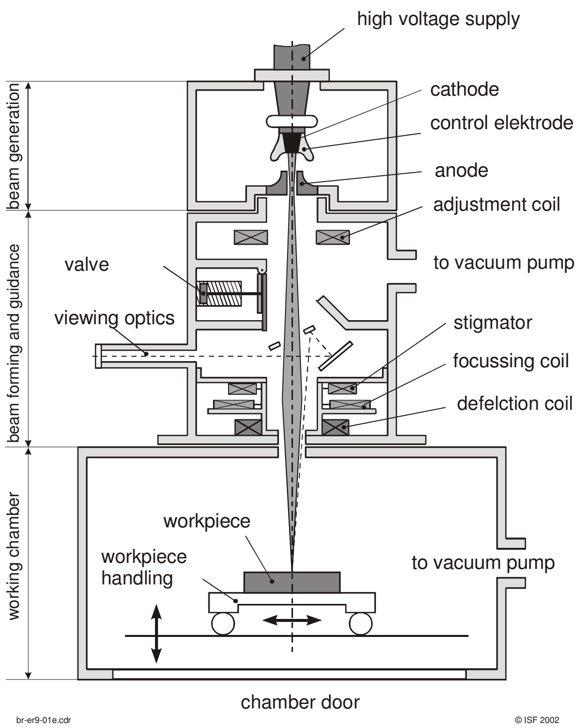
9.

Electron Beam Welding

The application of highly accelerated electrons as a tool for material processing in the fusion, drilling and welding process and also for surface treatment has been known since the Fifties. Ever since, the electron beam welding process has been developed from the laboratory stage for particular applications. In this cases, this materials could not have been joined by any industrially applied high-production joining method.

The electron beam welding machine is made up of three main components:

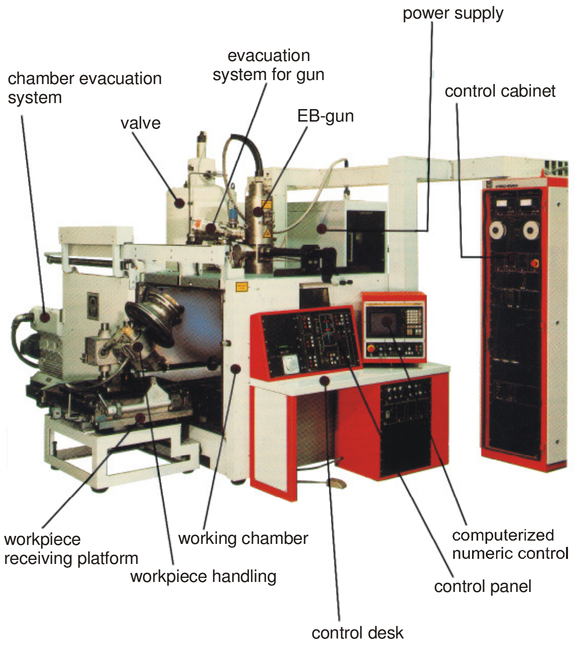
beam generation, beam manipulation and forming and working chamber. These components may also have separate vacuum systems, Figure 9.1.



Schematic Representation of an Electron Beam Welding Machine

Figure 9.1

A tungsten cathode which has been heated under vacuum emits electrons by thermal emission. The heating of the tungsten cathode may be carried out **directly** - by filament current - or **indirectly** - as, for example, by coiled filaments. The electrons are accelerated by high voltage between the cathode and the pierced anode. A modulating electrode, the so-called “Wehnelt cylinder”, which is positioned between anode and cathode, regulates the electron flow. Dependent on the height of the cut-off voltage between the cathode and the modulating electrode, is a barrier field which may pass only a certain quantity of electrons. This happens during an electron excess in front of the cathode where it culminates in

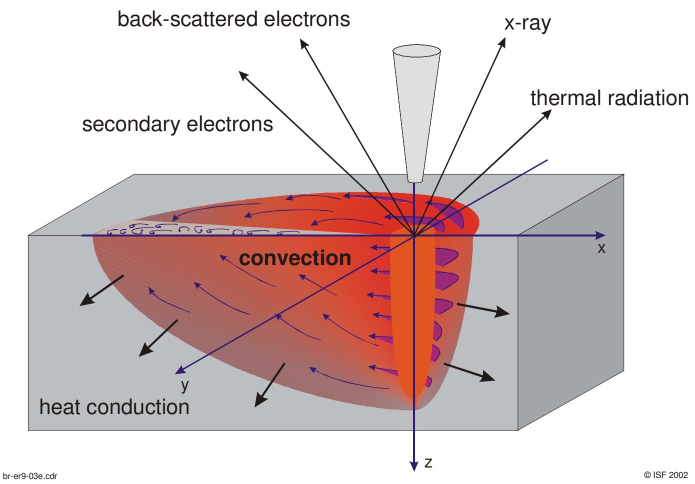


All-Purpose EBW Machine and Equipment

Figure 9.2

form of an electron cloud. Due to its particular shape which can be compared to a concave mirror as used in light optic, the Wehnelt cylinder also effects, besides the beam current adjustment, the electrostatic focussing of the electron beam. The electron beam which diverges after having passed the pierced anode, however, obtains the power density which is necessary for welding only after having passed the adjacent alignment and focussing system. One or several electromagnetic focussing lenses bundle the beam onto the workpiece inside the vacuum chamber. A deflection coil assists in maintaining the electron beam oscillating motion. An additional stigmator coil may help to correct aberrations of the lenses. A viewing optic or a video system allows the exact positioning of the electron beam onto the weld groove.

The core piece of the electron beam welding machine is the electron beam gun where the electron beam is generated under high vacuum. The tightly focussed electron beam diverges rapidly under atmospheric pressure caused by scattering and ionisation development with air. As it would, here, loose power density and efficiency, the welding process is, as a rule, carried out under medium or high vacuum. The necessary vacuum is generated in separate vacuum pumps for working chamber and beam gun. A shut-off valve which is positioned between electron gun and working chamber serves to maintain the gun vacuum while the working chamber is flooded. In universal machines, Figure 9.2, the workpiece manipulator assembly inside the vacuum chamber is a slide with working table positioned over NC-controlled stepper motors. For workpiece removal, the slide is moved from the vacuum chamber onto the workpiece platform. A distinction is made between electron beam machines with vertical and horizontal beam manipulation systems.

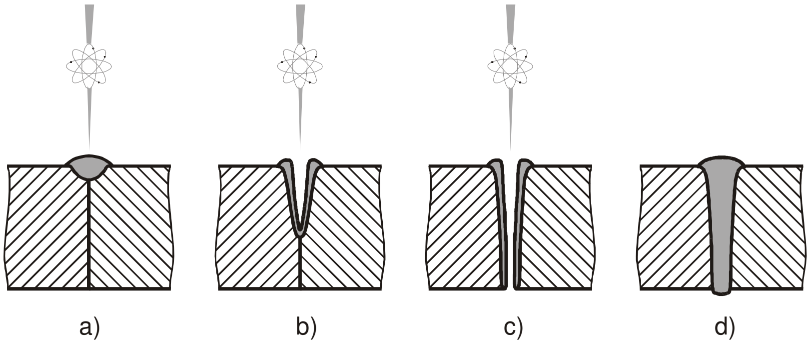


Energy Transformation Inside Workpiece

Figure 9.3

The energy conversion in the workpiece, which is schematically shown in Figure 9.3, indicates that the kinetic energy of the highly accelerated electrons is, at the operational point, not only converted into the heat necessary for welding, but is also released by heat radiation and heat dissipation. Furthermore, a part of the incident electrons (primary electrons) is subject to backscatter and by secondary processes the secondary electrons are emitted from the workpiece thus generating X-rays.

The impact of the electrons, which are tightly focussed into a corpuscular beam, onto the workpiece surface stops the electrons; their penetration depth into the workpiece is very low, just a **few µm.** Most of the kinetic energy is released in the form of heat. The high energy density at the impact point causes the metal to evaporate thus allowing the following electrons a deeper penetration. This finally leads to a metal vapour cavity which is surrounded by a shell of fluid metal, covering the entire weld depth, Figure 9.4. This deep-weld effect allows nowadays penetration depths into steel materials of up to 300 mm, when modern high vacuum-high voltage machines are used.



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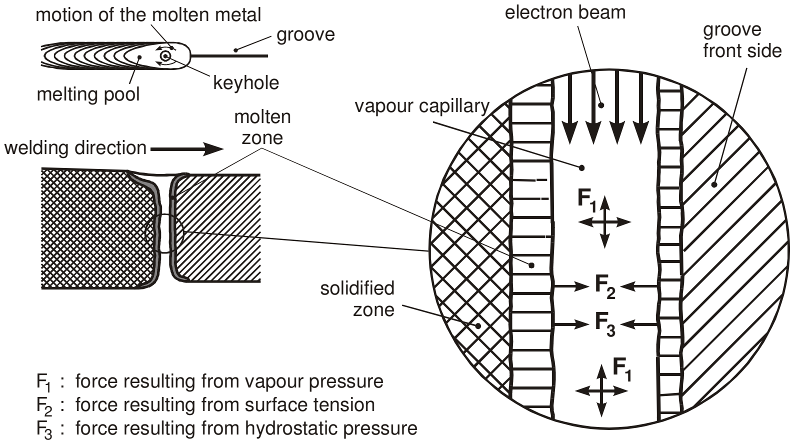
Principle of Deep Penetration Welding

Figure 9.4

The diameter of the cavity corresponds approximately with the beam diameter. By a relative motion in the direction of the weld groove between workpiece and electron beam the cavity penetrates through the material, Figure 9.5. At the front side of the cavity new material is molten which, to some extent, evaporates, but for the most part flows



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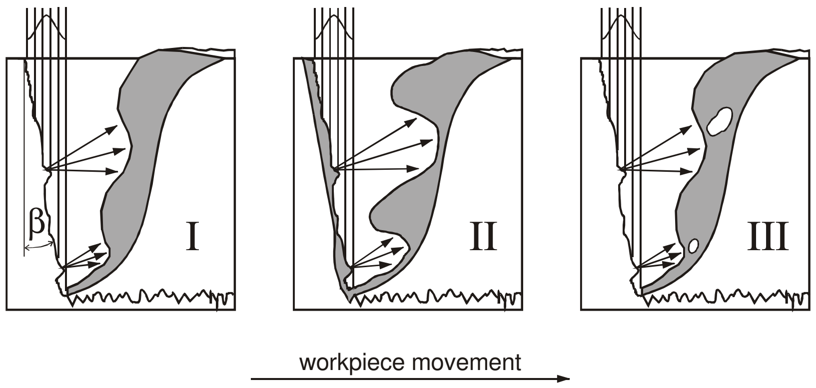
Condition in Capillary

Figure 9.5

around the cavity and rapidly solidifies at the backside. In order to maintain the welding cavity open, the vapour pressure must press the molten metal round the vapour column against the cavity walls, by counteracting its hydrostatic pressure and the surface tension.

However, this equilibrium of forces is unstable. The transient pressure and temperature conditions inside the cavity as well as their respective, momentary diameters are subject to dynamic changes. Under the influence of the resulting, dynamically changing geometry of the vapour cavity and with an unfavourable selection of the welding parameters, metal fume bubbles may be included which on cooling turn into shrinkholes, Figure 9.6.



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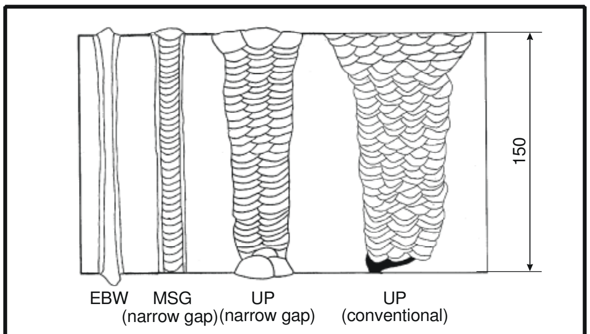
Model of Shrinkage Cavity Formation

Figure 9.6



	EBW	MSG (narrow gap)	UP (narrow gap)	UP (conventional)
welding current	0,27 A	260 A	650 A	510 A
welding voltage	150.000 V	30 V	30 V	28 V
groove area	896 mm^2	2098 mm^2	4905 mm^2	5966 mm^2
number of passes	1	35	81	143
filler metal	0	23 kg	54 kg	66 kg
melting efficiency	7,7 kg/h	5 kg/h	13 kg/h	9 kg/h
energy input	$64 \cdot 10^3$ kJ	$128 \cdot 10^3$ kJ	$293 \cdot 10^3$ kJ	$377 \cdot 10^3$ kJ
welding time	27 min	4 h 35 min	4 h 11 min	7 h 20 min

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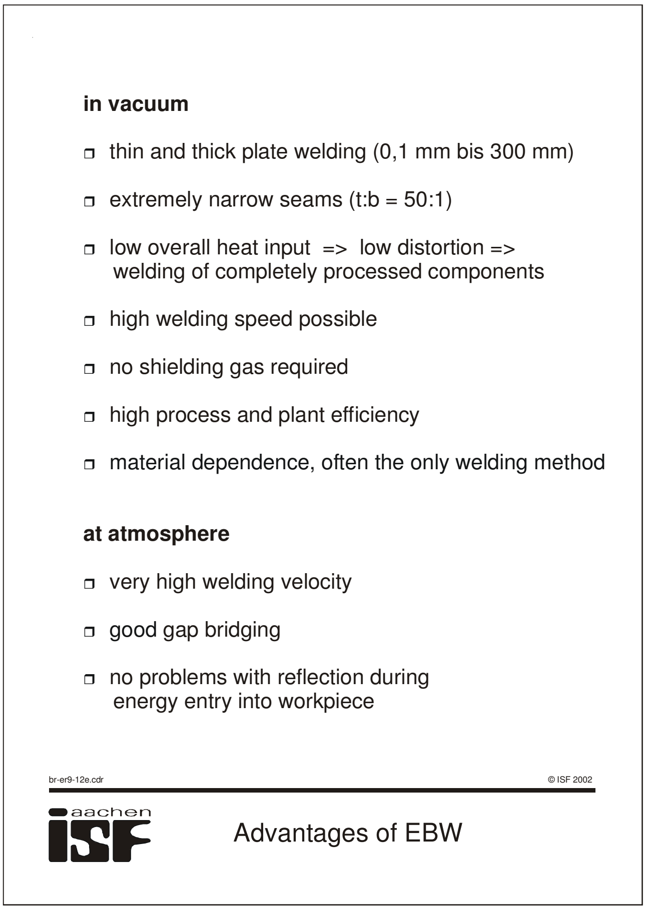
Comparison of EB, GMAW and SAW-Narrow Gap and Conventional SAW

Figure 9.7

The unstable pressure exposes the molten backside of the vapour cavity to strong and irregular changes in shape (case II). Pressure variations interfere with the regular flow at the cavity backside, act upon the molten metal and, in the most unfavourable case, press the unevenly distributed molten metal into different zones of the molten cavity backside, thus forming the so-called vapour pockets. The cavities are not always filling with molten metal, they collapse sporadically and remain as hollow spaces after solidification (case III). The angle ß (case I) increases with the rising weld speed and this is defined as a turbulent process. Flaws such as a constantly open vapour cavity and subsequent continuous weld solidification could be avoided by selection of job-suitable welding parameter combination and in particular of beam oscillation characteristics, it has to be seen to a constantly of the molten metal, in order to avoid the above-mentioned defects. Customary beam oscillation types are: circular, sine, double parabola or triangular functions.

Thick plate welding accentuates the process-specific advantage of the deep-weld effect and, with that, the possibility to join in a single working cycle with high weld speed and low heat input quantity. A comparison with the submerged-arc and the gas metal-arc welding processes illustrates the depth-to-width ratio which is obtainable with the electron beam technology, Figure 9.7. Electron beam welding of thick plates offers thereby decisive advantages. With modern equipment, wall thicknesses of up to 300 mm with length-to-width ratios of up to 50 : 1 and consisting of low and high-alloy materials can be welded fast and precisely in one pass and without adding any filler metal. A corresponding quantification shows the advantage in regard of the applied filler metal and of the primary energy demand.

Compared with the gas-shielded narrow gap welding process, the production time can be reduced by the factor of approx. 20 to 50. Numerous specific advantages speak in favour of the increased application of this high productivity process in the manufacturing practice, Figure 9.8. Pointing to series production, the high profitability of this process is dominant. This process depends on highly energetic efficiency together with a sparing use of resources during fabrication.



in vacuum

- ☐ thin and thick plate welding (0,1 mm bis 300 mm)
- ☐ extremely narrow seams (t:b = 50:1)
- ☐ low overall heat input => low distortion => welding of completely processed components
- ☐ high welding speed possible
- ☐ no shielding gas required
- ☐ high process and plant efficiency
- ☐ material dependence, often the only welding method

at atmosphere

- ☐ very high welding velocity
- ☐ good gap bridging
- ☐ no problems with reflection during energy entry into workpiece

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Advantages of EBW

Figure 9.8

in vacuum

- ❐ electrical conductivity of materials is required
- ❐ high cooling rates => hardening => cracks
- ❐ high precision of seam preparation
- ❐ beam may be deflected by magnetism
- ❐ X-ray formation
- ❐ size of workpiece limited by chamber size
- ❐ high investment

at atmosphere

- ❐ X-ray formation
- ❐ limited sheet thickness (max. 10 mm)
- ❐ high investment
- ❐ small working distance

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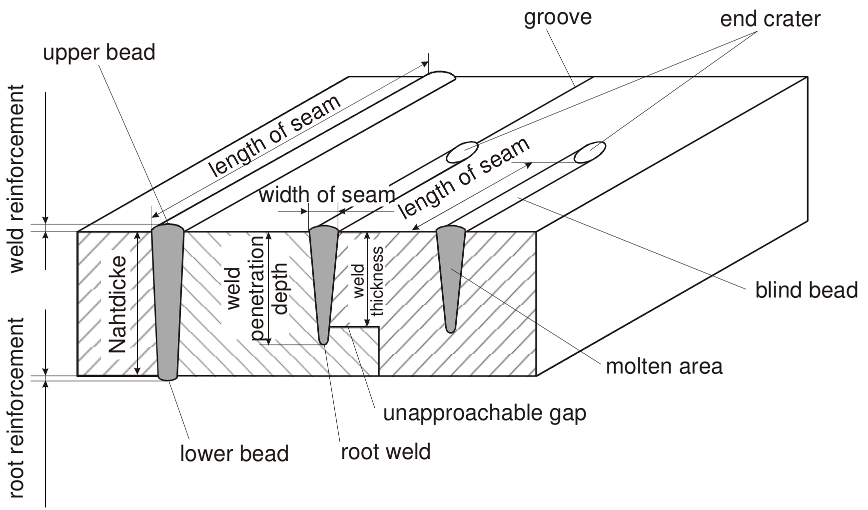
aachen ISF Disadvantages of EBW

Figure 9.9

Considering the above-mentioned advantages, there are also disadvantages which emerge from the process. These are, in particular, the high cooling rate, the high equipment costs and the size of the chamber, Figure 9.9.

In accordance with DIN 32511 (terms for methods and equipment applied in electron and laser beam welding), the specific designations, shown in Figure 9.10, have been standardised for electron beam welding.

Electron beam units are not only distinguished by their working vacuum quality or the unit concept but also by the acceleration voltage level, Figure 9.11. The latter exerts a considerable influence onto the obtainable welding results. With the increasing acceleration voltage, the achievable weld depth and the depth-to-width ratio of the weld geometry are also increasing. A disadvantage of the increasing accelerating voltage is, however, the exponential increase of X-rays and, also, the likewise increased sensitivity to flash-over voltages. In correspondence with the size of the workpiece to be welded and the size of the chamber volume, high-voltage beam generators (150 - 200 kV) with powers of up to 200 kW are applied in industrial production, while the low-voltage technology (max. 60 kV) is a good alternative for smaller units and weld thicknesses. The design of the unit for the low-voltage technique is



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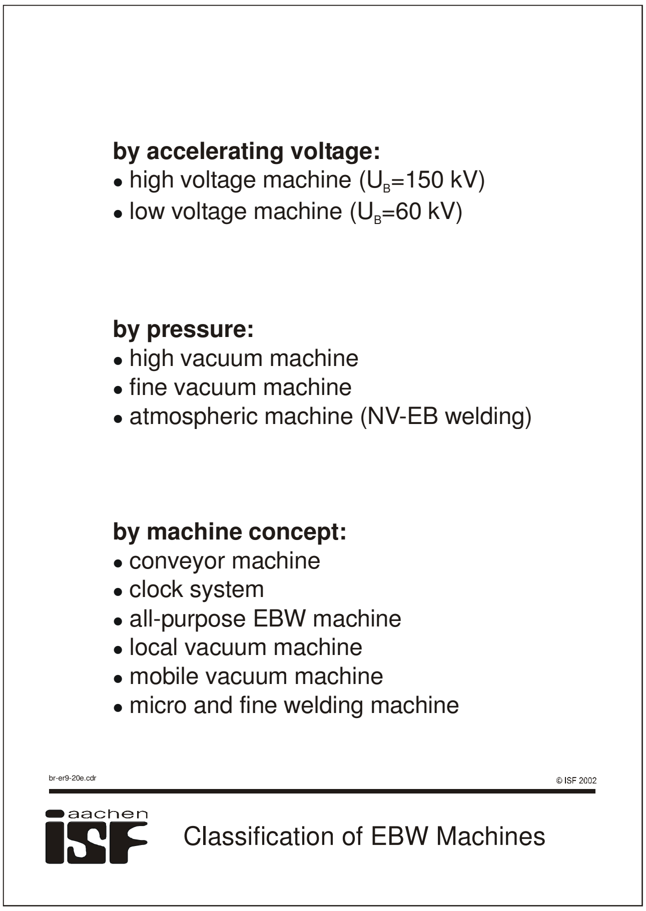
aachen ISF Basic Definitions

Figure 9.10

simpler as, due to the lower acceleration voltage, a separate complete lead covering of the unit is not necessary.



by accelerating voltage:
- high voltage machine (U_B=150 kV)
- low voltage machine (U_B=60 kV)

by pressure:
- high vacuum machine
- fine vacuum machine
- atmospheric machine (NV-EB welding)

by machine concept:
- conveyor machine
- clock system
- all-purpose EBW machine
- local vacuum machine
- mobile vacuum machine
- micro and fine welding machine

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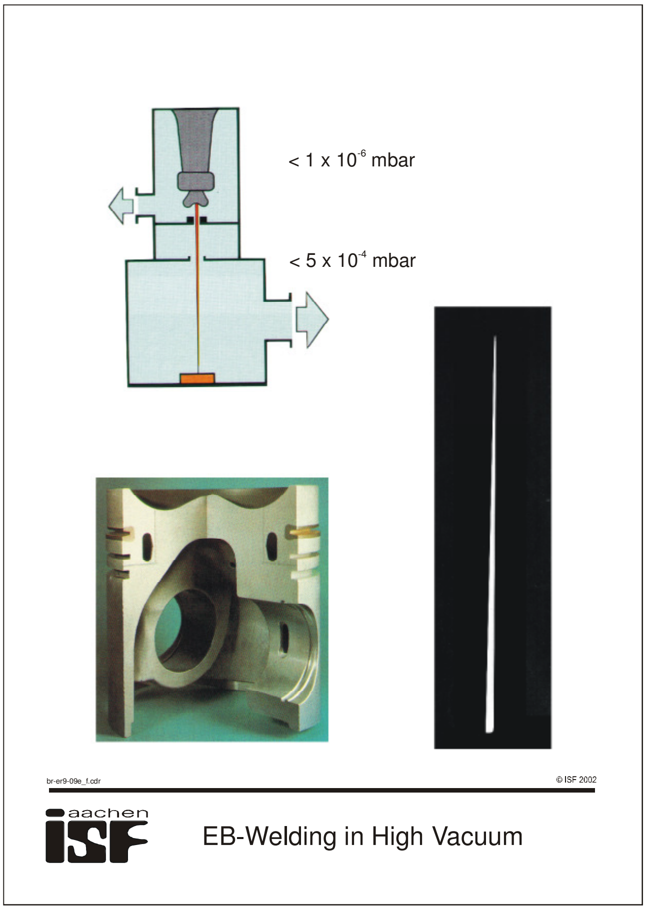
aachen ISF Classification of EBW Machines

Figure 9.11



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aachen ISF EB-Welding in High Vacuum

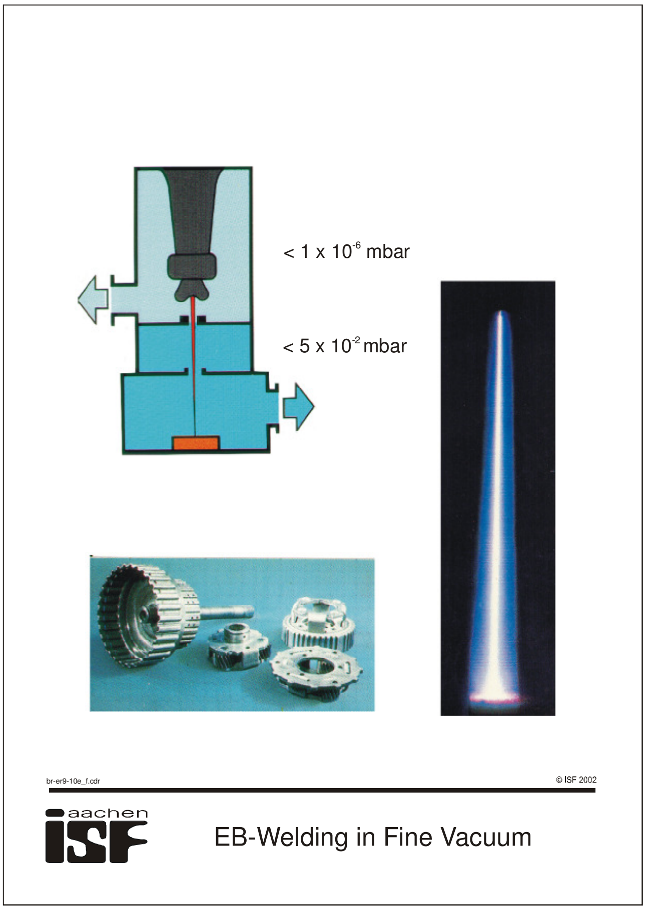
Figure 9.12

While during the beam generation, the vacuum (p = 10^{-5} mbar) for the insulation of the beam generation compartment and the prevention of cathode oxidation is imperative, the possible working pressures inside the vacuum chamber vary between a high vacuum (p = 10^{-4} mbar) and atmospheric pressure. A collision of the electrodes with the residual gas molecules and the scattering of the electron beam which is connected to this is, naturally, lowest in high vacuum.

The beam diameter is minimal in high vacuum and the beam power density is maximum in high vacuum, Figure 9.12. The reasons for the application of a high vacuum unit are, among others, special demands on the weld (narrow, deep welds with a minimum energy input) or the choice of the materials to be welded (materials with a high oxygen affinity). The application of the electron beam welding process also entails advantages as far as the structural design of the components is concerned.

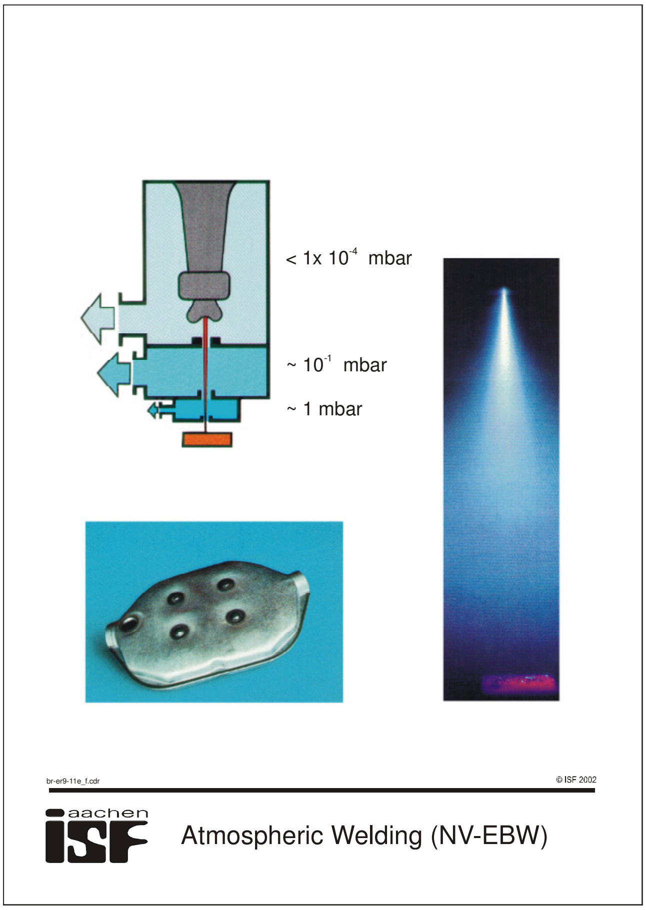
With a low risk of oxidation and reduced demands on the welds, the so-called “medium-vacuum units” ($p = 10^{-2}$ mbar) are applied. This is mainly because of economic considerations, as, for instance, the reduction of cycle times, Figure 9.13. Areas of application are in the automotive industry (pistons, valves, torque converters, gear parts) and also in the metal-working industry (fittings, gauge heads, accumulators).

Under extreme demands on the welding time, reduced requirements to the weld geometry, distortion and in case of full material compatibility with air or shielding gas, out-of-vacuum welding units are applied, Figure 9.14. Their advantages are the continuous welding time and/or short cycle times. Areas of application are in the metal-working industry (precision tubes, bimetal strips) and in the automotive industry (converters, pinion cages, socket joints and module holders).



EB-Welding in Fine Vacuum

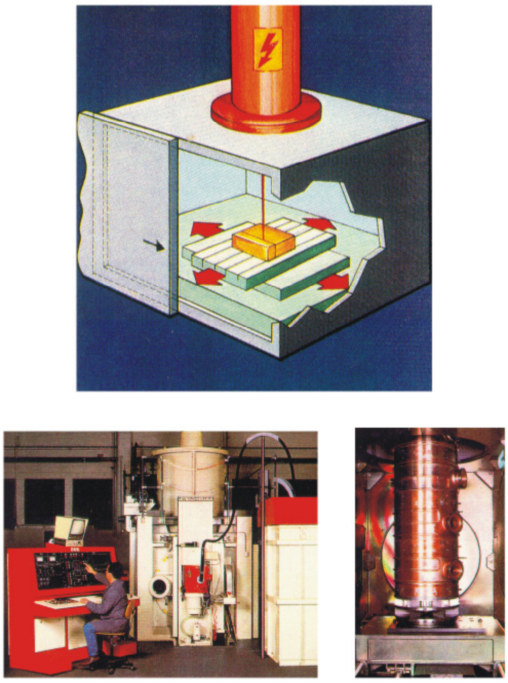
Figure 9.13



Atmospheric Welding (NV-EBW)

Figure 9.14

A further distinction criterion is the adjustment of the vacuum chambers to the different joining tasks. Universal machines are characterised by their simply designed working chamber, Figure 9.15. They are equipped with vertically or horizontally positioned and, in most cases, travelling beam generators. Here, several workpieces can be welded in subsequence during an evacuation cycle. The largest, presently existing working chamber has a volume of 265 m^3.



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aachen ISF Machine Concept - Conventional Plant

Figure 9.15

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aachen ISF EBW Clock System Machine

Figure 9.16

Clock system machines, in contrast, are equipped with several small vacuum chambers which are adapted to the workpiece shape and they are, therefore, characterised by short evacuation times, Figure 9.16. Just immediately before the welding starts, is the beam gun coupled to the vacuum chamber which has been evacuated during the preceding evacuation cycle, while, at the same time, the next vacuum chamber may be flooded and charged/loaded.

Conveyor machines allow the continuous production of welded joints, as, for example, bimetal semi finished products such as saw blades or thermostatic bimetals, Figure 9.17. In the main chamber of these units is a gradually raising pressure system as partial vacuum pre and post activated, to serve as a vacuum lock.

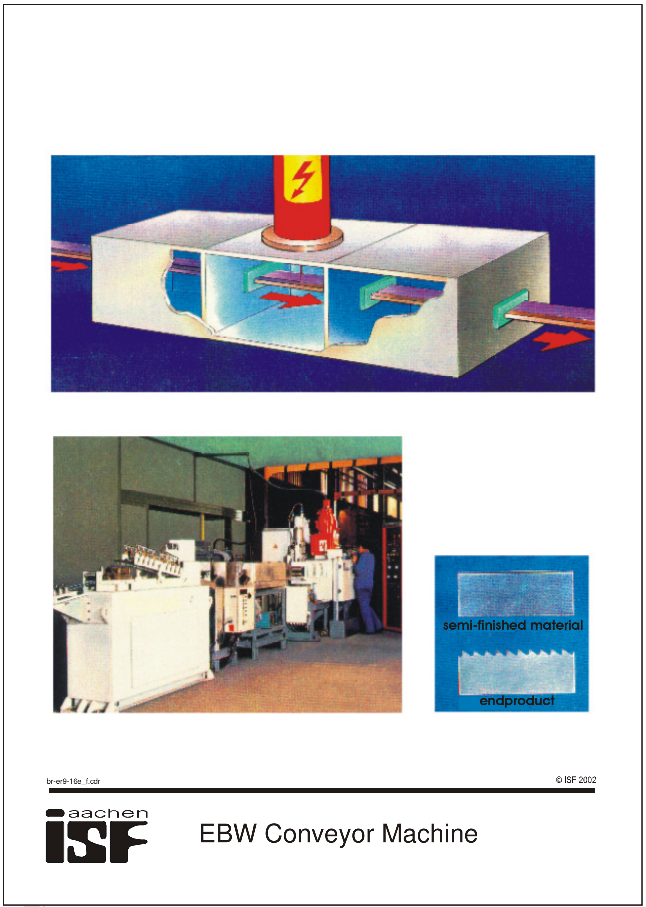


Figure 9.17

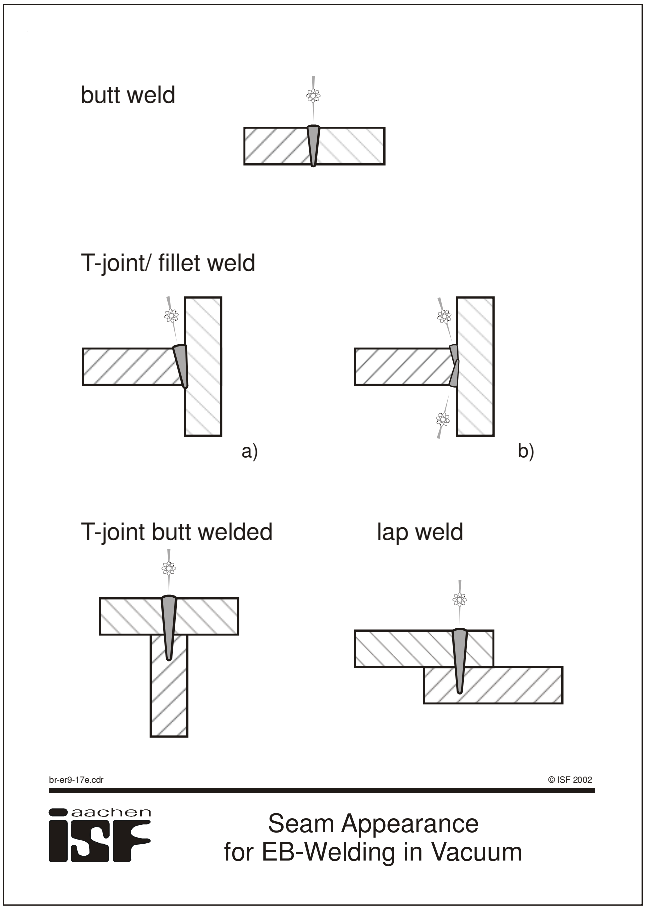


Figure 9.18

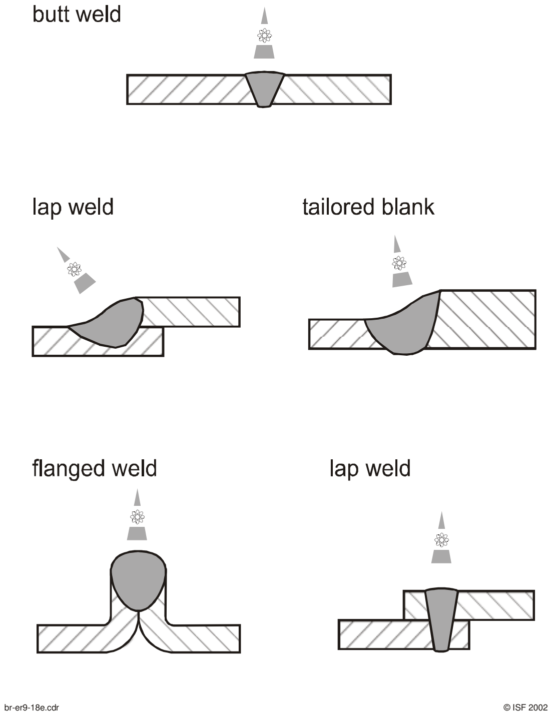
Systems which are operating with a mobile and local vacuum are characterised by shorter evacuation times with a simultaneous maintenance of the vacuum by decreasing the pumping volume. In the “local vacuum systems”, with the use of suitable sealing, is the vacuum produced only in the welding area. In “mobile vacuum systems” welding is carried out in a small vacuum chamber which is restricted to the welding area but is travelling along the welded seam. In this case, a sufficient sealing between workpiece and vacuum chamber is more difficult.

With these types of machine design, electron beam welding may be carried out with components which, due to their sizes, can not be loaded into a stationary vacuum chamber (e.g. vessel skins, components for particle accelerators and nuclear fusion plants).

In general the workpiece is moved during electron beam welding, while the beam remains stationary and is directed onto the workpiece in the horizontal or the vertical position. Depending on the control systems of the working table and similar to conventional welding are different welding positions possible. The weld type preferred in electron beam welding is the plain butt weld. Frequently, also centring allowance for centralising tasks and machining is made. For the execution of axial welds, slightly oversized parts (press fit) should be selected during weld preparation, as a transverse shrinkage sets in at the beginning of the weld and may lead to a considerable increase of the gap width in the opposite groove area. In some cases also T-welds may be carried out; the T-joint with a plain butt weld should, however, be chosen only when the demands on the strength of the joints are low, Figure 9.18. As the beam spread is large under atmosphere, odd seam formations have to be considered during Non-Vacuum Electron Beam Welding, Figure 9.19.

In order to receive uniform and reproducible results with electron beam welding, an exact knowledge about the beam geometry is necessary and a prerequisite for:

- tests on the interactions between beam and substance
- applicability of welding parameters to other welding machines
- development of beam generation systems.



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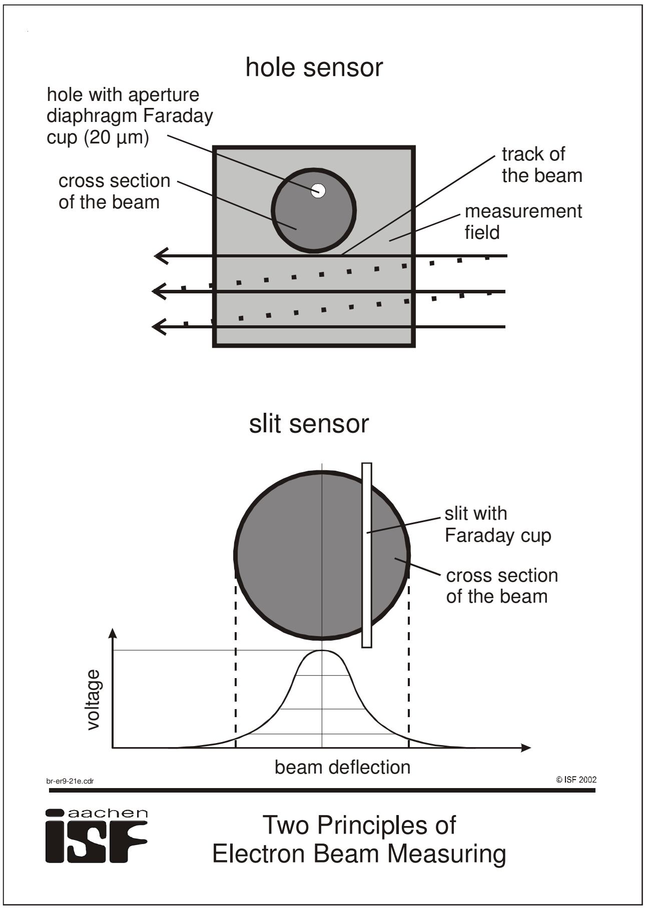
Seam Appearence at Atmospheric Welding (NV-EBW)

Figure 9.19

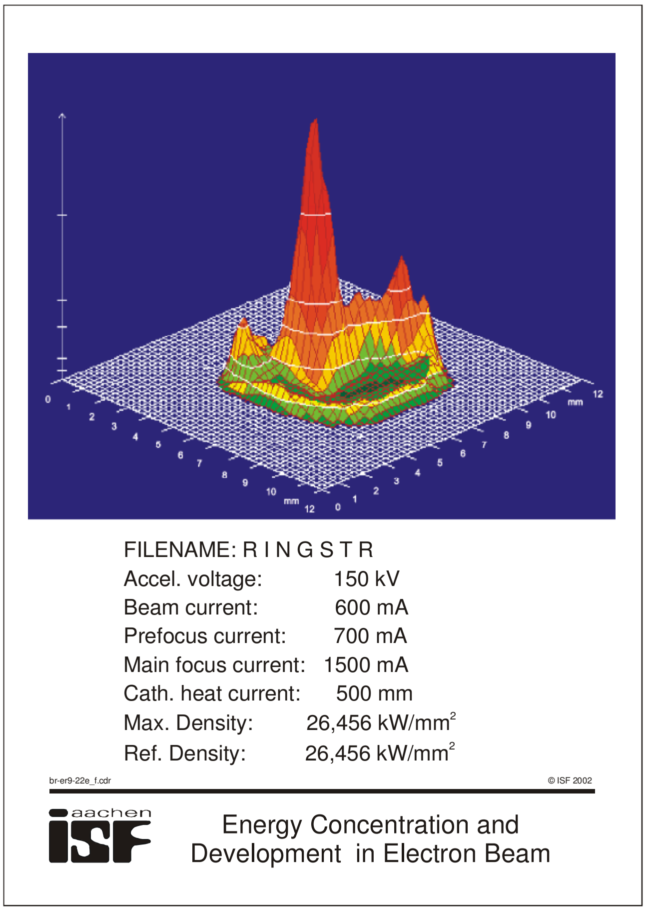
The objective of many tests is therefore the exact measurement of the beam and the investigation of the effects of different beam geometries on the welding result.

For the exact measurement of the electron beam, a microprocessor-controlled measuring system has been developed in the ISF. The electron beam is linearly scanned at a high speed by means of a point probe, which, with a diameter of 20 µm is much smaller than the beam diameter in the focus, Figure 9.20. When the electron beam is deflected through the aperture diaphragm located inside the sensor, the electrons flowing through the diaphragm are picked up by a Faraday shield and diverted over a precision resistor. The time progression of the signal, intercepted at the resistor, corresponds with the intensity distribution of the electron beam in the scanning path. In order to receive an overall picture of the power density distribution inside the electron beam, the beam is line scanned over the slit sensor (60 lines). An evaluation program creates a perspective view of the power density distribution in the beam and also a two-dimensional representation of lines with the same power density.



Two Principles of Electron Beam Measuring

Figure 9.20



FILENAME: RINGSTR
Accel. voltage: 150 kV
Beam current: 600 mA
Prefocus current: 700 mA
Main focus current: 1500 mA
Cath. heat current: 500 mm
Max. Density: 26,456 kW/mm^2
Ref. Density: 26,456 kW/mm^2

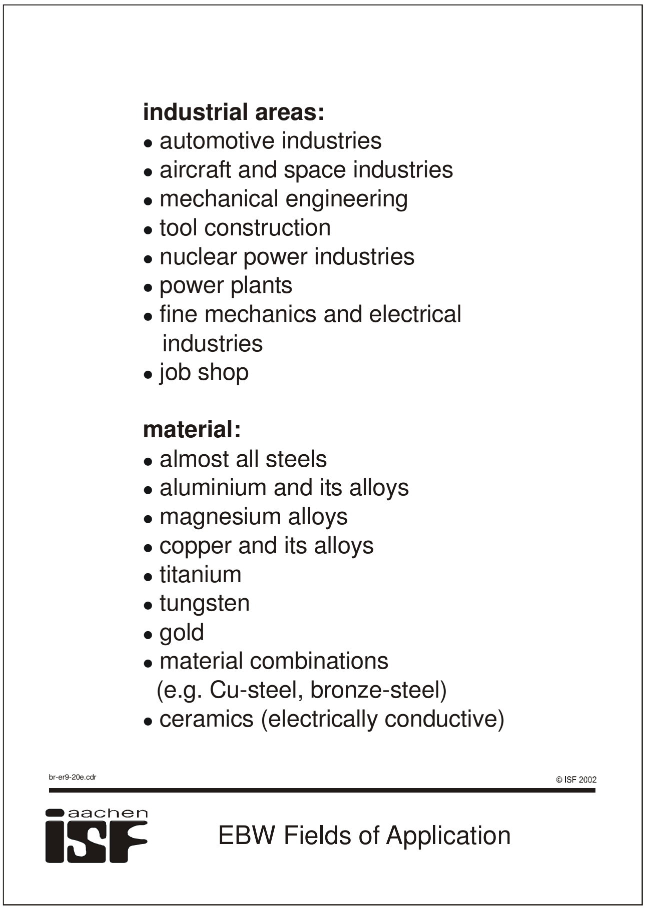
Energy Concentration and Development in Electron Beam

Figure 9.21

An example for a measured electron beam is shown in Figure 9.21. It can be seen clearly that the cathode had not been heated up sufficiently. Therefore, the electrons are sucked off directly from the cathode surface during saturation and unsaturated beams, which may lead to impaired welding results, develop. During the space charge mode of a generator, the electron cloud is sufficiently large, i.e., there are always enough electrons which can be sucked off. In the ideal case, the developed power density is rotationally symmetrical and in accordance with the **Gaussian distribution curve.**

The electron signals are used for the automatic seam tracking. These may be either primary or secondary electrons or passing-through current or the developing X-rays. When backscattered primary electrons are used, the electron beam is scanned transversely to the groove. A computer may determine the position of the groove relative to the beam by the signals from the reflected electrons. In correspondence with the deflection the beam is guided by electromagnetic deflection coils or by moving the working table.

This kind of seam tracking system may be used either on-line or off-line.



industrial areas:

- automotive industries
- aircraft and space industries
- mechanical engineering
- tool construction
- nuclear power industries
- power plants
- fine mechanics and electrical industries
- job shop

material:

- almost all steels
- aluminium and its alloys
- magnesium alloys
- copper and its alloys
- titanium
- tungsten
- gold
- material combinations (e.g. Cu-steel, bronze-steel)
- ceramics (electrically conductive)

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EBW Fields of Application

Figure 9.22

The broad variation range of the weldable materials and also material thicknesses offer this joining method a large range of application, Figure 9.22. Besides the fine and micro welding carried out by the electronics industry where in particular the low heat input and the precisely programmable control is of importance, electron beam welding is also particularly suited for the joining of large cross-sections.