ELECTRON BEAM WELDING

The fundamentals of a fascinating technology

Volker Adam, Uwe Clauß, Dr. h. c. Dietrich v. Dobeneck, Dr. Thomas Krüssel, Dr. Thorsten Löwer

pro beam

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2011
1st edition: 4000 printed
Publisher: pro-beam AG & Co. KGaA, www.pro-beam.com

Cover picture:
„Electron beam welding with filler wire in a vacuum“
Photo: Sascha Mushack, pro-beam technologies GmbH, Burg.

In-house printing, in-house publication
Printed in Germany
www.pro-beam.com

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1. Preface

“Innovations come from passion, not from contentment.”
Ferdinand von Steinbeis (economic-policy specialist of Württemberg, 1807-1893)

Over 50 years after the discovery of the deep penetration effect in welding in 1958, electron beam welding is no longer a new technology, but a mature one, in use and proved with about 7500 plants having been build round the world about half of them still in operation. Nevertheless, in the past 10 years many new possibilities have been opened up at pro-beam, the beginnings of which were already there but which could only really be developed with the benefit of modern control technology. These are innovations that have arisen in the daily practical experience of welding. Also, the constant demand for quality and its documentation has brought some innovations that make use of the special capabilities of the electron beam.

One would think that a single-pass process of welding that deals with joining very small components with welding depths around 0.1 mm up to very large components with welding depths up to 200 mm in steel would be widely familiar. However, this is not the case. There are few universities that teach their engineering students about electron beam welding. In consequence, there is also a lack of knowledge about this process in industry. This is partly because of the complexity of the technology. The equipment involves classical precision mechanical engineering, combined with vacuum technology, high-voltage technology, magnetic flux constants, very fast control technology and, not least, with electron optics that today is taught at only one German university.

The achievable welding speeds can often not be increased, because of the material involved. Therefore, the latest ideas aim at achieving shorter cycle times by systematically eliminating the auxilliary process times, especially for evacuation. This is done by introducing load locks for shuttle, transfer and cycle machines. The shortest time for One-Piece Flow is at present 5 seconds. Evacuating a large chamber volume of 600 m^3 takes just 30 minutes. If it takes a further 80 minutes to complete a weld of 12 m length and 100 mm depth, electron beam welding is several times as fast as TIG or submerged arc welding done in several layers.

Optimising all of that is the job of the equipment manufacturer. But the operator of such machines would also like to be informed about how they work and to understand them. His area of work, electron beam welding itself, has a number of special characteristics that partly relate to the speed of the process: because of the rapid self-quenching the grain growth, for example, is inhibited or supersaturated solid solutions occur. A particular advantage is the possibility of making narrow (or also wide) parallel welds which enable the manufacturer to join ready made parts with very low warpage. This enables other upstream and/or downstream operations to be eliminated, such as straightening. The ability to use electron beam welding to join different materials gives opportunities for rationalization by combining low-cost and high-cost materials according to the function required.

The aim of this little book is to inform you, the interested reader, of the basics of electron beam welding, and to encourage you to use the knowledge you gain to look around in your area of work for opportunities to benefit from electron beam welding. The opportunity to try this in one of our 32 plants in the pro-beam group area of contract welding should facilitate your decision on using electron beam welding without involving high up-front investment costs. And, if you have too few items for running your own electron beam machine, we shall be happy to take on your jobs for small and large-series production, as we do for over 1.000 other satisfied customers of pro-beam.

Dr. h. c. Dietrich v. Dobeneck

2. The basics of the process

2.1 Electrons

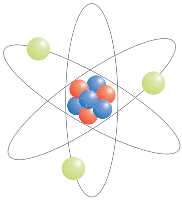


Figure 1: Atoms consist of a nucleus of protons and neutrons, surrounded by a shell of electrons.

The thermal tool „electron beam" is a narrow beam of highly accelerated electrons. These are elementary particles contained in every atom and they carry a negative electrical charge. Responsible for the mechanical and chemical properties of the atoms they also act as the energy carrier of the electric current. To obtain free electrons for a beam, they must first be released from the atoms. This is achieved by heating an emitter electrode.

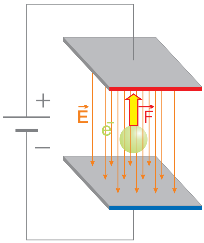


Figure 2: As a result of the Coulomb force $\vec{F}$, the electron in the electrical field $\vec{E}$ experiences an acceleration in the direction of the anode.

Because of their charge, electrons can be influenced in two ways: In electric fields they are accelerated towards the anode (positive electrode); the so-called Coulomb force is acting on them. In electron beam machines too, the electrons are accelerated by this force. In the process they absorb energy resulting in an increase of speed. The amount of energy absorbed by an electron during this process is mainly determined by the voltage difference through which the electron passes. For example, an electron accelerated through a voltage of 150 kV, reaches about 63 percent of the speed of light. Therefore, to describe the energy of the electrons, the accelerating voltage is stated.

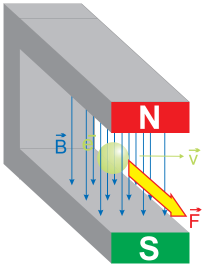


Figure 3: The Lorentz force $\vec{F}$ acts on the electron in a magnetic field $\vec{B}$ and is perpendicular to the direction of motion $\vec{v}$ and to the field lines.

The second way of acting on electrons is with magnetic fields: The so-called Lorentz force affects the direction of motion of the electrons. They are deflected perpendicular to their trajectory and to the field lines, without changing their speed. In a welding machine, magnetic fields are used in various places. They are used in forming and deflecting the beam and for creating magnetic lenses. Parasitic magnetic fields from the material being welded have an effect on the beam that is not desired. These interfering fields therefore have to be kept as low as possible.
Having described the physical basis of the electrons, we can now look at the beam and its properties.

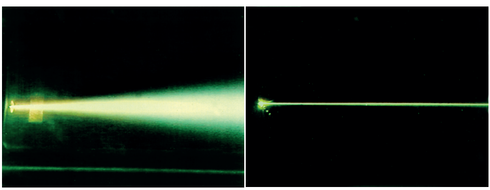


Figure 4: Beam expansion: An electron beam in a residual gas (500 mbar) shows beam expansion from multiple scattering (left); at 50 mbar, the expansion is almost absent (right).

The electric fields within the atoms naturally also have an influence on the electrons. When electrons meet atoms (e.g. a workpiece, or air) they are scattered (deflected) by them and give up a part of their energy to these atoms, increasing their temperature. For an electron beam in gas, e.g. in a poor vacuum, this means that the beam becomes wider. In Figure 4 we see, firstly, how an electron beam due to the injection of residual gas becomes wider and wider as a result of multiple scattering and, secondly, that this expansion depends on the density. This is why it is preferable to work with a vacuum in electron beam machines.

2.2 Electron beam

Figure 5: Effect of the beam: The workpiece heats up strongly, and X-rays are produced. Some electrons are scattered back and can be used for monitoring.

The desired effect of the electron beam on the workpiece is to heat the material over the smallest possible area. It must be molten and partly vaporised to create a weld or to make holes.

	Mg	Al	Ti	Cu	Fe	W
60 kV	35µm	23µm	14µm	7µm	8µm	3µm
120kV	112µm	72µm	43µm	22µm	25µm	10µm

Table 1: Penetration depths of electrons in various metals.

If an electron beam hits on a metal, the electrons penetrate it. The penetration depth depends on the energy of the electrons (accelerating voltage) and the density of the metal (see Table 1). For example, electrons penetrate aluminium seven times deeper than tungsten. Normally the penetration depth is less than 0.1 millimetre, and most of the electrons are captured in the metal. A few electrons are scattered back by the atoms and they can leave the metal again. The number of these back-scattered electrons depends on the penetration depth and therefore, once again, on the material of the workpiece. A fraction of the energy of the electrons is released as X-rays. This radiation is unintentional, but cannot be avoided. Consequently the equipment must be shielded in order to avoid health risks. Typically the shielding is incorporated into the vacuum chamber.

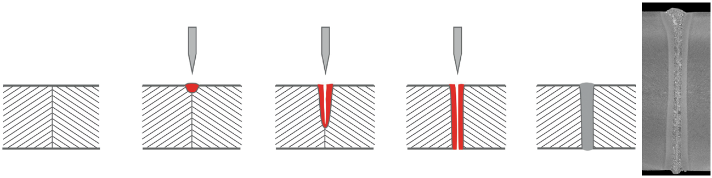


Figure 6: Deep-penetration effect: Melting and vaporising enable the beam to penetrate the material deeply. The weld pool penetrates the workpiece. Right: Micrograph of a full penetration weld in 50 mm thick steel, S355.

Although the electrons penetrate less than 0.1 millimetre into a variety of different metals, welding depths of several centimetres are possible. Responsible for this is the so-called deep penetration effect. The electron beam heats the metal so much that the metal melts and even vaporises in the centre. A capillary hole (keyhole) in the molten metal is created by the vapour pressure allowing the electron beam to pene-trate further into the workpiece. This effect makes it possible to use the electron beam to create deep and narrow welds.

2.3 Beam supply

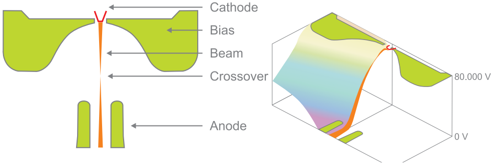


Figure 7: Cross-section of electron gun (left): The electrons are accelerated from the cathode to the anode. The graph on the right shows the potential in the electron gun, represented as height.

The purpose of the beam source is to make available a beam that is as narrow as possible, with low divergence and variable in power. If required, e.g. for wider welds, this can be slightly widened. To create an electron beam for welding or drilling holes, the first requirement is free electrons. These are emitted by hot materials, usually tungsten (W), on account of its high melting point, and in some cases tantalum (Ta) or lanthanum hexaboride (LaB6). This source of electrons can be heated directly by a current or indirectly by an additional heating element. The electrons are then accelerated by an applied voltage. Figure 7 shows a cathode that is directly heated by a current which also acts as an electrode. The electrical potential in the electron gun is represented as height in the graph on the right. As electrons run down this „potential slope", their speed increases. The energy they receive in this process is determined solely by the voltage between the cathode (negative electrode and electron source) and the anode (positive electrode). With an additional bias cup (Wehnelt electrode) a voltage can be used to control the beam current density. This enables much faster control of the beam current than by changing the heating current. Only by means of a high switching speed is it possible to drill holes with an electron beam (beam pulsing), and welding is much more accurate.

Choosing the electrodes skilfully can improve the shape of the beam. This turns the potential slope into a narrow „gorge“. A negative voltage on the bias cup pinches the beam and so reduces the current. At the same time the crossover moves towards the cathode. At low currents the beam diameter and divergence improve. During the welding process the accelerating voltage is usually kept constant and the beam current is used to control the power.

2.4 Beam optics

To be able to work with the electron beam, it must be directed to the workpiece surface. With magnetic fields it is possible to focus electron beams in a similar way to the focussing of light beams. If a current-carrying wire is „wrapped“ around the electron beam, this coil generates a field that acts like a lens. The focal length of this lens depends on the energy of the electrons, the current in the coil and the coil design. By altering the current in the coil the focus of the beam can easily be altered to different distances, giving a kind of „flexible lens“. This dependence on the current opens the way to fast electronic control. Given appropriate controls, rapid changes to the focal length are possible, that cannot be achieved by mechanical means.

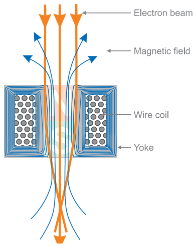


Figure 8:
Magnetic lens: When an electron beam passes through a coil it becomes focused after leaving it.

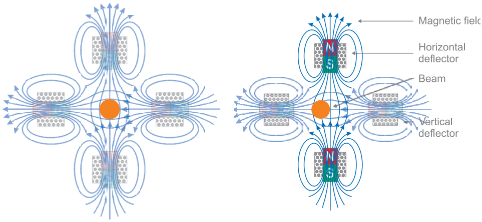


Figure 9: Deflection: In a homogeneous magnetic field perpendicular to the electron beam, the initially centred beam (left) is deflected sideways (right).

By arranging two coils perpendicular to the beam, creating a magnetic field similar to that of a horseshoe magnet, the electron beam can be deflected sideways. The magnitude of the deflection can, again, be controlled by the current in the coil. With a second pair of coils at 90 degrees to the first, the beam can be moved in any desired direction over the workpiece. Since this control is done without any mechanical movement, very rapid deflections are possible. Connecting a function generator to the deflector, very complex shapes can be created on the workpiece.

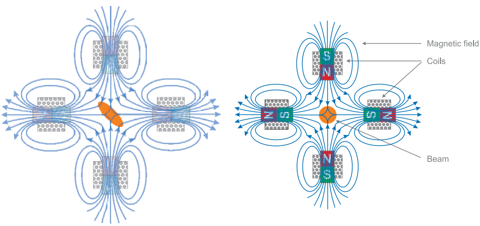


Figure 10: Beam shaping: With magnetic multipoles it is possible to correct astigmatism of the beam. The astigmatism (left) is corrected by magnetic fields (right).

With complicated arrangements of coils (magnetic multipoles) it is possible to modify the shape of the beam cross-section. This is usually used to correct the astigmatism, known from light optics, and thus to make the beam as circular as possible.

2.5 System configuration

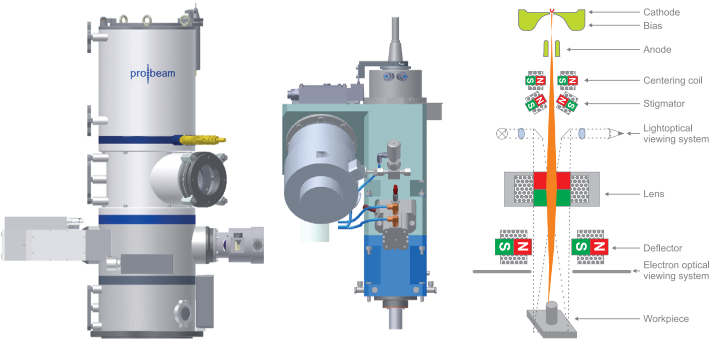


Figure 11: High-voltage column for high beam powers (left), low-voltage column for medium beam powers (centre), diagram of a beam column (right).

Depending on the configuration a complete electron beam column can consist of various components. Common to all of them is the electron gun with a cathode, Wehnelt and anode, a focussing lens and a deflector. There is the option of incorporating a centring deflector to adjust the beam to pass through the centre of the lens and so to minimise lens errors. A stigmator enables the beam shape (roundness) to be optimised. For certain processes it is useful to use an additional lens together with an aperture. It supports reducing the diffusion of process gas (metal vapours) into the electron gun.
There are further possibilities for variation in the geometry of the electron gun, the size of the cathode or the distance between the electron gun and the lens, the object distance. The relationship between the object distance and the image distance, or working distance, determines the image scale and so the beam spot diameter.

This way, the column can be optimised for the welding task and working distances.
The magnetic optics and the electronic control can also be matched to the requirements, providing an optimal relationship between speed, precision and cost.
Most electron beam columns are fitted with diagnostic systems for observing the welding process. In most cases this is a light-optical system with a CCD (charge-coupled device) camera or a telescope. A further possibility is evaluation of the back-scattered electrons, which can also be used to obtain images. Possible applications of these diagnostic systems are illustrated in chapter 5.

2.6 Beam characterisation

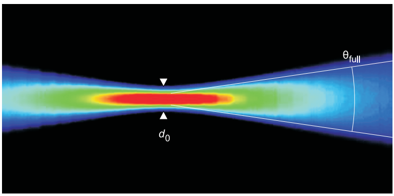


Figure 12: Beam caustic: Intensity measurement along the beam. This false-colour image has been greatly magnified vertically. The minimum diameter at the focus (d_0) and the divergence angle (θ_{full}) are indicated.

To characterise the quality of an electron beam, a number of features of the beam must be considered. An electron beam used for welding must supply enough energy to vaporise the metal. At the same time, the regions adjacent to the weld or the bore must be heated as little as possible. Therefore a large amount of power over a small area is required, i.e. a high energy density. The smallest possible width of a weld is determined by the minimum achievable beam diameter and by the welding speed. The narrower the beam diameter the more accurate and finer is the possible weld. For larger welding depths it is also important for the beam to remain narrow. If the beam expands too much, the vapour capillary cannot be formed over the whole thickness of the workpiece. The divergence indicates how strongly the beam expands. For large material thicknesses and large welding depths, a low divergence is necessary.

As is known from light optics, minimum beam diameter and divergence are related to each other. With a lens the beam diameter can be altered corresponding to the magnification, but the divergence changes at the same time in inverse proportion. The (normalised) product of minimum beam diameter (d_0) and the divergence (θ) is called beam parameter product (BPP), also known as emittance (ε) in accelerator physics. It is a constant of the beam and does not change with magnification.

$$\varepsilon = \frac{d_0 \cdot \theta_{full}}{4}$$

For example, a smaller focus distance can reduce the focus diameter (smaller image) but at the same time the divergence becomes worse. For a weld that is both narrow and deep, a small beam parameter product and a low divergence of the source are required. This cannot be improved by the optics, but is fully determined by the beam source.
Typical values for an electron beam welding machine are 1 to 2 mm mrad for the BPP with a beam diameter of 200 to 300 µm. For a laser welding machine these values would be, for example, 20 mm mrad and 600 µm.

[1] C. G. Menhard and Dr. T. Löwer: „The electron beam geometry – Definition, measurement and significance for the welding process“,: Welding and Cutting, issue 3/2009, page 138-1

3. Weldability of a component

Weldability is usually understood as the suitability of a given welding process for joining a component. According to DIN 8528-1 this general definition is supported by three external factors. The weldability of the component is not assured until it is established that all three, the material, the design and the fabrication method for the requested welding process permit the component to be welded.

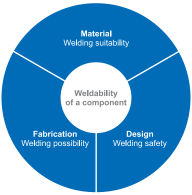


Figure 13: Factors that affect the weldability of a component according to DIN 8528-1.

In this context it is often the suitability of the material for welding that is decisive for determining weldability. That is also the reason why weldability is often considered to be the same as the welding suitability.
However, all three factors play an equally decisive role. For example, if the welding safety does not result from the design, the weld seam could fail prematurely leading, in the worst case, to failure of the component and a danger to human lives. The same goes for the weldability in the context of the fabrication procedure. Welding that meets the requirements can not be achieved until it is assured that all weld seams can be made in accordance with the specification (in respect of accessibility, heat conduction etc.).
In this context the suitability of the material for welding also has a decisive role. For the standard welding processes such as MIG/MAG or TIG, the number of materials suitable for welding is limited or the welding suitability first needs to be improved by complicated procedures such as appropriate heat treatment or by the use of buffer layers. In this matter electron beams provide a number of advantages, in some cases decisive, so that in recent years a significant increase in

the number of materials and material combinations suitable for welding has been possible with appropriate control and management of the process. Thus, for construction steels such as S335-grade and similar ones, or for heat-resistant steels for the petrochemical industry such as 13CrMo4-4 electron beam welding can be carried out without any preheating – in contrast to working with the arc welding processes.

If the material requires preheating to enable welding without defects, this can also be achieved in many cases with the use of an electron beam, resulting in a simplification of the production process. The required parameters are developed along with the welding parameters during process development and are later exactly reproduced in production.

4. Design considerations

4.1 Material and electron beam welding

Requirement criteria for applications in arc welding result in a large number of different weld seam geometries. Since using the electron beam usually does not require filler material in order to achieve the required welding depths that, depending on the material can sometimes be over 100 mm, the square-butt joint is the ideal preparation for welding. In various modified forms this joint geometry makes nearly every welded joint possible. In addition to the form of the joint, welded joints are divided into longitudinal and circumferential welds. In the case of circumferential welds, axial and radial welds can be distinguished for more accuracy.

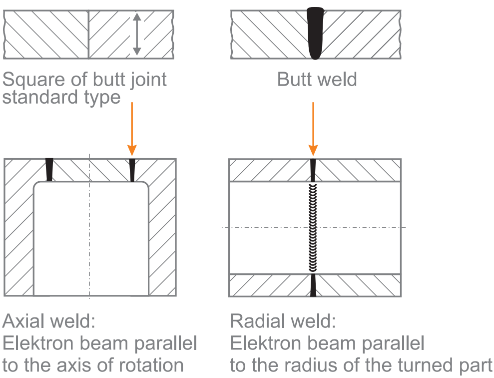


Figure 14:
General division of joints into longitudinal and circumferential welds.

For the basic joint as shown in Figure 14 there are many options in the details, some of which can only be implemented with the beam welding process. The form of the joint and the associated weld seam geometry form the basis for implementing welded joints of high precision and outstanding seam quality.

In electron beam welding the preparation of the weld seam is relatively simple, since the separate parts only need to be brought together into position with as little gap as possible („zero-gap“). The aim in this case is to have a gap of less than 0.2 mm. If, due to the fabrication procedure, this is not possible, the use of a filler wire may make it possible to weld the component without defects.

In such a case, compliance with the tolerances of shape and position is usually more important than the surface roughness at the butt joint. Particularly in deep welding, very smooth surfaces can make degassing of the joint gap difficult and lead to problems; for a large number of applications smoothed, ground, laser or water jet cut or even sawn butt joints are entirely adequate.

In selecting the seam preparation method it is important to ensure the sharpest possible edge without burrs on the upper surface of the joint. That enables accurate positioning using electron optics, which is beneficial both for preparation of separate parts and for better recognition in automated processes.

For welding in a vacuum, enclosed cavities are usually disadvantageous. If the welding process cuts into them possible excess pressure of the trapped air can lead to instability of the process. Cavities caused by machining should be kept as small as possible. It is therefore advantageous to always specify bevels and internal radii and their tolerances accurately (see Figure 15 left). Care must also be taken to ensure that the individual parts can then indeed be assembled without gaps. If, for example, an unfavourable combination of bevel and radius is selected, undesirable gaps can occur in the joint area (see Figure 15 right).

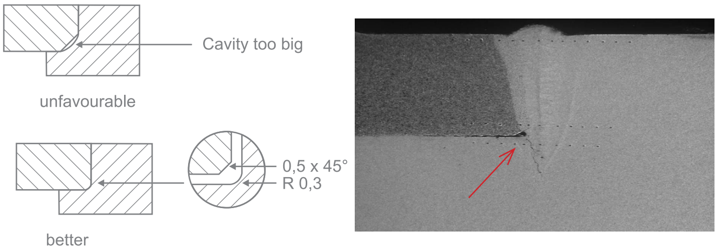
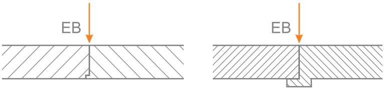


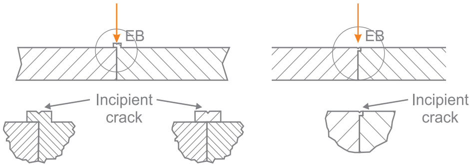
Figure 15: Left: Cavity permissible after processing. Right: Crack along the seam flank and to the weld root, starting from a cavity partly filled with melt

Particularly for welding round components in the shape of radial welds, component centring for accurate positioning is necessary. The centring can be done from the inside or from the outside.

Because of a simple preparation procedure and the more favourable relationship with respect to internal welding stresses, radial welds are very well suited both for large-scale manufacture and for highly stressed machine parts and are advantageous in comparison to axial welds.



Advantage	• Visible joint gap • Standard centring	• Visible joint gap • Root treatment to design dimension is possible • defined indication for NDT
Disadvantage	• unwelded gap • NDT - indications in root area	• added mech. effort for centring



Advantage	• Centring as **same-type** filler deposit • no unwelded • residual gap	• Centring as **different-type** • filler deposit (metallurgical influence) • no unwelded • residual gap	• no unwelded residual gap • Standard centring
Disadvantage	• concealed joint gap • mech. effort	• concealed joint gap • mech. effort	• concealed joint gap

Figure 16: The centring for radial welds.

When using this type of seam it is still important to ensure that the assembled parts contain no enclosed cavities which cannot be evacuated. If necessary the design should include vent holes or degassing slots.

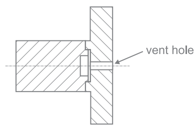


Figure 17: Component with vent hole.

In welding axial welds (Figure 18) centring of the parts is achieved in most cases through the positive locking of the turned parts as illustrated in examples 1 to 4 in Figure 18. The details of the fit are particularly significant here. With axial-seam welds there will either be a cross-sectional shrinkage leading to the formation of a gap on the opposite side or there is the risk of cracks resulting from high welding stresses in the case of a constrained shrinkage. Cleverly selected transition fits – such as H7/n6 or H7/r6 together with the slimmest possible weld seams of fusion welding processes – will adequately prevent these effects in most cases. Example 6 shows an axial stitch weld method which can also securely weld very thin sheets such as membranes. The area of the joint can then be increased by means of several concentric circular seams next to each other. When doing stitch welding it should always be kept in mind that the welding depth is only little related to the cross-section of the joint. Therefore it may be necessary to achieve the required joint area by a series of welds.

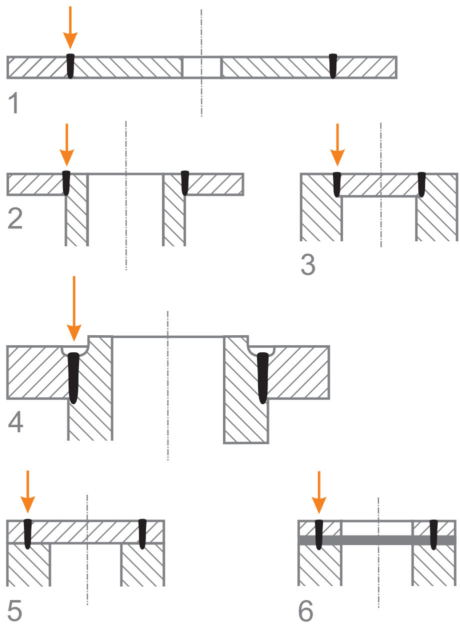


Figure 18:
Axial weld examples.
1 Butt weld
2 Corner weld
3 Corner weld with rebate for disk
4 Pipe-flange joint; Rebate for flange
5 Lap weld
6 Welding to attach a membrane; the applied ring prevents the membrane from „burning through"

For 1, 2, 3 and 4 a light press fit should be provided; for 5 and 6 the parts are pressed together by a clamping device.

The characteristic narrow electron beam of high energy density - high precision as regards impact position and energy input controllability - makes it possible to weld seams that are inaccessible or difficult to access (Figure 19).

The versatile properties of the electron beam provide the creative designer with numerous ways of achieving economical and technically ingenious solutions while complying with the hints for designing in a „weld-friendly" way. In this matter, the small volume of the weld pool and the steepness of the sides of the weld seams are significant advantages for the process.

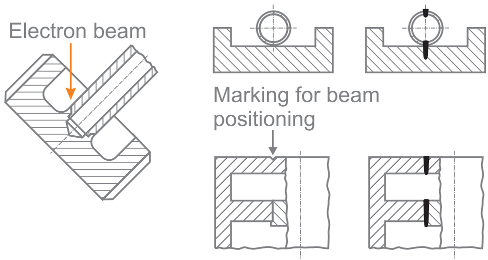
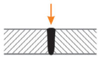
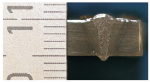
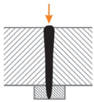
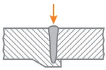
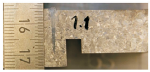
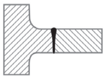
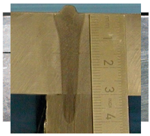
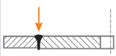
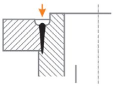
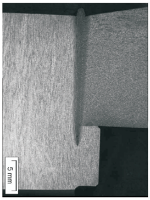
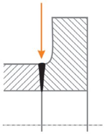
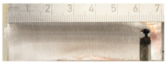
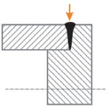
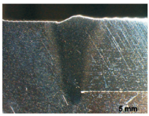
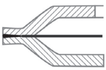


Figure 19:
Joints which are difficult to access (left) or inaccessible (right).

These properties result in the lowest angular distortion and the least shrinkage and contraction of all fusion welding processes. Warpage and distortion can be minimized during parameter development and reliably reproduced in production. Hence the designer can design to the desired final dimensions and avoid the need for expensive mechanical reworking. The methods are most suited for marking of new parts or repair of machining faults on high value finished parts.

4.1.1 Examples of shapes

Designation	Drawing	Actual piece	Material
Simple square-butt weld			Material: S960QL
Square-butt weld with weld bead support			Material: S355NL
Square-butt weld with centring lip			Material: TiAl6V4
T joint with square butt weld for high strength requirements			Material: AiSi316L
T joint with square butt weld for low strength requirements			Material: G-AlSi10Mg an EN AW 5083
Lap weld			Material: 16MnCr5
Axial weld - simple square-butt weld			Material: 1.4404

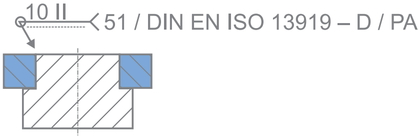
Axial weld - pipe-flange joint			Material: S355 an 42CrMo4V
Radial weld - square butt weld pipe-flange joint			Material: V-2905 an E355
Radial weld - square butt weld, fixing by press-fit			Material: 18CrNi
Radial weld - flare seam			Material: 42CrMo4V

Further information and examples are available in the DVS information sheet 3201.

4.1.2 Standards-compliant representation of EB welds in engineering drawings

EB welds are represented in engineering drawings in a similar way to other welding methods. An example is shown in Figure 20.

Figure 20: Standards-compliant representation of EB welds.

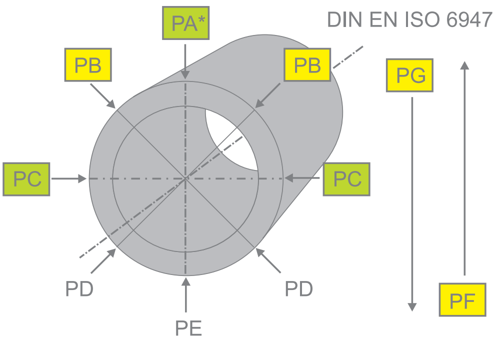


Symbols:

10 II	Welded joint as butt weld, all-round, depth 10 mm from arrow side
51 (511)	Symbol for electron beam welding to DIN ISO 4063 (EB in vacuum)
DIN EN ISO 13919 – D	Indicator of weld seam quality (assessment group)
PA	Welding position

Since, for all welding processes the welding position has a decisive influence on the seam geometry and on the specific properties of the seam, it is essential to be indicated in a standards-compliant weld seam designation.
The possible welding positions are defined in EN ISO 6947 and are shown in Figure 21 and Figure 22.

Figure 21: General view of the welding positions defined in EN ISO 6947.



*limited depth for through-welding because of the melt behaviour

The designation takes the form of two letters, of which the first is „P“ for „Position“. The second letter then indicates the position, starting with A at the top. The typical flat position is then designated „PA“ and the overhead position is „PE“.

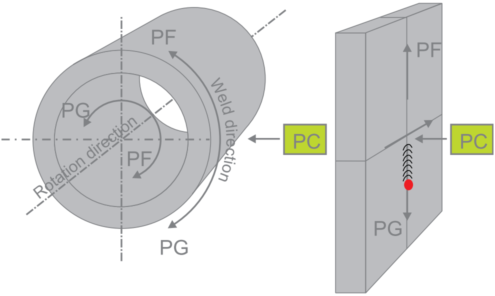


Figure 22: Diagram of the constrained positions PF and PG for cylindrical and flat parts.

In addition to these basic positions there are the vertical up (PF) and vertical down (PG) welds.
In electron beam welding, position PA is the most commonly used, which results from the mostly fixed position of the electron gun relative to the component. Some installations also provide the option of welding in position PC, which is possible either through the use of a second horizontal electron gun or by exchanging the vertical electron gun into a horizontal position. When used together with a rotation device, welding can then also be done in positions PF and PG. Further welding positions are possible only in installations with a mobile electron gun.

4.1.3 Design requirements for electron beam hardening

Hardening with the electron beam is a surface treatment. A number of variants are distinguished, with a first coarse classification into those

with a structure transformation in the solid phase and those in the liquid phase. In comparison with other processes, electron beam hardening has the advantage that the component surfaces can be hardened with nearly no warping, without heat tinting or scaling, with exactly defined location and without melting. This usually makes reworking unnecessary and the process can then be the last processing step before delivery. Using a vacuum prevents the application of coolants. Instead, a sufficiently fast cooling of the workpiece areas to be hardened results from the very good thermal conductivity of the metal components, giving the so-called self-quenching effect. The self-quenching effect - the rapid cooling of the thin heated boundary layer into the cold interior of the workpiece - leads to particularly good hardness values.
However, to make the process effective, a number of design features are required. For example, ferritic parts with good accessibility of the surface to be hardened and an adequate wall thickness are suitable for hardening provided the material is martensitically hardenable (C m% ≥ 0.18). However, for smaller wall thicknesses, only a limited self-quenching through the workpiece can be achieved, resulting in lower achievable hardness values and hardening depths. Unsuitable parts include those that either have no accessibility for the electron beam or have walls that are too thin so that either the required hardness or the hardening depth will not be reached.

4.2 Weldability of materials

4.2.1 Electron beam welding

Electron beam welding as a thermal metal working process belongs to the fusion processes, which means the metallic conductive material is heated until it melts. By different beam deflection patterns, adjusted and controlled by oscillation, the power input is highly flexible and well adaptable to the relevant task. This requires an accurate view at the metallurgy of the materials employed, since different materials and combinations of materials can be unsuitable or be suitable only conditionally for welding. In contrast to most other processes, the specific properties of electron beam welding make it suitable for a wide range of materials and material combinations, including some that can be used in arc welding either not at all or only with great difficulty. For example, it makes possible very great welding depths combined with narrow weld seams and a small heat affected zone (HAZ). In addition to minimising warping, this has the advantage that materials such as AlCu alloys which are subject to hot cracks can be welded with the electron beam process.
On the other hand, particularly for the high carbon steels, the narrow heat affected zone often makes hardness peaks unavoidable so that in some cases special heat treatment is required for reducing the hardness in the heat-affected zone. In certain cases the heat treatment can be achieved by means of multiple electron beam processes.
If no filler material is used, no further influence on the weld pool metallurgy is possi-

ble so that, for example, the vaporising of alloying elements cannot be compensated. However, the small volume of the weld pool means that this influence can often be neglected.

4.2.2 Aluminium and its alloys

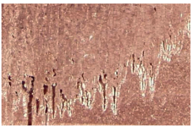
Aluminium-based materials, because of their low specific density and good thermal conductivity, are finding an ever-widening range of applications in our daily lives, particularly in lightweight constructions.
For this material, electron beam welding is a very suitable process because the high-melting oxide film that interferes with other processes is easily destroyed by the momentum of the electrons. Etching the workpiece surface in the weld area before welding reduces the oxide layer and thus improves the flow behaviour and weld quality with reduced porosity. Furthermore, with electron beam welding no problems arise from reflection of the beam resulting in reduced energy input. It is possible to achieve welding depths of 200 mm and more with very good aspect ratios.
The widely used 5000-series (AlMg) alloys have good properties with electron beam welding; for the 2000 (AlCu), 4000 (AlSi) and 6000 (AlMgSi) series, specific precautions are sometimes required to avoid hot cracks. The risk of hot cracks depends strongly on the differing alloy contents, heat conduction and the stresses during welding or as a consequence of the welding; therefore, no general statement can be made about this. Chemical changes in these materials caused by the welding process are almost always negligible.

In contrast, with the 7000-series of alloys, vaporising of the zinc component can result in a different material composition in the weld seam, which has an effect on the mechanical properties.
Besides the influence of the alloy constituents in particular for aluminium the manufacturing process has an effect. Whereas for example wrought alloys, depending on the composition, can be welded relatively unproblematic, there is in particularly for cast alloys the risk of increased formation of pores that could be due to high hydrogen content in the workpiece. Multiple welding passes or the use of a multi-pool technique can assist the degassing of the hydrogen so that satisfactory results can be achieved in these cases also.

4.2.3 Copper and copper alloys

In contrast to most other welding processes, most copper alloys, with the exceptions of brass and nickel silver, are relatively easily weldable with the electron beam. The high energy density of the electron beam makes it possible to weld copper, even without preheating, to a depth of over 50 mm in a single pass.
Even supposedly pure copper can contain significant quantities of impurities or alloying elements such as oxygen, sulphur, phosphorus or carbon. These affect the welding suitability, so that OFHC copper or copper types free of phosphorus and oxygen are preferred.
Particularly for the metals with high thermal conductivities such as aluminium or copper, „spiking" occurs during welding, described

by periodic changes to the welding depth. This effect is due to uneven vaporisation processes and distributions of pressure in the vapour capillaries. Since spiking only occurs in partial weld penetration, the recommendation is to weld copper either on a sufficiently deep recess that can fully accommodate the spikes or to make a full penetration weld. The same also applies to aluminium.



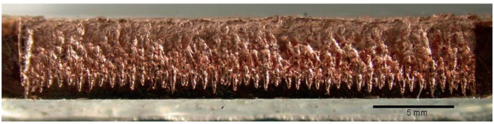


Figure 23: right: spiking when welding copper
left: root spiking - example of a CuCrZr alloy.

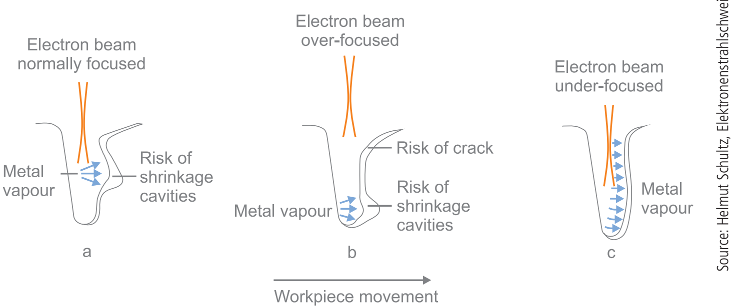


Figure 24: Model idea: relation between focus position and weld imperfections.

4.2.4 Heat-resistant and reactive metals

Given the very high power density of the electron beam and the requirement of working in a vacuum, not only materials with very high melting points can be welded, but also those that react strongly in environments with even only small quantities of residual gases.
For example, titanium and many of its alloys can be electron beam welded without any problems, without the risk of oxidation, carbide formation or hydrogen embrittlement, or the resulting hard-to-detect reduction of toughness of the material. For these reasons safety-critical titanium alloy components are electron beam welded in the aviation industry.
Further examples of applications of electron beam welding with titanium materials are implants (joint shafts) or surgical tools. Because of the high process stability and the absence of external influences such parts can be welded to a very high quality and are partially in use for decades.
The same applies to zirconium alloys and niobium that also react strongly to residual gases. Materials like these are used mainly in constructing nuclear reactors. In view of the high material costs, the quality of the welds must always be ensured, so that electron beam welding is often the only process that can meet the demanding requirements.
Such requirements also apply to tantalum, iridium, vanadium and their alloys, for which electron beam welding is successful. Here too, the level of impurities must be reduced since the weld quality and the achieved pro-

perties can be considerably affected.
It is also possible to weld tungsten, molybdenum and their alloys, given certain design conditions that take account of the low ductility of the weld seams. Indeed, in the case of tungsten, the electron beam is the only thermal welding process that is able to fuse tungsten. The commercially available tungsten components are usually liquid-phase sintered with nickel components. Because of the high temperatures, significant proportions of the nickel are vaporised during welding, resulting in a great reduction in ductility.

4.2.5 Steels and other ferrous alloys

Most steels suitable for welding with conventional fusion welding processes can also be welded with the electron beam. In particular, on account of the very narrow heat affected zone and the absence of hydrogen in the vacuum, many steels for which arc welding is only possible with considerable effort or allowing for degradation of properties (e.g. loss of strength in fine-grained structural steels), can be electron beam welded without such special pre-cautions.
Soft iron and iron containing silicon, such as that used in transformers and electric motors, can be electron beam welded easily.

4.2.6 Austenitic, duplex, and high-alloyed steels

Austenitic steels - in particular the high-alloyed full austenites - with their excellent corrosion resistance are employed in various areas of industry where high resistance to corrosive media is important, such as in desalination plants, in the chemical industry and in oil refineries. However, the high cost of alloy constituents such as nickel makes these materials very expensive. Duplex materials with a structure containing equal proportions of ferrite and austenite are an interesting alternative to the full austenites. Duplex materials have a corrosion resistance similar to that of the full austenites but are available at much lower cost.

By observing certain boundary conditions welding of full austenites is easily controllable. For arc welding special precautions are required for excluding oxygen or post treatment of the surfaces to avoid scaling that cannot be allowed in corrosive environments. In these cases electron beam welding with its oxygen-free process environment has decisive benefits. Duplex steels and austenitic materials are often nitrogen alloyed. Welding parameters are required that minimise the risk of pore formation due to nitrogen degassing and, particularly in duplex steels, compensate the disadvantage of nitrogen loss by the stability of the phase equilibrium. In the welding of duplex steels, nitrogen degassing results in a shift of the phase equilibrium towards ferrite, with the result that corrosion resistance can no longer be assured. Nowadays the use of appropriate process techniques and filler materials make it possible to use electron beam welding for duplex steels as well, fully assured the corrosion resistance.

For the types that can be precipitation-hardened, electron beam welding causes a slight reduction in tensile strength that can, however, be restored by the use of aging processes.

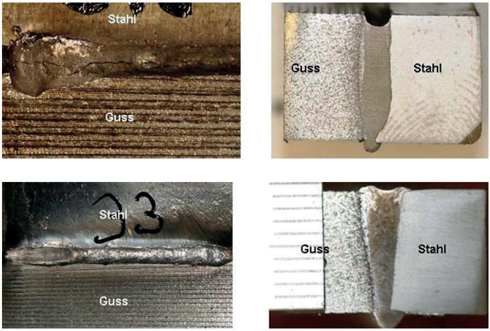
In many applications high-alloyed steels are used in original welded condition even for transmission components of aircraft turbines or cars. NiCrMo steels such as high-alloyed creep-resistant steels can be welded without preheating even with a considerable thickness. Again, good purity parameters are advantageous, particularly when good toughness properties are required.

4.2.7 Construction steels, corrosion-resistant ferritic steels and tempered steels

Ferritic steels are usually easy to weld; the welding suitability is particularly dependent on the carbon content because of the formation of martensite. Ferritic steels with up to 0.2% carbon content are considered to be suitable for welding; with higher carbon contents preheating is usually required. This can be done with an external preheating in a furnace or with a multi-pool technique. In these cases the beam jumps between different positions so that in the first position preheating takes place in the weld direction and in the second position the actual welding is done. This method can be used, for example to weld 42CrMo4 without preheating for wall thicknesses up to 20 mm. A further example is hard welding of gear wheels in the automotive industry. This is the welding of case-hardenable steels such as 17CrNiMo5 or 16MnCr5 that are welded after carburizing and hardening. Because of the high carbon content in the boundary layer, it is necessary to remove the boundary layer in the joint zone, e.g. by hard turning. In addition, these pieces are usually preheated between 150 to 180°C before welding, to reduce the tendency to crack due to hardening in the weld metal.

4.2.8 Cast iron

For metallurgical reasons, cast iron is usually considered not suitable for welding. Other than for welding ductile globular cast iron, electron beam welding of cast iron is not recommended.
Because of economical production and good damping properties, cast iron is still very popular in certain areas. For example, there has long been an increased interest in producing worm gears for transmissions, particularly in heavy machinery, by welding bronze and cast iron. At present such components are produced by bolting or pressing, causing disadvantages in weight and load capacity. In recent years however, both research and use under realistic conditions have brought real advancements in electron beam welding of combinations like these so that today the production of such worm gears as welded parts is possible. It must be kept in mind however, that the weld can have a greater formation of pores. However, experiments on test rigs have shown that with the correct arrangement the required strength values can be achieved. Because of the thermocouple effect however, it is recommended not to exceed a welding depth of 20 mm in partial penetration. Larger penetrations would require welding from both sides.



Guss=cast; Stahl=steal

Figure 25: Comparison of welding dissimilar metals GJS440-15 and S235, without filler (top) and with filler (bottom).

A further example of the use of cast iron in practice is the weld of dissimilar metals GJS440 to S235 (Figure 25). It is evident here that the use of both, suitable preheating and suitable filler materials has achieved a considerable reduction of the hardness peaks in the weld. This gives a significant reduction in the risk of hardening cracks.

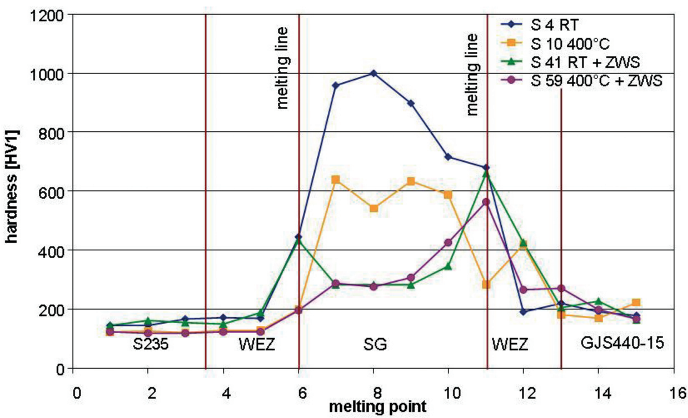


Figure 26: Comparison of hardness profiles in the joint zone in electron beam welding JS440 to S235.

The hardness profiles in Figure 26 show the influence of preheating and the filler material on the formation of hardness peaks in the weld.

Without the filler material and preheating and in consequence of the high level of trapped carbon the hardness values are in the region of 1000 HV1, resulting in a very high risk of cracking. Only if hardness values of around 600 HV1 or less can be achieved in the joint zone and in due consideration of boundary conditions can such a joint be welded free of cracking. For this, preheating and filler materials can be used for electron beam welding.

4.2.9 Nickel and Nickel alloys

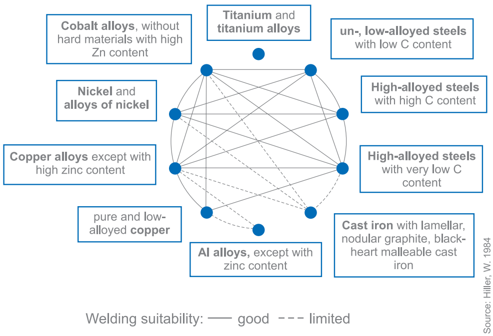
Pure nickel, nickel-copper alloys and many nickel-iron alloys can be welded without difficulty. In contrast to arc welding, the complex high-temperature alloys with high creep resistance and high temperature resistance values such as Inconel 617 can certainly be welded crack-free. The reasons for that are the low metallurgical disturbance caused by the beam and the low thermal stresses. For the more complex superalloys some precautions are, however, necessary to avoid the formation of cracks during the heat treatment after welding. With the use of multi-beam technology, suitable post-heating can create compression stresses that suppress such hot cracks.

4.2.10 Welds of dissimilar metals

It is one of the big advantages of electron beam welding that the beam is so intense that even different materials with widely separated melting points and different thermal conductivities can be successfully welded. Because of metallurgical incompatibility and the formation of undesirable intermetallic phases, not all combinations of different metals are suitable for welding, but

many different materials can be combined. Because of the thermocouple effect, the welding of different materials can cause large thermoelectric currents that result in strong magnetic fields which deflect the electron beam. The significance of this phenomenon depends on the combination of materials and on the magnetic and electrical properties of the materials and the geometry of the component.
Where the combination of different materials in the melt causes embrittlement, it is often possible to still produce a weld seam by including transition materials that are compatible on both sides.
Figure 27 shows the welding suitability of various combinations of metal.

Figure 27:
Welding suitability of combinations of different materials



4.2.11 Electron beam hardening / electron beam remelting

Electron beam hardening occurs through the conversion of a ferritic-pearlitic matrix structure into a martensitic structure and is only possible for ferritic steels or cast iron with suitable carbon content. For the formation of an adequate proportion of martensite, carbon contents of over

0.3 percent are necessary. Since electron beam hardening is a surface process, with cooling through the component mass, full hardening of the part is not possible. The achievable depth of hardening is strongly dependent on the alloy content since this affects the thermal conductivity of the material. For example, the hardening depth of high-alloyed tool steels is less than that of low-alloy case-hardening or hot-work steels and is about 0.5 to 1 mm. The maximum achievable hardening depths are about 1.5 mm with hardness values around 650 HV10 or 53 HRC.
The following qualitative relationship applies for hardening the same material in the solid phase: The maximum achievable hardness is lower with increasing hardening depth.
Some alloys, like iron or aluminium based alloys, show increased hardness in the weld metal after welding. By selective process parameter control the effect can be used for remelt hardening, a hardening process in liquid phase.
Often higher hardening depths or hardness values are required that can only be achieved with electron beam remelting. In contrast to solid phase electron beam hardening, this usually requires post-machining of the component since the dimensional accuracy is often not retained after the remelting. An example is the remelting of cast iron materials for producing wear-resistant ledeburitic boundary layers.
A further application for electron beam remelting is its use with light metals, where the remelting can refine the grain and thereby produce an increase in the wear resistance.

Further reading:
Elektronenstrahl-Randschichtbehandlung,
Prof. Dr.-Ing. habil. Rolf Zenker, Dr.-Ing. Anja Buchwalder,
pro-beam (2010)

4.2.12 Electron beam coating / reconstruction / prototypes

In recent years increased efforts of industry reveal employing of coatings and composite laminates, particularly in the area of wear protection. This is above all a result of increased costs of raw materials making it unprofitable to manufacture wear-resistant parts from solid material. There is in this context a wide range of technological processes for deposition welding with a wide range of materials. In these processes a wear-resistant and often expensive material in the form of powder, wire or strip is applied to a less wear-resistant cheaper base material. The base material then exhibits the required wear-resistance properties on the coated working surfaces. Making huge cost savings possible without the loss of functionality.
Here too, electron beam welding can contribute to an increase in process efficiency. The advantages are obvious: In addition to the saving of the process gases required for other processes, the dilution can often be reduced in electron beam welding without a loss of adhesion. This means that the required layer properties can be achieved with less coating material. An example with a particularly huge application potential is the use of wear-resistant but expensive materials (e.g. Stellite) to coat low-cost base bodies subject to wear.

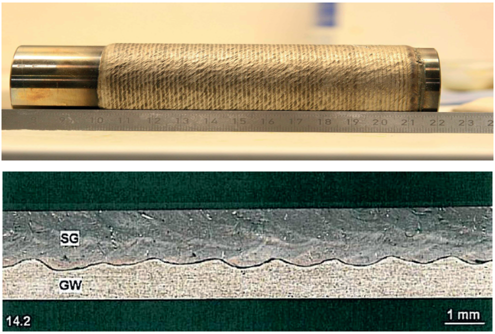


Figure 28:
Two-layer Stellite 6 on qualification material (top), longitudinal section (bottom).

In process technology, electron beam surfacing can be done only with filler materials in the form of wire or strip. There are various designs, in which the wire is fed either from outside via a pressure stage into the chamber or where the wire supply is directly integrated in the chamber.
In addition to the saving of process gas already mentioned, electron beam surfacing has the further advantage that reactive materials can be used as coating material.
A further example is deposition welding of copper (Figure 29), since there is often a requirement for copper-based alloys particularly for plain bearings or maritime applications. This is either because of their emergency running and low-friction properties or because of their anti-fouling characteristics. The use of surfacing with suitable copper materials onto low-cost base materials enables component costs to be considerably reduced while increasing the component functionality and improving component properties.

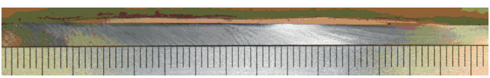


Figure 29:
Cu coating on CrNi steel.

Electron beam coating is not limited to improving the properties of existing parts, but can also be used for the rapid prototyping of new parts. This has many advantages. For example, castings moulds or elaborate machining from solid material are then not necessary. Instead, a structure is built up layer by layer from the required material in wire form. Because of the good dimensional properties only a little finishing work is required. Figure 30 shows an example of this manufacturing process.

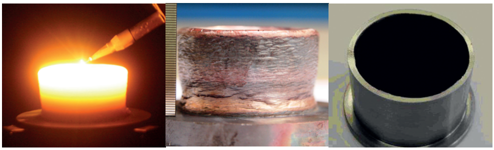


Figure 30: Sequence of steps for rapid prototyping of three-dimensional structures by means of an electron beam (surfacing) (left: building the structure; centre: resulting structure; right: structure after turning).

4.3 Fabrication (magnetism, cleaning, clamping devices)

4.3.1 Magnetism

The electron beam is deflected by electric and magnetic fields. This property is used in generating and shaping the beam. Near the weld itself, undesired deflections can, however, cause position errors or incomplete fusion. Equipment such as clamps and other devices near the beam should therefore either be made of non-magnetic materials or must be demagnetised to a value less than 1 Gauss (0.1 mT).
In ferritic steels, magnetism can result from machining the parts, in particular from grin-

ding (e.g. tooth flanks) or other fine working in addition to magnetised clamps or magnetised lifting devices. In these cases either the entire item or the region of the weld must be partially demagnetised.

4.3.2 Cleaning

As with other fusion welding processes, cleaning in the area of the weld is an important quality-relevant step in the fabrication process. The surfaces around the joint must be free of oxide film, grease, oil, lubricants and traces of paint. In a vacuum these impurities vaporise, mainly explosively and cause significant defects in the weld. The cleaned area on the top surface of the component should be at least three times as wide as the required welding depth.

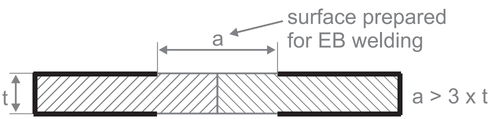
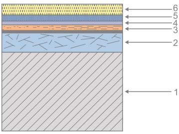


Figure 31: Recommended area of parts to be cleaned for electron beam welding.

The cleaned area should, after cleaning, be bare, grease-free metal and free of films of material that resulted, for example, from carburizing, nitriding, anodizing, phosphating etc. In addition there are certain basic requirements for the geometry of the joint zone. The difference in height of the parts in the joint zone must be not more than a few millimetres, depending on the welding depth and the requirements of the item; for small welding depths, a difference of less than one millimetre can have a negative effect on the result of the weld.
All these remarks make clear the importance

of careful and thoroughly preparing the part to enable good weld results. Therefore further details of cleaning the surfaces will now be given.
An example of film layers on the surface of a metallic material is shown in Figure 32.



1 metal
2 warp plane in the metal
3 oxide layer
4 layer of adsorbed gases
5 adsorbed water
6 coating of polarised molecules (oils and greases)

Figure 32:
Film layers on the surface of a metallic material.

It is distinguished between chemical and mechanical methods of cleaning.
The usual chemical methods include:

- degreasing with alcohol
- vapour degreasing
- alkaline cleaning with aqueous solution

These processes are suitable for removing layers 4, 5, and 6, and adequate in most cases, because machined workpieces without oxide film are often employed. For certain materials on which an oxide film forms rapidly, e.g. aluminium and aluminium alloys, it may be necessary to treat, if possible immediately prior to the welding, with acids, lyes or mixed series of baths.
In the mechanical cleaning processes, contaminants down to the base material are reached, removing layers 1 to 6. This includes:

- abrasive blasting
- grinding
- brushing with metal brushes (as close as possible the same type of material)

Mechanical cleaning methods are very effective but they leave a surface that is extremely susceptible to renewed oxidation, so they have to be used immediately prior to the welding.
In practice it has proved effective to give the parts a basic cleaning with alkaline cleaning processes, and then immediately before joi-

ning simply clean the weld surfaces again with alcohol, e.g. isopropanol or acetone.
In practical use, mechanical and chemical cleaning methods are usually combined.
A large number of tips and recipes for chemical cleaning of various metals can be found in the German Welding Society's „DVS information sheet 3213" titled „Recommendations for the cleaning of joints to be electron beam welded".

4.3.3 Clamping devices

After demagnetizing and cleaning the separate pieces, the surfaces to be welded must be brought into position for the electron beam. As with conventional welding there are also three options here:

1. tack welding in a tack weld fixture (e.g. TIG, preferably without filler material or similar)
2. fitting the separate parts in a clamping and welding device
3. pressing or hot joining of the separate parts, then tight fitting

Option 3 is particularly suitable for rotationally symmetrical parts. It is not advisable to supercool one of the items during assembly, e.g. with liquid nitrogen, because atmospheric moisture will then freeze on the weld surface which will then cause considerable problems from the formation of pores and shrinkage cavities.
In designing welding devices it should be note that 20 to 30 percent excess beam power is required for a sound formation of the under bead. A powerful high-energy electron beam will therefore always leak from the under bead. It should be stopped by suitable auxiliary pieces or replaceable components in the fixtures to avoid

damaging the component and/or the expensive fixture. It will also avoid unnecessary heating of the component or fixture. Figure 33 presents various solutions for the problem.

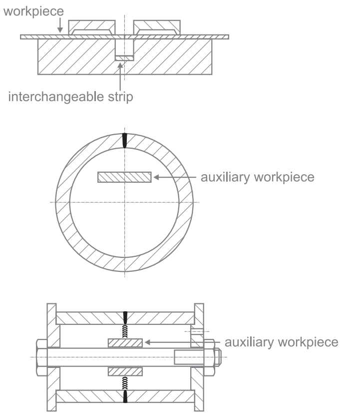


Figure 33: Examples of clamping devices with exchangeable components to protect from melt and spatter.

Source: Helmut Schultz, Eletronenstrahlschweißen

Since the welding is usually done without filler material, gaps should be avoided as far as possible when clamping or preassembling the individual parts. As a guideline for permissible gap width, 1 to 2 percent of the welding depth, but no more than 0.3 mm can be stated. Deviations from these values are possible from experience, but possibly require proofing with a real workpiece.

Since no machining forces and only very low warping (process-specific) occur in electron beam welding, the requirements for the strength of the fixture are small compared to clamping devices for conventional welding processes. It is much more a question of high accuracy for good repeatability to meet the precision demands possible with electron beam welding.

4.3.4 Setup of the joint for the welding process

Due to the process, electron beam welding requires an in-slope and out-slope. This is where the beam is ramped up to full power and ramped down. In these regions for linear welds the full welding penetration can not be achieved and incomplete fusion may occur. Therefore these areas need to be machined afterwards. If that is not possible or requires too much effort, run out plates can be used, attached at the start and end of the weld.

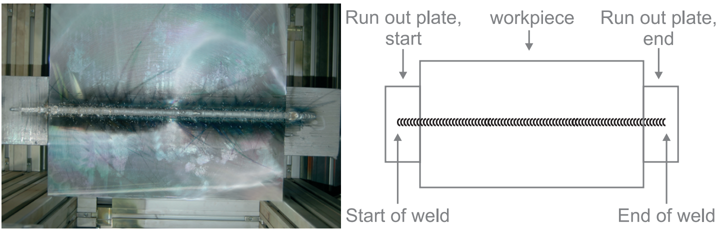


Figure 34:
Use of run out plates in welding linear seams

5. The electron beam as a multi-functional talent

5.1 Tool for quality assurance and diagnosis

5.1.1 Automatic beam alignment

One of the most important prerequisites for optimal welding results is a well aligned electron beam. With demands on quality of the welds increasing, the effort required for aligning the electron beam increases as well. Most important and elementary step aligning the beam is to focus the electron beam onto the surface of the workpiece in order to achieve the smallest possible beam diameter and the highest achievable power density. To minimise movement of the beam with focus changes, and to achieve an optimal power density distribution, the electron beam must be centred on the optical axis of the lens. Beam columns with particularly high power densities are additionally equipped with a stigmator in order to compensate possible beam astigmatism and attain a rotation-symmetrical beam profile. After all steps have been carried out, the beam profile will approximate a Gaussian distribution which for good welding results should always be aimed for.

To ensure a constant product quality a well aligned beam is particularly important for industrial applications. Since electron beam welding often only represents one step within the production chain, personnel is lacking with specialist knowledge of electron beam technology who is able to align the electron beam reliable and, above all, reproducible. Furthermore, even the alignment results of experienced operators show distinct differences if compared to each other.

In contrast automatic beam alignment ensures an operator independent beam setup with steady quality and lowest setup parameter scatter close to the optimum setting. Figure 35 illustrates the different setup scenarios.

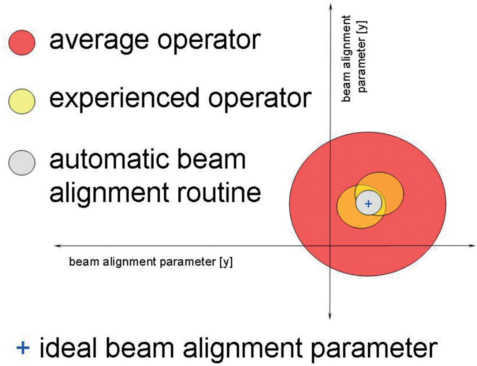


Figure 35: Centring and stigmatising each have two adjustable variables, the alignment axes X and Y. The possible errors in the two axes combine to form an error area. While an average operator of the equipment will produce a relatively large error area, experienced operators are much better at reproducing their alignment results. Nevertheless the mean values of their results often have distinct differences. Automatic beam alignment clearly minimises the error area and is always very close to the optimal alignment values.

For automatic beam alignment pro-beam introduced a passive sensor without electrical connection. That enables three-dimensional beam measurement acquiring power density distributions in various planes along the beam axis. The sensor is small and robust, does not limit the space in the vacuum chamber and can, for example, be mounted in direct proximity to the workpiece. After beam alignment is started, it runs fully automatically for about 45 seconds. Following the alignment procedure, the results (Figure 36) are displayed on the screen. On the left, the achieved beam profile is displayed in false colour. On the right a summary of the setup parameters together with the machine constants for centring and stigmatisation are displayed. Additionally, a so-called form factor is shown. This value represents the comparison of the measured beam profile and a corresponding Gaussian distribution. It is use for evaluation of the achieved power density distribution. All values determined during the automatic beam alignment are automatically recorded.

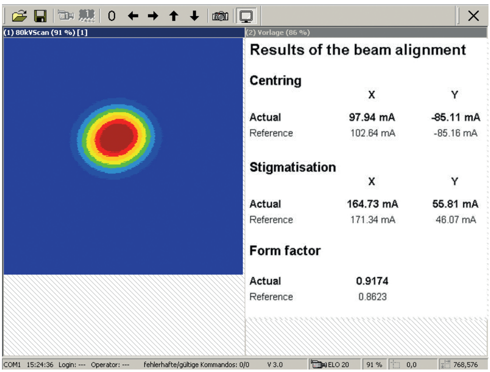


Figure 36: On the left of the results screen of the automatic beam alignment, the achieved beam profile is displayed in false colour. On the right a summary of the values found for the centring and stigmatising is shown, compared with the machine constants.

5.1.2 Monitoring of the workpiece

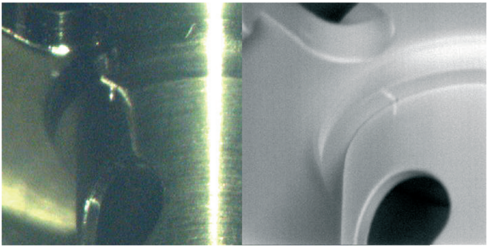


Figure 37: Comparison of a CCD camera image (left) with an electron-optical image (right) of the same workpiece.

Two fundamentally different techniques are available for monitoring of the workpiece in the vacuum chamber. One technique is the light optical monitoring using a CCD camera or a telescope. The other is the electron-optical technique, where the surface of the workpiece is scanned with the electron beam similar to a scanning electron microscope. Beam deflection is used to scan the workpiece line by line simultaneously recording the amount of electrons back-scattered from the metal workpiece surface at each point. These electrons by use of special sensors create images that have an impressively high contrast of 1:15 000. Since even 75 kW electron guns achieve a resolution of down to 80 µm with a small beam current, the smallest details of conventional workpiece surfaces can actually be shown.
Figure 37 shows the comparison of a CCD camera image with an electron-optical image of the same workpiece. Both images have a comparable high resolution. A common disadvantage of the CCD imaging is the metallic glint of workpiece surfaces, with light reflections affecting the viewing of cylindrical components in particular. On the other hand, electron-optical monitoring provides mainly

undisturbed imaging of virtually any region of the workpiece, if accessible for the welding beam.

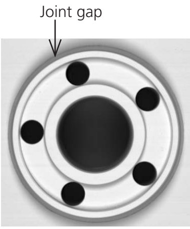


Figure 38: The electron-optical image of this component is impressive for its very high contrast of all component contours.

Figure 38 is an example of the very high contrast of electron-optical imaging. The picture shows a component with a large recess of about 15 mm diameter in the centre, five holes of 4 mm diameter in a shallow recess and an axial joint gap next to a rim of about 10 mm height. Despite the rim, the joint gap is clearly recognisable. The holes have an impressively high contrast with the component surface. All edges are clearly visible along the contour.

A further useful characteristic of the pro-beam electron-optical monitoring is the ability to distinguish different metals. It enables reliable detection of joints that are hard to detect with light-optical monitoring (see Figure 39).

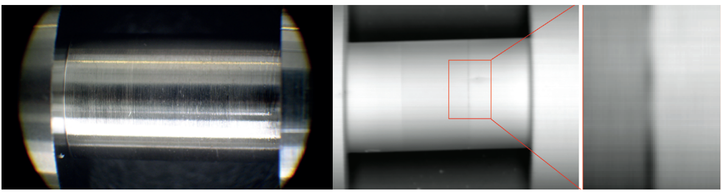


Figure 39: A component with a smooth machined surface where the joint gap is so narrow that it is not more evident than the traces of machining. In the electron-optical image on the right, the joint can be seen, because of the high contrasted imaging and also because of the different materials.

5.1.3 Automatic seam tracking

Industrial applications, particularly for mass-production, generally demand a high degree of automation and reproducibility. These

requirements are met by the electron beam welding, thanks to the versatility of electron-optical monitoring. With it even complex applications and arrangements can be monitored and analysed.
Frequently encountered tasks in electron beam welding are radial and axial welds. Particularly suited for automatic seam tracking is the recording of the developable surface of the joint gap with a line scan. Decisive advantage of this type of analysis is that not only the position of the joint can be determined. In fact all defects that could arise in the processing become visible in the diagnostics. This way, the tool – electron beam and machine – is automatically checked.

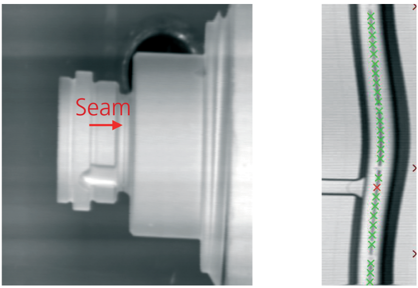


Figure 40: Electron-optical image of a pressure sensor for injection systems (left) and the details of its joint gap (right). The green and red crosses are reference points for automatic seam tracking.

In the electron-optical image (Figure 40) the position of the radial joint is marked with an arrow. The joint gap is in a very narrow depression but, in contrast to light-optical monitoring, it is clearly visible. The unrolled joint and its surrounding edges imaged by using a line scan are shown in Figure 40. Due to the high contrast ratio of the monitoring, the joint is clearly visible despite its location being unfavourable for any kind of imaging, and hence can be detected automatically.

Electron-optical monitoring opens up a range of opportunities for position determination of a welding joint. Figure 41 shows on the left a flange with two tubes to be welded. For automatic seam tracking an electron-optical image of the whole flange is created, shown on the right side of Figure 41. Evaluating the image both openings of the tubes are detected and the coordinates of their centre points determined. Knowing the diameter of the tubes they are automatically welded.

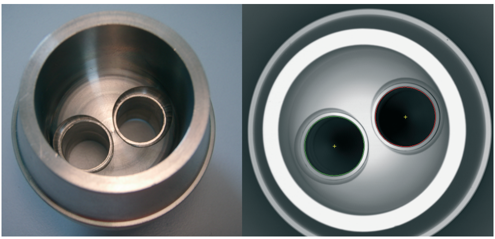


Figure 41: Photograph of a component (left) and its electron-optical image (right). The calculated centre points of the tubes are marked with small crosses.

Even in areas where until now the complexity of the component has resulted in the work being entirely manual, welding can be automated by using high contrast electron-optical monitoring. An example is the fully automatic processing of a „ring-of-vanes“ for an aircraft engine (see Figure 42).

A ring-of-vanes consists of several separate segments that are tacked, welded and cosmetic welded in separate work steps. Because of possible deformation during the work, repositioning is required for each weld. The smooth metallic surface, the unfavourable angle of view and the poor accessibility of the joint make positioning with light-optical monitoring extremely difficult. On the other hand, observation with electron-optical monitoring can easily be parameterised in such a way that the high contrast is maintained over the whole course of the joint.

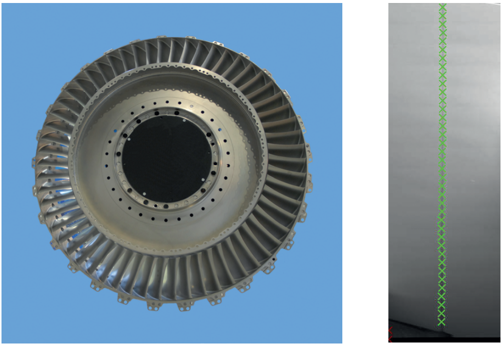


Figure 42: On the left a Ring-of-Vanes for aircraft turbines (diameter 1600 mm, Trent 900); on the right an electron-optical image of a joint between two vanes and its evaluation.

Electron-optical monitoring also enables imaging and measurement of long structures and joints of several metres in length without breaks and a resolution in the range of 1/10 mm. This way, again, the tool – electron beam and machine – is accurately examined before the process begins. Deviations that affect the process can be reliably detected and corrected before or during the welding. An example is shown in the following illustration.

Figure 43: Cooling plate with meandering cover of cooling channel to be EB welded (left); electron-optical image of the joint (top), generated by running along the joint and recording the contour with a line scan. Despite the complex structure the weld path relative to the workpiece can be accurately measured, even for long joints.

5.1.4 Control of the process

As with monitoring and positioning of the workpiece, the two viewing systems also compete in monitoring the process. The classical way of monitoring the welding process, which has been standard until now, uses light optics for viewing. Monitoring the welding process with a CCD camera, for example, enables to see how the melt is flowing, whether the keyhole remains uniformly open or whether there is significant spatter. For controlling and tracking the beam position, electron-optical monitoring is again well suited due to the high contrast and without the need for illumination of the process that could interfere in some operations. Taking the images, the welding process is regularly interrupted for a very short time to make a scan at the current welding position. The resulting electron-optical image shows the joint, the keyhole and, to some extent, the area of the melt and its solidification. This diagnostic technique, called ELO-Online at pro-beam, enables for example to weld octagonal structures of up to 15 m in length as shown in Figure 44 despite the distortion due to heat input during welding. Because of the 45° joint and the associated reflections beam position control using light-optical monitoring is not applicable.

The short withdraw of the electron beam from the weld pool in order to take the electron-optical scan during welding can also be used for automatic position control of the electron beam. The back-scattered electron signal is evaluated as like in automatic seam tracking and the beam position corrected accordingly.

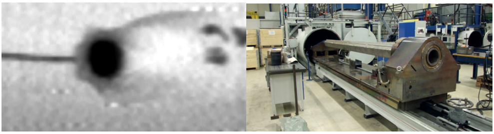


Figure 44: On the left the electron-optical image of a welding process clearly showing joint and keyhole, but also something of the flowing and solidification of the melt. On the right, a component is shown that can only be welded with ELO-Online.

5.1.5 Quality checking

There are various possibilities for monitoring and checking the weld quality with electron beam welding.
Since all the beam parameters relevant for the welding process are electrical settings, it is a simple matter to monitor and record these parameters.
In addition, the very high contrast of the electron-optical monitoring can be used to monitor the quality of the upper bead of the weld seam in taking an image after the welding process. The image is used to detect reinforced welds, lack of fusion, washover, undercuts and spatter on the upper bead of the weld.
In addition to evaluating the back-scattered electrons of the workpiece surface the generated X-ray radiation penetrating the component can be recorded and analysed. The resulting images provide a view inside the

component and can make pores and joint defects at the weld root visible. In certain cases X-ray diagnostics can also be used for positioning the component.

The high contrast of the electron-optics and the absence of interfering reflections make the open pore easy to recognize in the electron-optical image.

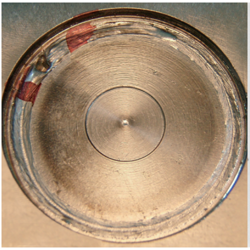


Figure 45: A photo of an axial weld with an open pore

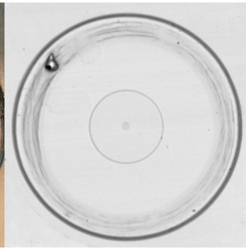


Figure 46: The electron-optical image of the same weld.

5.2 Fast deflection, multi-beam welding

The magnetic optics used in electron beam technology can change the direction of the beam virtually with no inertia effects.

On the one hand this can be used to follow the weld contour by beam deflection. On the other hand small oscillations within the weld pool are performed in order to enlarge or in particular for deep penetration welding to stabilize the keyhole. Lack of fusion and porosity in the weld can be prevented. If the beam deflection is fast enough that the thermal inertia of the beam is overcome and it acts at several positions almost simultaneously, it is called multi-beam technology. The beam can be flexibly programmed and have the same or varying effects at different locations on the workpiece.

To demonstrate the flexibility and high speed of the deflection system, Figure 47 shows a picture projected onto the work table of an electron beam machine. The principle and the projection frequency are comparable with those of a television set.

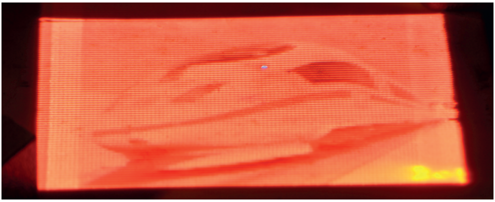
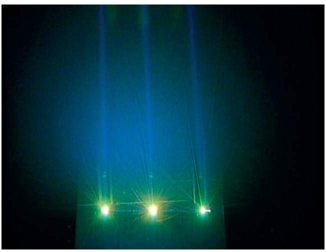


Figure 47: A picture (an ICE train) is drawn on the workbench of an electron beam machine.

However, the main use of the multi-beam technology is for welding. Main benefits are reduction of welding time, elimination of process steps and decrease of distortion.

5.2.1 Multi-beam welding

Multi-beam welding can weld multiple joints simultaneously, with parallel joints in the simplest case. The beam jumps between the weld pools at a defined frequency, with the resulting holding times on the weld spots.



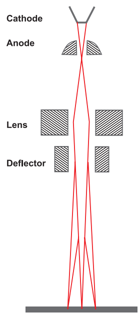


Figure 48: Multiple-beam process of three weld seams (left) schematic representation of a 3-beam process (right).

The process is performed so rapidly that the thermal inertia of the welding process is overcome. The beam returns quickly to the keyhole, which is typical for deep welding, preventing it from collapsing. The minimum jumping frequency between the pools required

for the process is determined by the properties of the workpiece material, the number of weld pools and the welding speed. The dynamics of the deflection system puts a limit on the upper jumping speed. Deflection speeds up to 2.2 x 10^6 °/s or, expressed as a frequency, 2.2 MHz with a deflection of 1 degree.
Axial welds are another example for the application of multi-pool welding. Here, a number of symmetrically positioned weld pools produces a circular weld seam by rotating the workpiece as shown in the model or with the beam travelling along the joint (Figure 49). The "simultaneous" welding at several locations results in minimum distortion and uniformly distributed stress in the component. Reduced process times due to shorter weld lengths and redundancy for taking result in higher productivity.

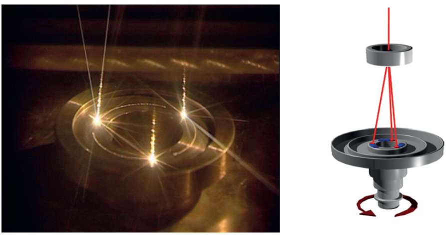


Figure 49: Welding an axial weld with three pools and moving beam (left). Model of welding an axial weld with three pools and moving workpiece (right).

In the particle filter shown in Figure 50, the filter pockets are joined to the plate using two axial welds and 60 linear welds of thermal conduction welding. Since the sintered material requires only low welding speeds, it is possible to have 60 weld pools that first weld the inner axial seam by rotating the welding pattern, then the 60 bags by increasing the amplitude (Figure 50 right) and finally the outer axial weld. Care must be taken to ensure that sufficient power is available since it is distributed over 60 pools.

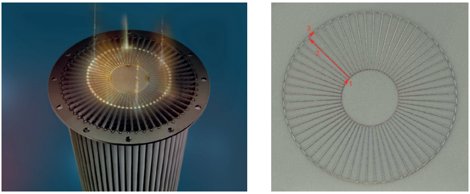


Figure 50: Welding with 60 beams on a soot filter (left). Welding sequence with 60 beams; example for one beam (right).

To gain a further degree of freedom in the multi-beam technology, the focusing lens can be extended with an additional fast dynamic lens that enables changes of focus at a speed comparable to the fast deflector. These changes of focus can be synchronised with the beam deflection, i.e. with a multi-beam pattern where individual pools can have different focus values.
This makes it possible to employ the multi-beam technology on components where a number of welds are required at different working heights. With conventional methods, these welds have to be executed individually. Using the fast deflection, both weld seams can, e.g. as shown in Figure 51 left, be done simultaneously but one at over-focus and the other at under-focus. The focus positions provide different weld results for the two seams. By synchronising the deflector and the lens in this application, two identical weld seams can be performed, with both seams welded at the optimum focus position.

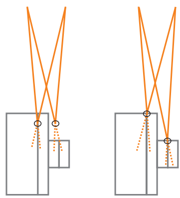


Figure 51: Radial welds with the 2-beam technique, left without and, right, with the dynamic lens.

5.2.2 Multi-process technology

The same principle has an application in combining weld and cosmetic seam. In this case, however, the welding processes are done at a single working height and not in parallel but one after the other. The trailing beam is out of focus and therefore softer than the leading welding beam, so it smoothes the upper bead of the weld seam.

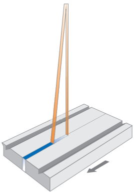


Figure 52: Weld and cosmetic seams with different focus positions.

Welding aluminium die casting the use of the multi-beam technology has a different benefit. Target is not to work more efficiently and save time, but to solve a welding and material specific problem. Due to the nature of the manufacturing process (casting process and release agent) aluminium die casts have a relatively high content of inclusions that degas during the welding process and cause increased porosity of the seams. By using a multi-beam pattern, the degassing of these impurities from the material can be supported and the porosity reduced (see comparison in Figure 53). This is done with several pools (three in this example) of different power, a few millimetres apart above the weld joint, allowing the inclusions a relatively long time to rise to the surface of the melt.

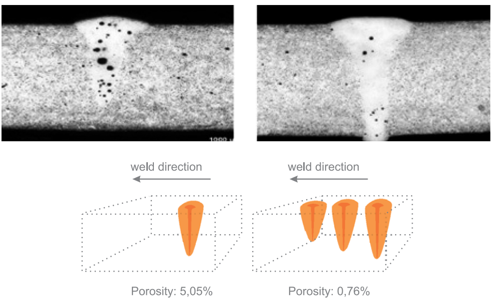


Figure 53: Welding result of single- and multiple-beam process.

A similar beam configuration is used for local pre-heating of high-carbon steels. These materials tend to produce stress cracks in the weld and in the heat affected zone. It is common in industry to heat the whole component in an oven before welding. However, this takes a considerable amount of time and energy. For components that have already been hardened, pre-heating of the whole component is not permissible. By using an electron beam and the multi-beam technology, the pre-heating can be confined to the area of the weld and be done in parallel with the welding, so that even hardened components do not lose their intrinsic hardness. Energy is applied by the pre-heating beam in the form of a small weld pool, not just on an area but with a certain penetration, and so the introduction is targeted and faster.

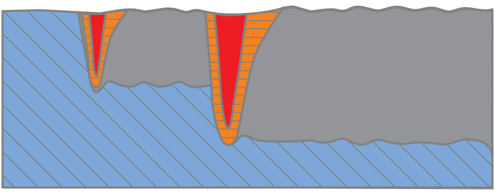


Figure 54: Preheating with an additional small weld pool.

Further more it is possible to use the multi-pool technology to weld materials that tend to hot tear cracking with conventional welding methods because of low temperature melting alloy components and the stresses that arises from welding.

Two patterns trailing the weld pool at some distance to the left and right introduce energy in the form of heat. These zones can take the form of a defocused beam or a scan field. Melting of the surface is avoided. The heated zones cause the material to expand. Pressure resulting from the expansion compensates the tensile stress in the solidification zone of the weld pool, the material can solidify without crack formation.

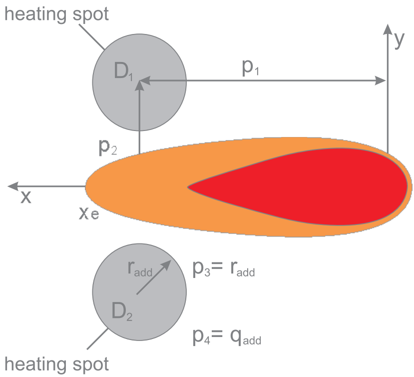


Figure 55: Elimination of hot tear cracks by use of two heat zones running in parallel to the weld.

5.2.3 Surface treatment technology

All the application examples mentioned in association with multi-beam welding can be applied in a similar way to surface treatment techniques such as hardening and remelting. The benefits of surface treatment using electron beams are that energy is introduced only locally into areas to be treated thereby minimise overall distortion. Being performed on multiple tracks or fields simultaneously, this

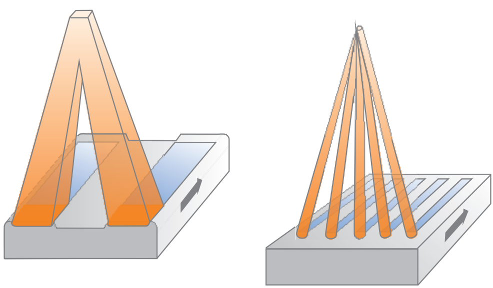


Figure 56: Multi-pool method in surface treatment technology.

technique is also very economical (Figure 56). Various exposure strategies, methods how the beam transfers energy into the workpiece, can be employed. In the simplest case it is a conventional line scan. For example using this method for hardening, large hardening depths cannot be achieved without causing surface remelting. Therefore, special deflection patterns are available, which by holding the temperature constant with low intensity for a relatively long time, achieve higher hardening depths.

6. Electron beam machines

The electron beam as a software-controlled welding tool is characterised by high flexibility, accuracy and reproducibility. These characteristics have led to widespread industrial use of this tool. Modern electron beam (EB) systems are machines controlled by programmable logic controllers (PLC). Installations with computerized numerical control (CNC) are capable of automating the EB processes. The prerequisites for operating the electron beam machines, such as the process vacuum, are automatically generated and monitored in the machine.
The high energy efficiency of electron beam technology and the process media that are not required (e.g. inert gas) result in benefits for both economy and ecology.
In addition to the standard machines, special designs are usual for large-scale applications, and they are influenced by the pieces to be processed. In these cases the required process times are significant in addition to the dimensions. A large number of designs of machines has been developed that implement the movement of the parts under the electron beam in the vacuum in very different ways.
Before coming to examples of EB machines, a series of terms will be defined to help in understanding the concepts used for the machines.

6.1 Definitions

For planning the different job steps in manufacturing and for determining the economic aspects of using a machine, various times are defined.

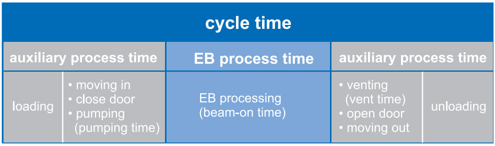


Figure 57: Graphical representation of cycle time, auxiliary process time and EB process time

The times for loading and unloading depend on the workpiece and are therefore not machine parameters. These times should not be considered when different machine designs are compared. They are, however, a component of auxiliary process time and therefore have a big influence on the productivity of the EB machine.

The **cycle time** includes the EB process time and all auxiliary process times and is the sum of all the times required for production of the workpiece. It is a determinant in calculating manufacturing costs.

The **EB process time** is the total time required for the actual EB process. It contains all the time contributions that arise from the start to the end of the process. Auxiliary process times outside this are not included.

The **beam-on-time** is the time during which all the conditions for switching on the electron beam are met and during which the processing with the electron beam occurs.

The **auxiliary process time** is the time required to bring about the prerequisites for the EB process. It is divided into work-piece dependent and machine-dependent auxiliary process time.

The **workpiece-dependent auxiliary process time** is the time required for loading and unloading and, where applicable, for aligning the workpiece on the EB machine.

The **machine-dependent auxiliary process time** is the time for moving the workpiece in and out, operating the doors and the pump and vent times.

Pump time is the time required to create the vacuum in the working chamber required by the EB process.

Vent time is the time required to create standard pressure in the working chamber.

In determining the economics of a machine, the availability for the work process is of great importance.

The availability of a machine is the probability or the measured value, that the machine fulfils certain requirements within an agreed time period (total time). It is a quality criterion of a machine. It is defined in terms of the time during which the machine is available:

$$\text{availability} = \frac{\text{total time - down time}}{\text{total time}}$$

The availability of EB machines is usually in the range 80 to 98 percent.

The **down time** is the period of time in which the machine is not available because maintenance work is being carried out or there is a fault present.

6.2 Machine examples

The following presents a number of machine design types, their typical time parameters and examples of their industrial use.

We distinguish mainly four groups of design of EB machines:

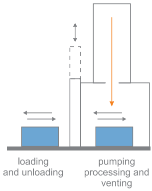


Figure 58:
Chamber machine

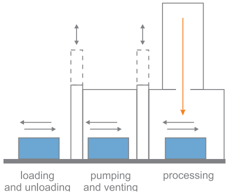


Figure 59:
Load lock machine

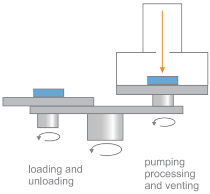


Figure 60:
Cycle machine

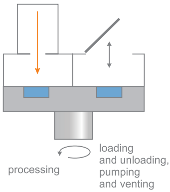


Figure 61:
Load lock cycle machine

6.2.1 Chamber machine

The principle of the chamber machine is the basis of all EB machines. In an enclosed chamber (the recipient) the parts are moved relative to the electron beam by a kinematic arrangement. Access to the chamber is usually through a door covering the whole cross-section of the chamber. Varying designs in which the chamber is opened by doors swinging upwards are also in use. The work chamber ensures booth mechanical strength of the machine in withstanding the working vacuum and protects the machine operator from the X-rays generated by the process. The working vacuum of the machine is usually in the range 2×10^{-2} to 7×10^{-4} mbar and is dependent on the application. For processing reactive materials (e.g. niobium) a vacuum in the range 10^{-5} to 10^{-6} mbar can also be implemented.

The kinematics system used for moving the workpieces within the chamber is very dependent on the task in hand. Standard solutions are a coordinate table installed on the floor of the chamber on which various fixtures can be mounted. The fixtures produce additional movements for rotating, tilting or lifting the workpieces.

A feature of the chamber machine is the high level of flexibility that, with appropriate kinematic devices, enables virtually any type of part to be processed. The cycle time of the chamber machine is very dependent on the workpiece-dependent and the machine-dependent auxiliary process time. For each processing cycle the entire chamber volume has to be evacuated and vented. The duration of pumping time for the chamber is directly related to the investment in the installed pump power.

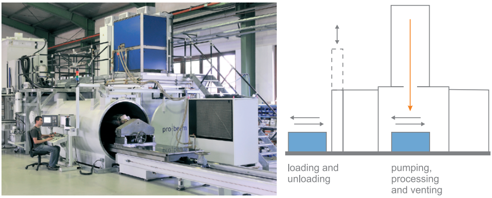
Figure 62: Chamber machine K7 (chamber volume 700 l).

Figure 62 shows a chamber machine of compact design. All the components required

for operation of the machine were mounted on a base frame. The work chamber is accessible through a sliding door. The EB generator is installed on the top of the chamber. By making it possible to move the generator the available working space of the chamber can be significantly increased. Typical auxiliary process times for this machine are in the range 5 to 10 minutes, of which the pumping time, depending on the pump equipment and the required vacuum, (2×10^{-2} to 7×10^{-4} mbar) is 1 to 4 minutes.
The advantages of the machine are the low space requirement and its high level of flexibility. By using suitable fixtures, a large variety of parts can be processed. In addition to applications for short production runs, it is an excellent design for research and development departments. A feature of the chamber machine is that the auxiliary process time is a considerable proportion of the cycle time, particularly when the process times are short. Figure 63 shows the tilt & turn fixture of a chamber machine. The fixture is mounted on a coordinate table which is positioned in an X-Y coordinate system by a CNC controller. On this fixture a workpiece can be rotated to any angle under the beam. The auxiliary process times per part can be reduced if several parts can be processed per machine loading. The illustration shows a multi-piece fixture for processing up to 9 pieces.

Figure 63: Tilt & turn fixture (right) and multiple fixture for processing up to 9 pieces (left), guide plate for injection system (centre).

Figure 64: Chamber machine K190 (19 m³ chamber volume).



The shape and size of the chambers are characterised by the pieces to be processed. The machine shown in figure 64 is designed for processing long items. The central unit of the machine is a functional cube that carries the EB generator equipment. Pipes are attached to both sides of the cube to provide the required travel of the workpiece within the chamber. The workpieces are moved linearly (X axis) under the electron beam. Other movements orthogonal to this can be realized by shifting the EB generator horizontally or vertically. Typical auxiliary process times for this machine are in the range 10 to 20 minutes, of which the pumping time, depending on the pump equipment and the required vacuum, (2×10^{-2} to 7×10^{-4} mbar) is 5 to 15 minutes.

The advantage of this machine is the ability to process long axially symmetrical workpieces. By making use of the ability to shift the generator, the available working space is considerably enlarged without affecting the auxiliary process times. Despite the specialization, the machine is suitable for a wide range of workpieces.

Figure 65: Chamber machine K640 (64 m³ chamber volume).

Processing large workpieces requires corresponding chamber capacities, like the equipment shown in Figure 65. In a volume of 64 m^3 the workpieces can be arbitrarily moved under the beam as required on a coordinate table on the chamber floor, with a fixture that has a rotation axis (A axis), a tilt axis (B axis) and a lift axis (Z axis). All the axes are CNC-controlled, that can be superimposed on the beam deflection if required. For loading, the complete fixture can be moved onto the run-out platform with the chamber door open. This enables a crane to be used for loading and unloading.
Typical auxiliary process times for this machine are in the range 15 to 25 minutes, of which the pumping time, depending on the pump equipment and the required vacuum, (2×10^{-2} to 7×10^{-4} mbar) is 10 to 20 minutes.
An application example, shown in Figure 67, is the front bearing housing of a turbofan jet engine for a passenger aircraft type Airbus A380 (Figure 66). This item consists of a number of separate titanium parts that are held in a fixture in the chamber and welded together. The position and geometry of the joints make it necessary to rotate and tilt the item during welding. When the work is done manually the EB processing time for this item is about 8 hours. With the use of automated seam tracking the EB processing time is brought down to less than 4 hours.

Figure 66: Airbus A380 with Rolls-Royce Trent 900 engine.
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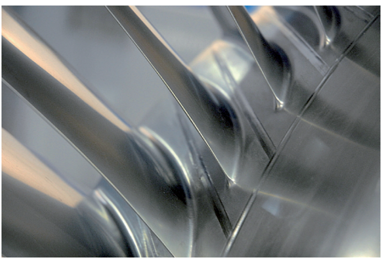

Figure 67: Detail of an automatically welded front bearing housing.

Figure 68: Large-chamber machine type K6000 (chamber volume 630 m3) with internal EB generator on the robot arm (left), EB welding aluminium panels for Ariane 5 (top right), repair of a guide vane carrier of a gas turbine, (centre), rotation fixture with copper vessel, (bottom).

With the processing of very large workpieces, the principle of the EB generator mounted on the exterior of the chamber reaches its limits. With the need for reasonable working distances, the accessibility to the necessary processing locations becomes unachievable. In addition, the complex kinematic requirements for such pieces require a large constructional effort. The solution is to use a movable EB generator in the interior of the work chamber. A robot arm mounted on a gantry on the side wall carries out the movement of the EB generator. The pieces are brought into the chamber on a mobile pallet. Fixtures that can be fitted on the pallet perform

further movements of the workpiece (e.g. rotary devices for rotating the workpiece inside the chamber).
Typical auxiliary process times for this machine are in the range 60 to 80 minutes, of which the pumping time, depending on the pump equipment and the required vacuum, (2 x 10^{-2} to 7 x 10^{-4} mbar) is 30 to 50 minutes. Since the EB process times for working on very large workpieces can be up to 20 hours (long lengths and large welding depths), this still gives a very good ratio of process time to cycle time of over 90 percent.
The big advantage of this type of machine is that the workpiece-dependent auxiliary process times have been parallelised. The workpieces can be fitted and removed in another location independently of the EB machine. The cycle for the EB machine therefore begins immediately when the mounted workpiece is brought into the machine. Since, for workpieces with large volumes, the workpiece-dependent auxiliary process times are often much longer than the process times, the use of several workpiece carriers enables a very high productivity. The principle of the internal EB generator makes the machine flexible and usable for the most varied applications.

Figure 69: Section of a railway frog point welded with an electron beam.

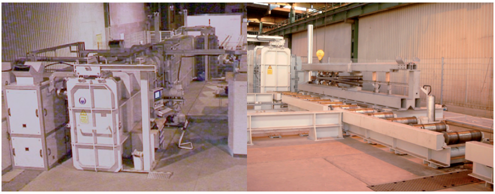

Figure 70: EB machine with special fixture and external transporter system.

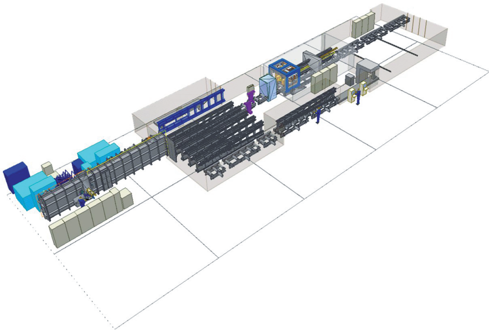

Figure 71: Schematic picture of a complete plant for producing EB-welded railway frog points.

For an appropriate degree of loading of a machine it is sensible to develop a customized design. This will have the work chamber and the kinematic arrangements matched to the specific requirements. The use of several EB generators can also be economical in some circumstances.

Figure 70 shows an example of such a single-purpose system. An application from railway technology opens up for EB welding of standard rail profiles a big potential for the production of railway frog points. The EB machine is a chamber design equipped with two horizontally operated EB generators. By moving the generators the position of the electron beam can be adjusted relative to the location of the joint. The positioning is done online during the EB welding process.

As is shown by Figure 71, the EB machine is only part of the whole system. The technical prerequisites for the pre-weld and the

post-weld temperature treatment require a heating machine to be integrated (UMH - Uniform Magnetic Heating) and a transport system. The design of the installation has the goal of implementing the entire process.
The advantages of the customer-specific solution are the optimum matching to the technical requirements of the process. This enables the increased investment in such a plant to be paid back in a short time by the simultaneous auxiliary process times and as a result a more efficient production.

6.2.2 Cycle machine

Cycle machines are, in their design principle, chamber machines in which a work chamber of the smallest possible size is used with a compact workpiece carrier as part of the work chamber. The machine has two positions: the load-unload position and the working position.
The parts are loaded on the workpiece carrier in the atmosphere. For the feed, standard components are used. Depending on the type of cycle machine, up to 4 pieces can be taken per workpiece carrier. Cycle machines are usually designed as single-purpose machines.

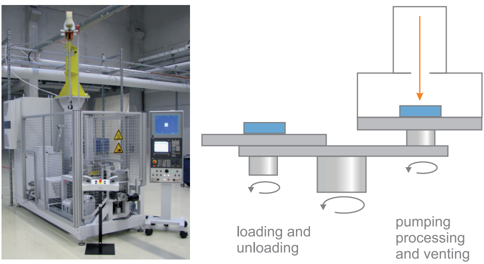

Figure 72:
Cycle machine cell

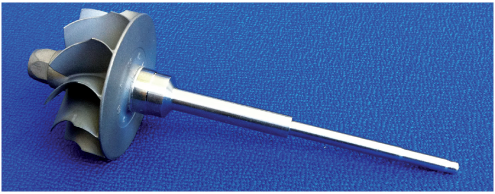

Figure 73: turbo charger shaft and wheel

Figure 74: drive shaft

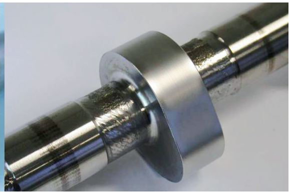

Figure 75: camshaft

The advantage of the cycle machine is the parallelizing of loading and processing. This reduces the auxiliary process time to be in the range 4 to 10 seconds. The compact design of the machine gives a small requirement for floor space. All the components are assembled on a platform that is compatible with containers. The cycle machine is well suited to automation and for sequences of production processes. The machines are characterised by low costs of investment, operation and maintenance. An important factor for the highest possible productivity is that the process time is longer than the auxiliary process time.
The short cycle time makes it possible to implement modern fabrication strategies such as one-piece flow which is particularly applicable in the automotive industry.

6.2.3 Load lock-type chamber machine (shuttle and transfer)

The idea of the load lock shuttle machine is a further development of the chamber machine with the aim of reducing the auxiliary process times. This is achieved by the addition of a lock chamber to the work chamber. The machine therefore consists of:

1. Station for loading and unloading
2. Lock chamber for pumping and venting
3. Work chamber.

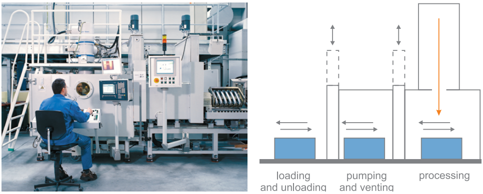

Figure 76: Load lock-type chamber machine, type S20.

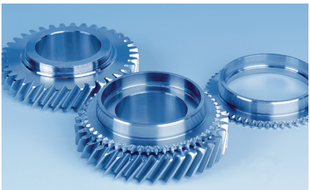

Figure 77: Electron beam welded gear wheel.

Depending on the size of the parts to be welded, one or several workpieces are moved between the stations on pallets or fixtures. There are therefore 3 pallets in circulation.
The workpieces are loaded onto the pallets on the loading-unloading station. The pallet on atmosphere is automatically moved into the lock chamber for the next step. At the same time, on the parallel track, a pallet with processed workpieces is moved to the loading-unloading station. After the lock door is closed the lock chamber is evacuated. For the next step, the pallet under vacuum with processed workpieces is moved out of the work chamber into the lock and on the parallel track a pallet is moved into the work chamber. After the work chamber door is closed, the EB processing can begin immediately, as the work chamber is always kept under vacuum (7×10^{-4} mbar).

For the processing of the pieces, the pallet in the work chamber can be moved over the whole chamber floor by a coordinate table. If additional movements are necessary for processing the workpieces they can be implemented by further kinematic provisions on the pallet. After the end of the EB processing the pallet is moved to the next step into the lock and moved to the loading-unloading position in a further step. The time for the lock step is mainly determined by the EB time required for processing the pieces.

The big advantage of this design is that not only the workpiece-dependent auxiliary process times can be simultaneous, but also the times for pumping and venting. This reduces the auxiliary process time to the time for moving the pallets in and out and for opening and closing the doors.

Typical auxiliary process times for a load lock shuttle machine with a 2 m^3 work chamber (type S20) are in the region of 30 seconds. Optimal operation is possible if the process time is longer than the lock chamber pumping time (about 60 sec.) and the time for loading and unloading at the first station. Since there is often room for more than 30 workpieces on the pallets, the auxiliary process time per workpiece then falls to under one second. In addition, the ejection of processed parts from the machine is easy to plan.

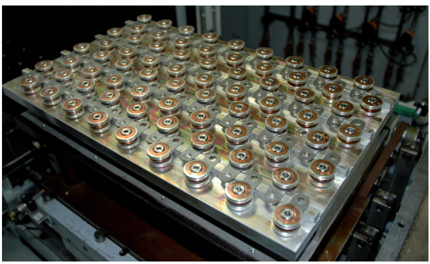

Figure 78:
Pallet of a load lock shuttle machine with 72 workpieces.

6.2.4 Load lock cycle machine (rotary indexing)

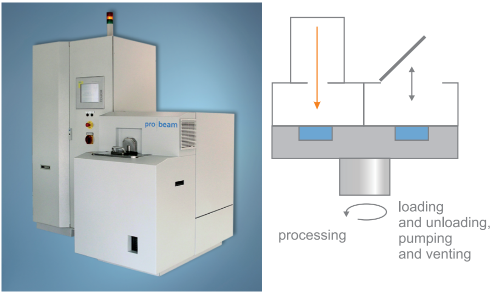

Figure 79:
Load lock cycle machine

The load lock cycle machine combines the efficiency of the load lock shuttle with that of the cycle machine.
Optimised for processing small workpieces, the typical chamber volume is 4 to 60 dm^3. The machine has two stations:

1. Loading and unloading station
   (also acts as lock)
2. Work station

After evacuation the pieces are brought by means of a rotary table into the work station under vacuum. Usually, the machine is operated with single-piece flow.
The advantages of the machine are short auxiliary process times due to the simultaneous loading and unloading and EB processing. Typical auxiliary process times of the machine are in the range 3.3 to 4 seconds. For efficient operation the EB process time should be longer than the pumping time in the loading and unloading lock station (about 3 to 8 sec.).

An application example of a load lock cycle machine is the GearCell shown in Figure 80. The system welds gear wheels for transmissions fully automatically. The entire production process requires a series of process steps such as parts recognition, washing, joining, heating, EB welding, brushing and concentricity check, to name only the most important. These steps are performed by individual modules. In the GearCell they were mounted on a platform corresponding to the production flow. Handling the pieces between the stations is done by standard components. The EB welding with the load lock cycle machine is one processing step in the whole process.

The advantage of this solution is a compact system that represents the whole manufacturing process. The very short cycle time makes it possible here too to implement modern fabrication strategies (one-piece flow) which are particularly applicable in the automotive industry.

Figure 80:
Production system, type GearCell, as a part of the production line for gear wheels.

7. Cost considerations and comparison with other manufacturing technologies

In considering and selecting manufacturing technologies, the costs are always, in the end of prime importance. The questions put in the following section and the remarks about the answers are intended to help the user to develop the right strategy when considering the costs. Specific calculated examples are not included because the external influence conditions must always be accurately described in a proper approach to this matter.

7.1 Are there alternatives to electron beam welding?

There are some products for which the use of electron beam welding is indispensable or for which technically there is no alternative. The answers to the following questions or combinations of them can lead to a unique characteristic of electron beam welding.

1. Is welding in a vacuum essential for the material or material combination?

2. Are there suitable filler materials on the market?

3. Is electron beam welding prescribed for the manufacturing because the parts are subject to qualification and only approved in conjunction with the process?

4. Is the permissible distortion only achievable with the use of a beam welding process?

5. Can the required welding depth also be achieved with laser beam welding (currently about 10-20 mm)?

The user then has the option of having the parts manufactured by a contract welding service or to invest in own machines. Even if, from an economics viewpoint, the required numbers don‘t appear to justify in-house production, there may be strategic reasons, e.g. shorter delivery times, or maintaining an in-house core competence in welding, that could be decisive. Sometimes the contracting-out of welding work is not possible because the process is an integral part of the manufacturing process (e.g. clean-room conditions for UHV components or sensors) or there are security or confidentiality considerations (e.g. in a research facility or in nuclear technology) that make it out of the question.
In these cases the decision makers are largely driven by the investment costs since the unit costs are wholly linked to them because of the planned under-use of the machines.
The selection criteria for a machine optimised for its intended use and thereby for costs are described in Chapter 6.

7.2 Is laser beam welding more cost-effective?

In the cases where from the technical viewpoint laser beam and electron beam welding give equally good results, the choice of process has to be based on economic considerations. Since this usually concerns mass-production applications, one can assume as a rule that the machines and equipment will be operated fully loaded. The decision makers are then mainly driven by the expected unit costs which, in turn, are influenced by the investment costs, availability, the expected life cycle of the products combined with the life expectancy of the machines, and the operating costs.

The investment costs for the beam sources for welding are (without affiliated machines), in the laser case, formed from a basic amount and linearly increasing costs per kilowatt (kW) of beam power. Modern laser beam sources such as fibre or disk lasers, that deliver results comparable to those from an electron beam for welding depths up to 20 mm, have a basic price of around € 35,000 (including the fibre and welding optics) plus about € 40,000 per kilowatt (as of 2011). The entry to electron beam technology nowadays begins at 6 kW beam power with prices of € 85,000 for a complete beam-generating system (as of 2011). With these beam sources, welding depths of about 20 mm can be achieved. The welding results then correspond to modern laser sources in the range of 10 to 15 kW. For the electron beam the investment costs in the range considered here are not power-dependent; with laser beam welding they increase nearly linearly with the intended welding depth. Depending on the required welding depth, direct comparison can show the electron beam to be somewhat more expensive for low power, but much more economical at the higher powers. In the manufacture of gearboxes, welding depths of 2 to 8 mm are often required and lasers with 1 to 4 kW beam power are used. In addition to the costs for the beam source there are the costs for the rest of the machine, both for laser beam and electron beam welding. The energy consumption of modern manufacturing equipment is becoming ever-more important.

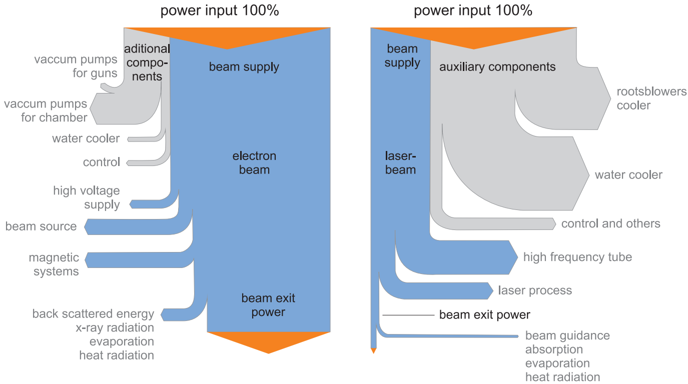

Figure 81: In laser beam welding, depending on the beam source, between 4% (Nd-YAG) and 25-50% (fibre and disk laser) of the consumed electrical energy acts on the workpiece. On the other hand, in electron beam welding, 60-70% of the consumed power can be used for thermal processing. Of all the fusion welding processes, this gives electron beam welding the highest energy efficiency. Source: DVS-ISF Aachen

7.3 Can electron beam welding be cheaper than conventional arc welding processes?

As with electron beam welding, arc welding processes have also developed considerably in recent years and feature a high level of automation. This includes in particular the narrow-gap welding methods (submerged arc (SAW), TIG, MAG) and SAW machines with up to seven wires used simultaneously.
When one looks purely at the welding process in comparing costs in the manufacturing process, seven factors are of great importance:

1. Welding speed and deposition rate (in the arc welding processes)
2. Consumption of filler material per metre of weld length
3. Consumption of energy and special gases (only arc welding)
4. Effort required for weld seam preparation
5. Auxiliary process times during welding
6 Cost per machine-hour
7. Reworking due to distortion

In arc welding the welding speed and the deposition rate are very process-dependent. In addition, the seam preparation, the material itself (e.g. maintaining the correct interpass temperature) and finally the required seam quality have a big influence on the weld times and therefore on the achievable overall weld costs.
In electron beam welding, no filler material at all is required in most cases. This implies that the welding costs are virtually independent of the material to be welded, i.e. welding one metre of stainless steel or titanium costs just the same as welding one metre of structural steel. The additional costs of the process are mainly limited to the power consumption, which is very low when compared to any other fusion welding process. Gases or suitable powders for protecting the weld pool are not required because the vacuum required by the process provides optimal environmental conditions.

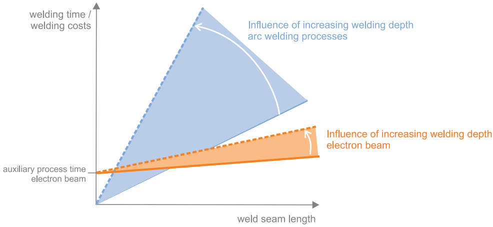

Figure 82: Despite the auxiliary process times required by the process, electron beam welding is often more economical than arc welding processes for increasing welding depths and seam lengths.

Chapter 6 has introduced auxiliary process times for electron beam machines and explained them in conjunction with various machine types. The auxiliary process time shown in Figure 82 for evacuation before welding and venting afterwards can, depending on the machine type, be just a few seconds (e.g. for load lock cycle machines) or up to 60 minutes (for very large chamber machines). During this time the arc welding processes have a certain advantage. Electron beam welding, because of its much greater welding speed, soon catches up however, so that in most cases the time is equalised after a small length of weld seam.

The crossover point for the costs of welding is usually reached later. The gradients of the straight lines in Figure 82 are mainly determined by the costs of investment, the welding depth and the costs of filler materials for arc welding processes. Electron beam welding usually incurs higher investment costs but the costs for filler materials are absent and the welding speed is more independent of the welding depth. The gradient of the line is therefore always very small for electron beam welding, whereas for the arc welding processes it is always steeper with increasing welding depth.

A numerical example:
In electron beam welding of steel with 100 mm welding depth, the welding speed is 8 minutes per metre of weld length (single-layer process). Arc welding processes require, for the same welding task, depending on the method and material, 2 to 5 hours for one metre of weld length (multi-layer process up to 150 layers) and in addition 20 to 30 kg of filler per metre of weld.
Further cost benefits of electron beam welding result from the simple weld preparation (smooth square butt) and the very low finishing costs because of the low distortion. Often reworking is not required and the welding process can then be at the end of the manufacturing chain. At the same time this means that the pieces can be finished on smaller (cheaper) machines before the welding is done.
The basis for deciding on a particular welding process therefore requires the relationships represented in Figure 82 to be quantified with data and facts determined accurately from the application under consideration.

The following statement is always applicable:
„The higher the weld depth, weld length and material costs, the higher is the cost advantage of electron beam welding compared to arc welding methods“

8. The pro-beam group

The pro-beam company was founded in 1974 as an electron beam subcontractor with two employees and two used machines. Today, after over 35 years of continuous growth, pro-beam has the status of a medium-sized company and employs nearly 300 people in four locations in Germany and two in other countries. The company operates over 30 electron beam welding machines, five electron beam drilling systems and a number of PACVD (Plasma-Activated Chemical Vapour Deposition) coating systems.

The electron beam machines have beam powers in the range of 1 to 45 kW and chamber sizes from 0.05 to 730 m^3. The PACVD systems with chamber sizes from 50 litres to 1 m^3 work with RF generators (13.56 MHz) in a power range from 1.2 to 5.5 kW. pro-beam processes orders for its customers on up to seven days a week, partly in three-shift operation. This makes pro-beam the largest electron beam subcontractor world-wide and the only company with decades of experience in the potential application fields of welding, drilling and finishing of surfaces by hardening, remelting and alloying as well as deposition welding by means of electron beam technology. Based on its experience from the wide range of contract work in the first 25 years, pro-beam has specified requirements for machine designs the market was not able to supply. In the past ten years, various machine types in electron beam technology have been developed in-house to production-readiness. pro-beam has beam technology of the highest quality and optimally efficient beam-control technology. Qualitative analyses of weld seams by evaluating various signals can be achieved with standard beam-generating systems. The pro-beam group is currently developing, with over 50 engineers and external institutions, further equipment and processes to open up new fields of application for the electron beam. The aim is to develop the technology-leading position of electron beam welding, electron beam drilling, electron beam surface treatment technologies and our leading position as supplier of systems and thereby secure the market leadership of the group. pro-beam is represented in relevant workgroups of the DVS (Deutscher Verband für Schweißen und verwandte Verfahren e.V. - German Association for Welding and Related Processes), IIW (International Institute for Welding) and DIN (Deutsches Institut für Normung - German Institute for Standardisation). The philosophy of the business is to be a partner with the customer from the statement of the process-technology problem until the end of the life-cycle of a product. To start with, the customer is offered competent advice in relation to topics in process technology, e.g. in the context of the technology of joining. Here the emphasis of pro-beam‘s innovative solutions is on the use of processes using beam techniques, with our own experience from both laser and electron beam technology at the centre of the expertise. When the technical matters have been appropriately addressed, the customer can have test pieces, prototypes and initial samples joined at pro-beam. In addition to individual items, whole runs can then be processed at the contract facilities of the group. From immediate delivery to just-in-time, the supply service is available round the clock when necessary. If a customer wishes to transfer the contract production to an in-house facility, pro-beam can develop the specific machine technology and build and supply it. This will ensure a smooth transfer of the process parameters from the contract operations to the in-house production without associated risks to quality. Temporary renting of plant to our customers when they have a short-term requirement for a high production capacity on their site has already been accomplished a number of times. When the supply of spare parts for a product no longer produced by the customer must be ensured, this can be assured by the pro-beam contract facilities problem-free, economically and to match the requirement. With the strategic approach described, pro-beam has developed from pure development of technical solutions in beam technology to a supplier of services for complex production requirements with the highest demands on quality. Numerous certificates of quality provide evidence of the appropriate expertise. For the future, pro-beam believes that many technical challenges can still be met with innovative processes using beam technology. To fulfil the prerequisites for that and then to implement the individual cases successfully, that is what our claim is about. We hope that with this book we are making a contribution to understanding and propagating the fascinating electron beam technology. It was and remains the central core competence of pro-beam.

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9. The authors of this book

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After reading mechanical engineering at the Technical University of Braunschweig, Volker Adam began his professional career in the company ETN GmbH & Co.KG as leader of the R&D project for a large-chamber electron beam system. From 1992 to 1994 he was the manager of the electron beam technology area at ETN. Appointed general manager in 1994, he expanded the operation to become a high-performance specialist contract welding company. With the integration of ETN GmbH & Co.KG into pro-beam AG & Co. KGaA, Volker Adam was appointed to the board of pro-beam Verwaltungs AG and has since then been responsible for Sales & Marketing and process technology of the pro-beam group. In addition, as manager of the pro-beam application center Europe in Burg/ Magdeburg he manages the world's largest contract site for electron beam technology, which has two of the largest electron beam chamber machines with around 630 m^3 chamber volume and employs nearly 80 staff.

Dipl.-Ing. Uwe Clauß, born 1968
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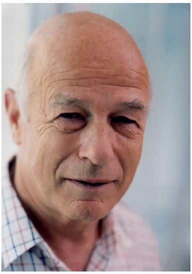
Uwe Clauß read electrical engineering at the Technical University of Dresden and at Heriot-Watt University in Edinburgh, Scotland. His diploma work was done at Harris Semiconductor, Mountaintop, PA, USA. From 1995 to 1997 he was an assistant in the power electronics department of the Technical University of Dresden.

That was followed by a position as sales engineer at HIGHVOLT, Dresden until 2004. During his period there, Uwe Clauß was responsible for developing the sales structure for the North American market during his stay in Manassas, VA, USA. In 2004 Uwe Clauß became a project engineer at pro-beam Anlagenbau GmbH, that was rebranded pro-beam systems GmbH in 2008 and since 2006 he has been responsible there for international sales in machines and installations in addition to contract work. He has implemented projects for electron beam welding machines and drilling systems in Germany and many other countries.



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Dietrich von Dobeneck read physics at the Technical University of Munich, continuing for a further five years as a scientific assistant working in plasma physics under Prof. Krempl. In 1969 he started at Steigerwald Strahltechnik GmbH with responsibility for marketing and electron beam drilling, and there he initiated rotogravure with the electron beam - a process followed by 25 years of intensive research and development. In 1974 he founded the company pro-beam in Munich as a contract production company with one assistant and two used electron beam machines. In 2001 he handed over the management of business operations to the next generation. In 2010 he received an honorary doctorate of the Technical University Bergakademie Freiberg for his life's work in science related to electron beam technology and for his commitment to the next generation of scientists.

Dr.-Ing. Thomas Bernhard Krüssel, born 1971
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Dr. Thomas Krüssel read mechanical engineering in Hannover. From 1999 to 2001 he led the welding technology department of the chair for materials technology in Dortmund. From 2001 until 2004, he was, among other things, leader of the specialist group for mechanical testing at the Institute of Materials Science in Hannover where he gained his doctorate in 2005 on the subject of „Centrifugal projection coating - iCPC - using the electron beam". Dr. Krüssel has been working for the pro-beam group since 2004. As works manager he planned and coordinated the setting up of pro-beam Verfahrenstechnik GmbH in Halle/Saale that was rebranded pro-beam technologies GmbH at the turn of the year 2008/2009. As its general manager he has been responsible for process development in the pro-beam group since 2009 and is a participant in various research and work-related committees such as DVS (Deutscher Verband für Schweißen und verwandte Verfahren e.V. - German Association for Welding and Related Processes) and the FVA (Forschungsvereinigung Antriebstechnik e.V. - Drive Technology Research Association).

Dr. phil. nat. Thorsten Löwer, born 1966
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Dr. Thorsten Löwer read physics at the University of Frankfurt.
He gained his doctorate at the Max-Planck Institute of Quantum Optics at Garching near Munich and at the University of Frankfurt. From 1991 to 1997 he was a scientific staff member at the Max-Planck Institute of Quantum Optics in the department for high-power lasers and laser plasmas and spent periods of research in Japan and France.
Dr. Löwer has been responsible at pro-beam since 1997 for the research and development area and for pro-beam equipment technology. He participates in working groups of DVS (Deutscher Verband für Schweißen und verwandte Verfahren e.V.), IIW (International Institute for Welding - German Association for Welding and Related Processes) and DIN (German Standards Institute).
He has been a member of the board of the pro-beam group since 2004.

Expression of thanks:
The authors would like to thank the following colleagues for supporting the preparation of the contributions for this book with their expertise:
Mr. Jürgen Fath, Mr. Georg Fischer,
Dr. Michael Maaßen, Mr. Alexander Maaz,
Mr. Eberhard Wagner.