EB welding chamber type K640 with Trent 700 ring of vanes

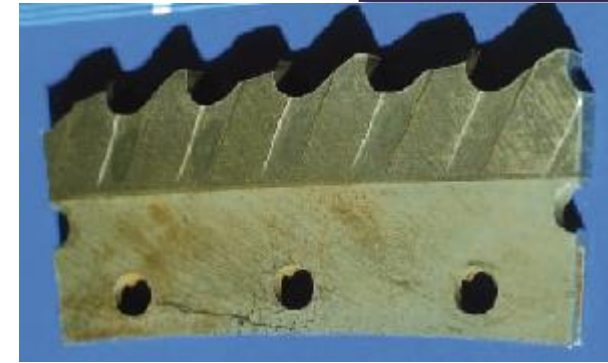
EBW – Applications

– Examples

GAS TURBINE HOUSING FOR EBW



ECONOMIC BRONZE-STEEL EB WELDED TO PRODUCE WORM GEARS



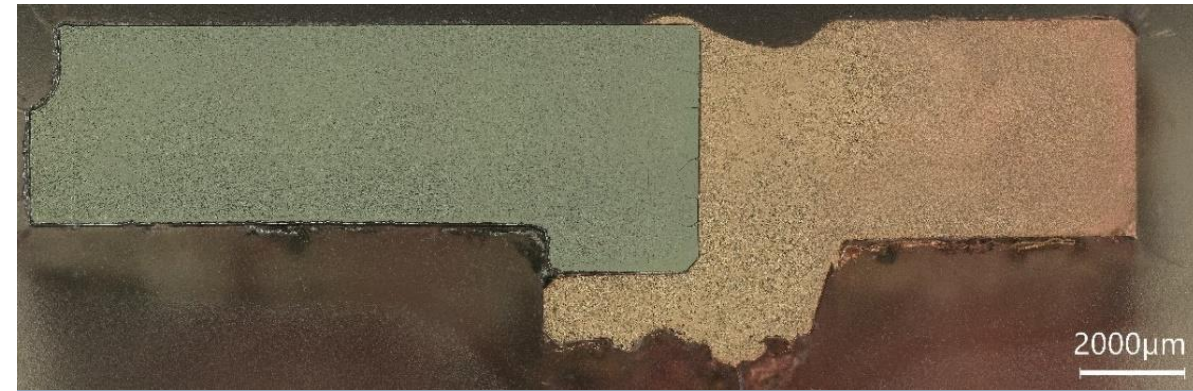
HIGH SPEED COLD SAW SEGEMENT EB WELDED WITH CARBON STEEL. SAVES 50% ON EXPENSIVE HIGH STEEL



Stainless steel and copper



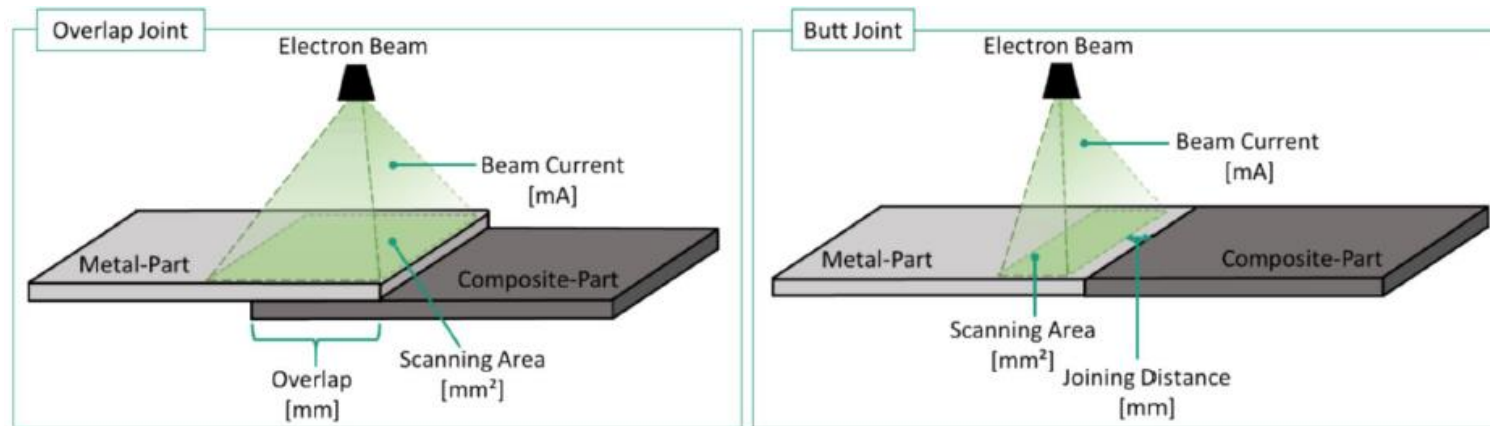
Nb and Cu tensile test showing advantageous rupture in Nb base material



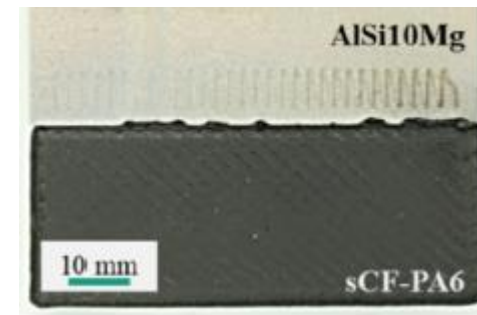
Nb and Cu

EBW – Applications

– Examples



OVERLAP JOINT



BUTT JOINT

Credit: MULTHEM

EBW – Applications

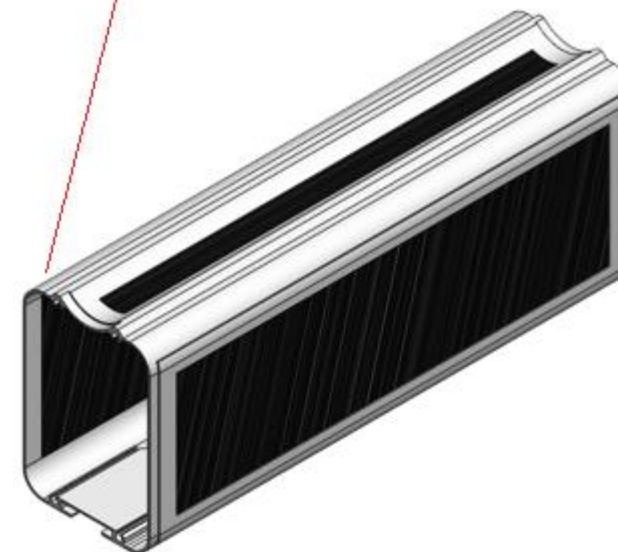
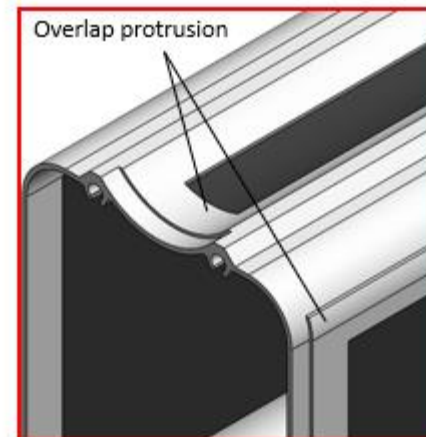
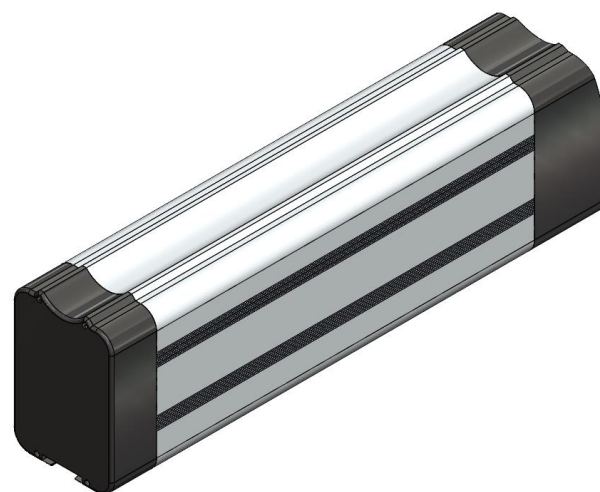


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– Examples



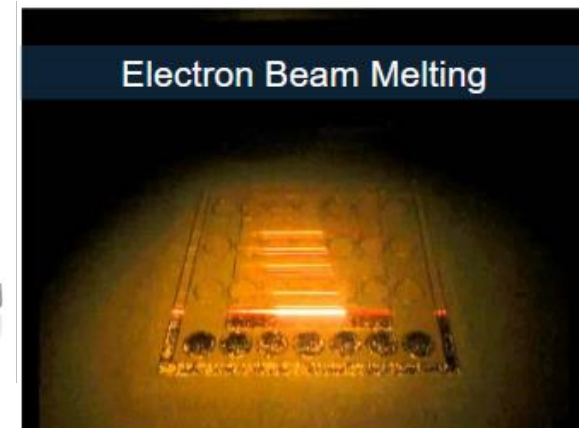
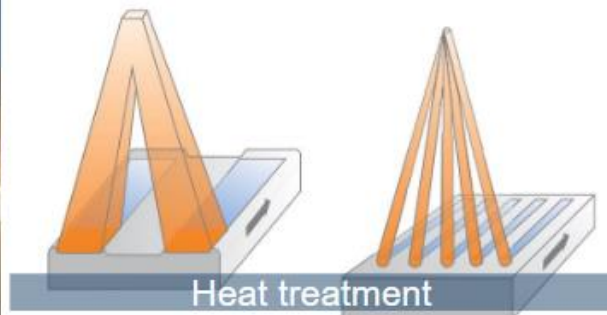
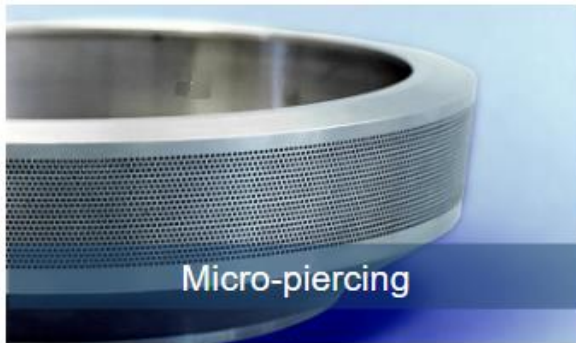
OVERLAP JOINT



Credit: MULTHEM

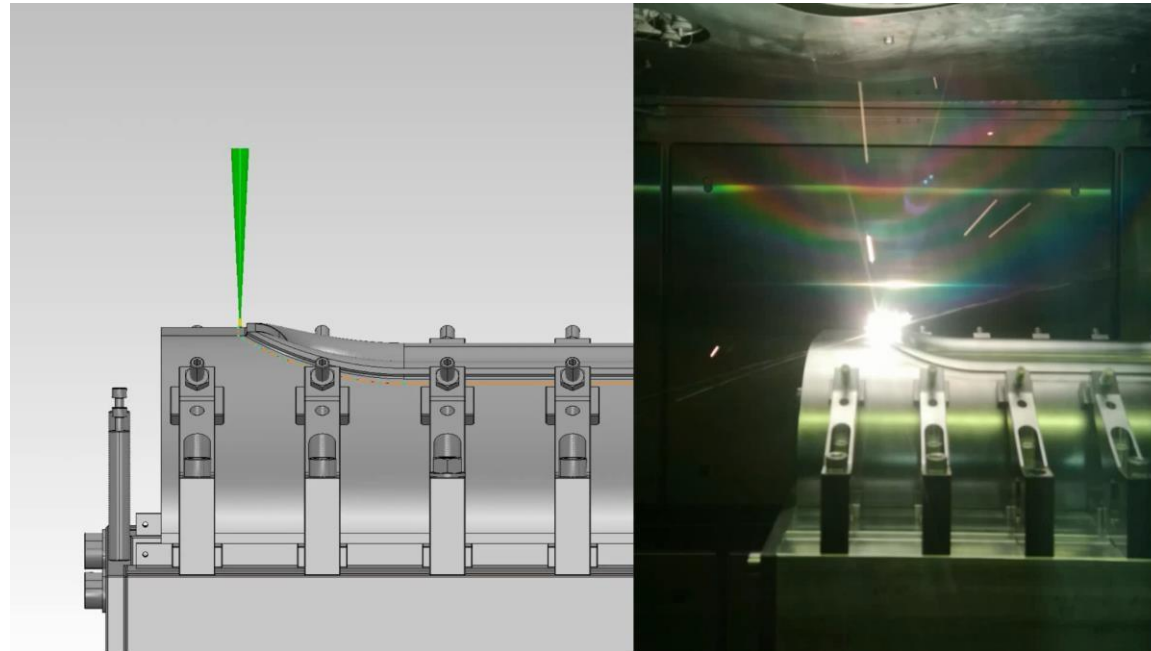
EBW – Applications

– Some Other Applications/Examples



EBW – Applications

– Some Other Examples



CAM ASSISTED MULTI-AXIS WELDING

EBW – Applications



– Summary

- Aerospace
- Automotive
- Defence
- Electronics Packaging
- Medical
- Oil And Gas
- Power
- Space (TWI)
- Engineering And Fabrication.

EBW – Limitations



- High equipment cost (~ 1M Euros)
- Work chamber size constraints
- Time delay when welding in vacuum
- High weld preparation costs
- X-rays produced during welding
- Rapid solidification rates can cause cracking in some materials

EBW – Limitations



– Comparison

	Weld Process		
	Electron Beam	Laser	Conventional / Manual
Typical Weld Cost	\$\$\$	\$	\$\$
Size restrictions	Limited to vac chamber size	Workstation dependant	None if done manually
Dissimilar Metals	Excellent	Good w stir welding	Challenging
Magnetic Materials	Challenging	Excellent	Process dependant
Depth (max penetration)	3 inches	1 inch	Shallow without multipass & notch
Width to Depth ratio (min w/d%)	Extraordinary (10%)	Excellent (25%)	Poor (various)
Heat Generated	Low/medium	Low (pulsed) / High (CW)	High
Purity (no electrode/filler)	100%	100%	Limited based on process
Repeatable	Highly with CNC	Highly with CNC	Limited / manual without CNC
Hard to reach area	Excellent	Good - gas coverage concern	Limited
Capital Investment (barrier to entry)	\$\$\$\$\$	\$\$\$	\$

EBW – Applicable standards



- AWS C7.1M/C7.1:2013 (Recommended Practices)
- ISO 15609-3 (EB)
- ISO/ASTM 52926-4:2023 (DED)
- ISO/ASTM 52926-5:2023 (DED)
- ISO 15614-11 (qualifications)
- ISO 14732 (welding operators)

Thank You



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