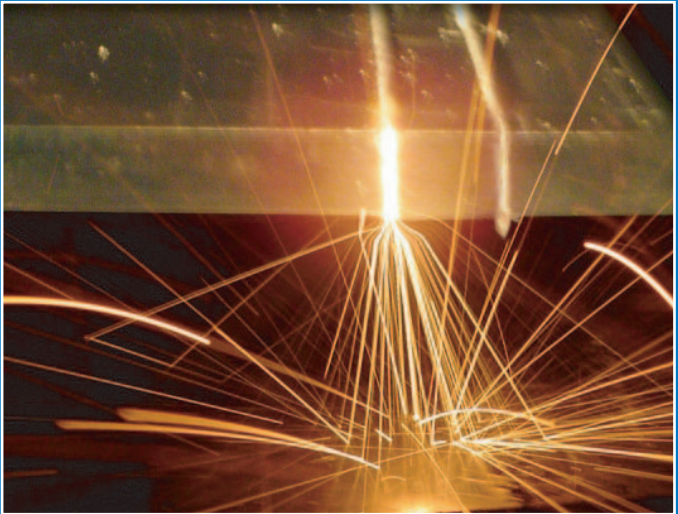# ELECTRON BEAM WELDING

Examples of 30 Years Job-Shop Experience

Dietrich v. Dobeneck

pro·beam

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Dietrich v. Dobeneck:
Electron Beam Welding
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Introduction

Fig. 1: Weld repairs to the MIR space station with a hand held EB gun.
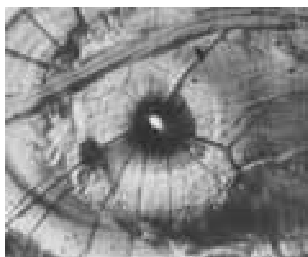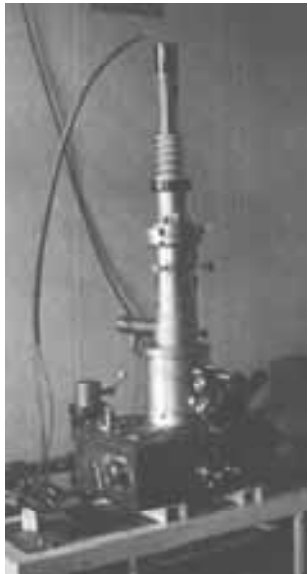
Figs. 2, 3 and 4: The beginnings of EB technology in 1949.

I became aware of Electron Beam welding [EBW] for the first time in 1969 in connection with Russia's Soyuz Space Mission, I knew nothing about this process and yet I was so fascinated, that I decided to build my career on this technology. After refining my skills in development and sales for five years I set up for myself as a welding and drilling job-shop in 1974. I would like to pass on my 30 years of experience of applications and observations. I also want to encourage the reader to make use of the enormous design and economic possibilities by using electron beam welding and also to help to avoid mistakes when you applied to your products.

The first laboratory electron optic gun columns were already in use in 1949 (fig.2), which were similar to electron microscopes; the first hole was drilled (fig. 3) and the first EB weld was performed (fig. 4), but full industrial use of EB welding did not start before the so called "deep welding effect" was discovered. 5 mm deep welds in zircalloy had to be performed for atomic reactors of the submarine Nautilus. Applications in the 1960's were mainly concentrated on reactor technology and aerospace industries. These two industries use reactive materials like titanium or zirconium alloys, which are still in use today and take advantage of being welded under a vacuum. Towards the end of the 1960's the automotive industry recognized the advantage of low distortion welding. Since then more than 1000 EB welders have been manufactured for joining gear components. In these years subcontracting work was mainly related to process development for prototypes and welding of small series. Other EB welded product lines emerged; heart pacemakers or hip prostheses for the medical branch. Many parts in general engineering and electrical components expanded the field of applications. Not before the middle of the 1990's, did the automotive industry and their suppliers began to subcontract large series

welding. A precondition for cost effective welding of large series parts was the development of flexible EB load-lock welding machines. As there are continuously changing requirements in the job-shop, equipment flexibility is an absolute requirement.

The single purpose machines used with automotive OEM's do not suit a subcontractor. Load-lock machines provide a cost effective solution by eliminating idle times required for pumping and venting. Today the scope of delivery is growing by including pre- and post EB operations, like quality control, cleaning, assembly, demagnetizing, preheating and in particular measures for quality assurance and associated documentation. The next change is already on the horizon; embedded production – the parts are not shipped to job-shop for processing, the sub-contractor installs his machines into the OEM's production line and operates them with his own staff. The trend of large industry to outsource difficult processes that are not part of their core competence opens up new chances to service companies, but requires important development efforts in the fields of equipment and processes in order to be cost competitive expected by automation whilst maintaining quality assurance.

Fig. 5: EB welded hip prosthesis from 1963.


Fig. 6: Synchromesh gear from 1964.

Fig. 7: Load-lock shuttle machine with 0.6 m³ vacuum chamber. Automated, rapid exchange of work pieces transferred through the open lock-door (right).

For me personally, this interplay between continuously emerging technical challenges to weld new products from a number of different disciplines, the contact with creative designers or materials experts and the entrepreneurial responsibility to keep the balance between risk and growth constitute the peculiar fascination of electron beam welding.

Fig. 8: Gantry traverse (12 x 6 m)mobile electron beam gun, mounted on a 3 m robot arm.
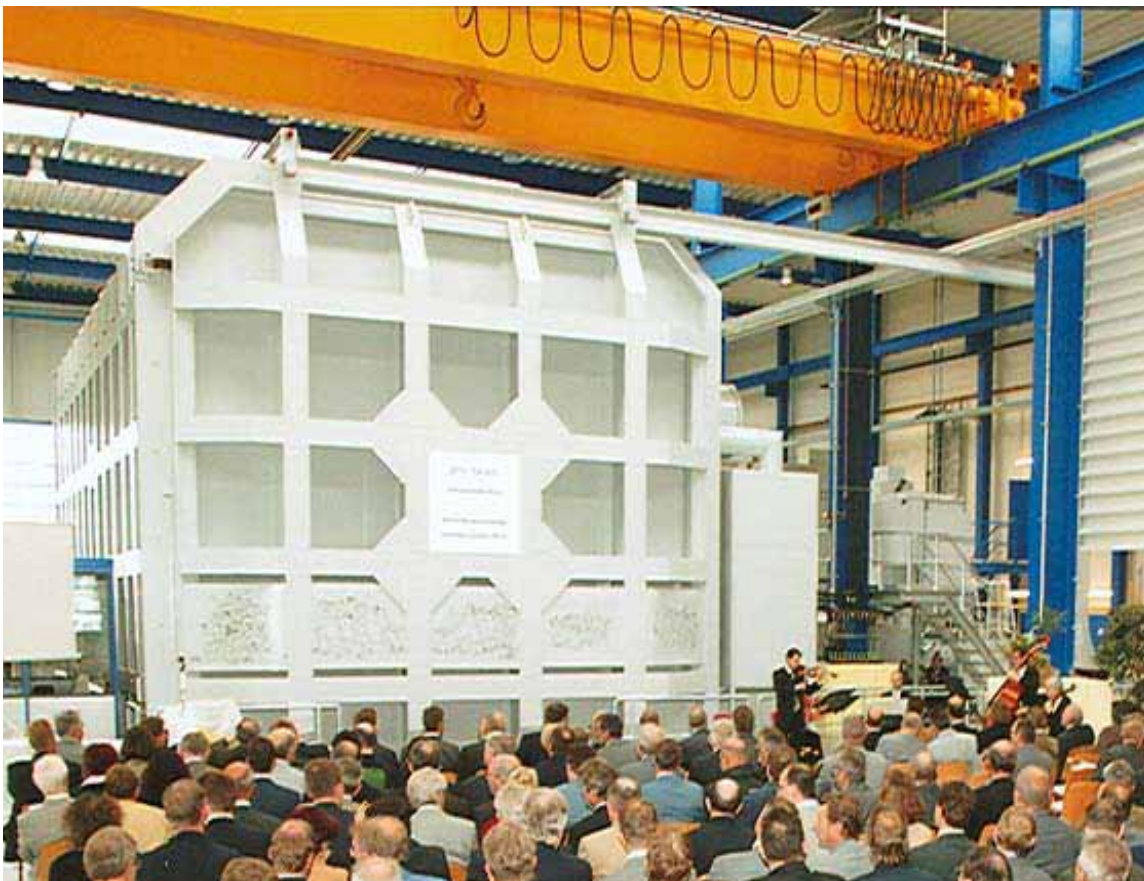
Fig. 9: Inauguration of large chamber electron beam welding machine - Burg 2004. Internal dimensions 7 x 7 x 14 m =630 m³.

Electron Beam welding according to materials

Electron beam welding of steel

The many alloying possibilities of iron with other metals or non-metals provide materials with a multitude of properties for use for a variety of different purposes. In practice, most steels are weldable by means of an Electron Beam without any special requirements such as pre-heating or using filler wire.

Fig. 10: Macro section of a horizontal weld in 200 mm structural steel.
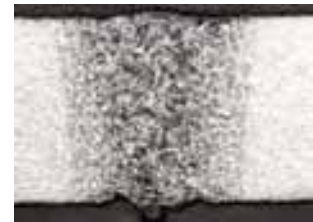
Fig. 11: Sheet metal from St 52.3,1 mm thick.

Fig. 12: Turbine housing made of heat resistant cast steel 15 Mo 3.

Unalloyed and structural steels

Steels with < 0.5% Si, < 0.8 % Mn, < 0.1% Al are defined as unalloyed. Unalloyed steels and structural steels with impurities according to EN 10025 at the upper level of the admissible tolerances for S< 0.05% <P< 0.08% and N< 0.01% are less suitable for EB welding. However with significantly reduced impurities, good welding results up to several hundred millimetres penetration can be achieved (e.g. St 52.3 or Ck 15 (Fig. 10).

Fig. 13: Seams of the clamping fixture.

Fig. 14: Clamping fixture made from St 52.3.

Free cutting steels have are excluded. With increasing killed content of carbon, starting at 0.25%, an increase of hardness has to be taken into account, with carbon above 0.35% (e.g. Ck 45) this is considerable and Ck 60 is only conditionally weldable with reduced thickness.

Fig. 15: Welded construction of a machine frame (St 52.3) as an alternative to using a casting.

Fig. 16: Detail of Fig. 15.

Fig. 17: Annealed sheet attached to a hub made from Ck 35.

Low and high alloyed steels

Low alloyed steels as e.g. fine grained steels, case hardening or nitriding steels (for welding the case has to be removed or not applied in the welding zone), as well as steels for high temperature service, construction steels and most heat treatable steels are readily EB weldable.

Fig. 18: Standard cutting tool with extension bar from 16 MnCr 5. Weld depth 20 mm.

An increased carbon content (>0,25%) and rapidly changing temperature cycle, results in a increased hardening effect. The hardness can be reduced by pre- or post heat treatments.

Fig. 19: The mostly used material for gear combinations in gearboxes is 16 MnCr5.

Steels that are partly sensitive to heat cracking such as CrMo- (Fig. 22) and NiCrMo- (Fig. 23) can be welded by using suitable filler material that at the same time improves toughness.

Fig. 20, 21: Twin gear made from 17 CrNi Mo 6, weld depth 9 mm.

Fig. 22: Macro section 25 CrMo4, weld depth 3 mm.

Many applications in machine building, turbine and gear manufacturing use high strength alloys which can readily Electron Beam welded without post heat treatment. With low alloyed steels with a carbon content between 0.25% to 0.5% (e.g. 34 CrMo 4) an increase of hardness may be expected and with a carbon content above 0.5% Hot and cold cracks (e.g. 100 Cr 6) may also be expected. Depending on shape and size of the joint, e.g. depending on the design, manganese steels like X120 Mn12, or non-magnetic steels (e.g. X40 Mn Cr 185) are EB weldable.

Fig. 23: cross section of a gear made from 21 NiCrMo 2.

Fig. 24: clutch spindle torsionally stiff but flexible for bending- Materials 31 CrMoV 9 or 30 CrNiMo 8.

Fig. 25: 250 mm extension of a cog tube from 42 CrMo 4 V, weld depth 20 mm. A modification to an existing part.

Stainless steels

Most of the stainless and acid resistant steels, such as austenitic, ferritic or duplex steels (Fig. 29, 30) are readily EB weldable.

Fig. 26: Micro-weld of X 22 CrNi 17, 0.5 mm thick with only 100 W beam power (note the coarse grain structure).

Fig. 27: Deep penetration weld in X5 CrNi 18 9, 1 mm wide, 25 mm deep with only 2.7 kW beam power.
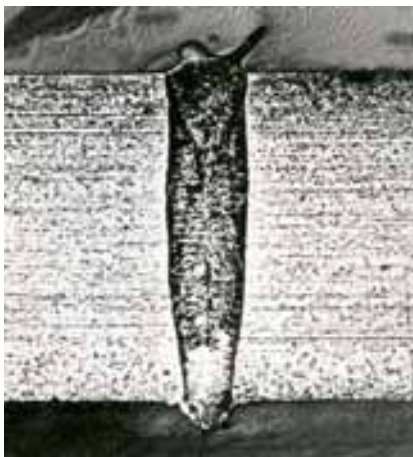

Fig. 28: Weld in X6 CrNiTi 18 10, 3 mm deep beam power 1.1 kW

Fig. 29: Longitudinal tube weld in duplex steel, 7mm wide, and 22 mm deep. Beam power 15 kW.

Nitrogen out-gassing when welding duplex and austenitic steels with high nitrogen, causes porosity and spatter. Heat resistant (e.g. X7Cr 13) and high temperature chromium steels with a nickel content < 2% (e.g. X20 CrMoV 12 1) as well as those with Ni > 2% + Mo (e.g. X12 CrNi 18 8 or X10 CrNiMo T 18 10) are suitable for EB welding. Also precipitation hardenable and martensitic stainless steels are suitable (e.g. X2NiCoMo18 9 5).

Furthermore cold ductile steel with specific heat expansions (e.g. 12 Ni 19 or Ni 36) are readily

Fig. 30: Decanting centrifuge 2.8 m high, weld depth 20 mm, duplex steel X2 CrNiMo N 22 5.

Fig. 31: Valve combinations for the drinks industry. For hygienic reasons, corrosion resistant, smooth seams without undercuts are absolute requirements.

Fig. 32: A narrow, 45 mm deep weld seam in austenitic steel.

Figs. 33,34: High-pressure valves made from hot-working steel.

weldable as well as ledeburitic cold working steels with C content > 1.5% (e.g. X 165 Cr Mo V12 or X 210 Cr 12). Hot working steels like X30 W Cr V 9 3 and 38 CrMoV 5 1 have limited weldability, whereas high speed steels in soft condition like S 6-5-2 or S12-1-4-5 show usually good weldability.

Fig. 35: Filter-module made from stainless steel.

Fig. 36,37: Circumferential weld and top view of a filter module.

Stainless steels have their main field of application in machine construction for food and beverage industry, the pharmaceutical and chemical industry and in construction for petrochemical and offshore industry.

Fig. 38: High-pressure fittings from X6 CrNiMoTi 17 12 2, weld depth 15-26 mm.
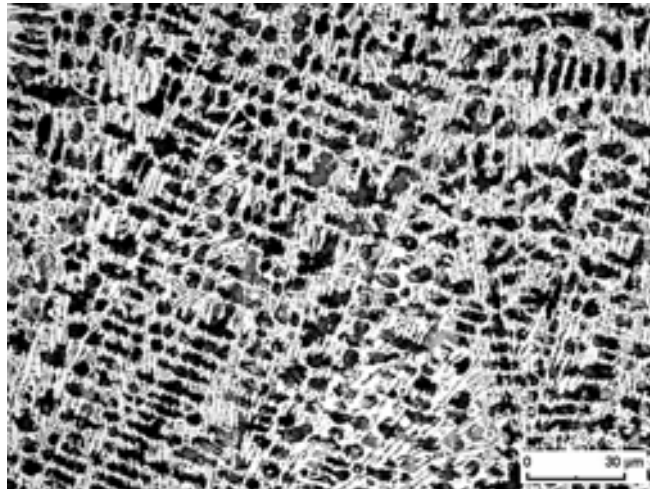

Fig. 39: Detail of Fig. 38.

Cast Iron

Cast iron in form of lamellar cast iron (GGL-25) or spheroidal graphite iron (GGG- 50) and also black malleable iron are not weldable. In combination with other materials, they may be welded with or without filler. (See dissimilar materials (Figs. 110, 111)).
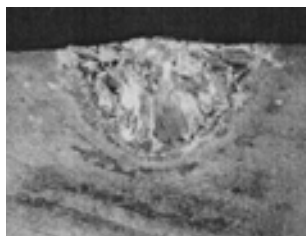

Fig. 40: Tubular porosity in welded GGG 60.

Fig. 41: Ledeburitic structure of rapidly quenched cast iron.

Soft Iron and Silicon Iron

In electric motor or transformer designs there are a number of applications for EB
welding of mild steel or silicon iron. Low penetration with wide seams produce low-loss joints.

*Fig. 42: Fractured surface of silicon iron.*

*Fig. 43: Transformer laminates of silicon iron.*

Electron Beam Welding of Aluminium, Magnesium and their Alloys

Aluminium

Aluminium has an increasing importance for light-weight designs in transportation: in aerospace, automotive, shipbuilding as well as in railroad carriage construction. From the welders point of view not only is the type of alloy important, but also the method of producing the component and it's design. Wrought alloys, both forged or extruded are usually readily weldable. Pure Al, Al Mn, AlMg as well as age hardening alloys such as AlMgSi 1, AlCuMg 1 and AlZn Mg Cu 1.5 are weldable as long as they are not restrained during shrinkage.
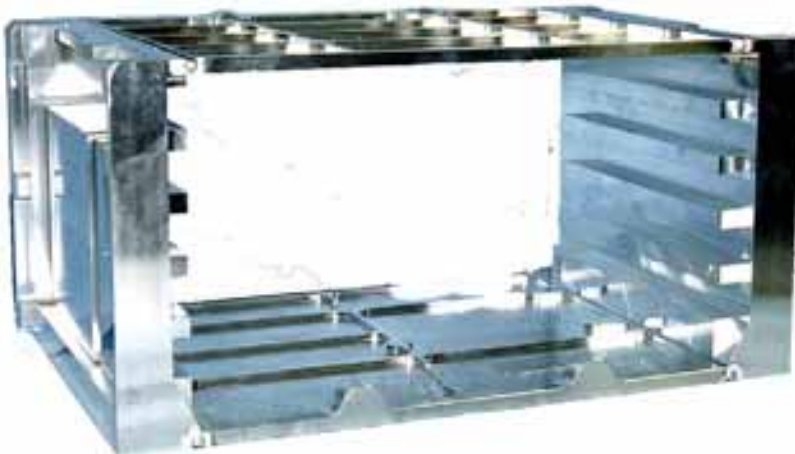
Fig. 44: Precision casing, EB welded from profiled aluminium plates.
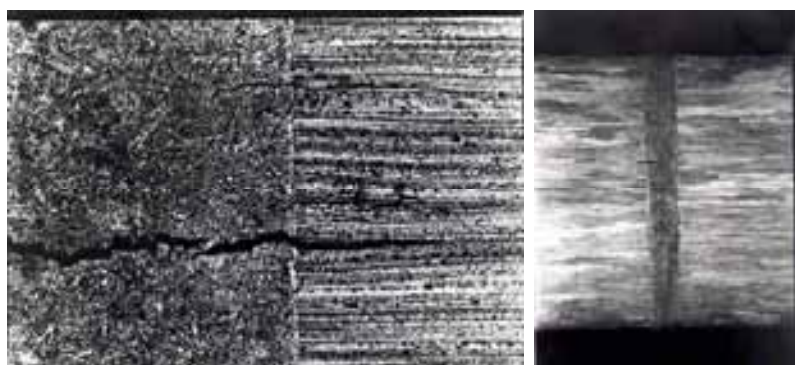
Figs. 45,46: At increased weld depths and higher welding speeds; both hot cracks and shrinkage cracks may occur (AlMgSi 1).
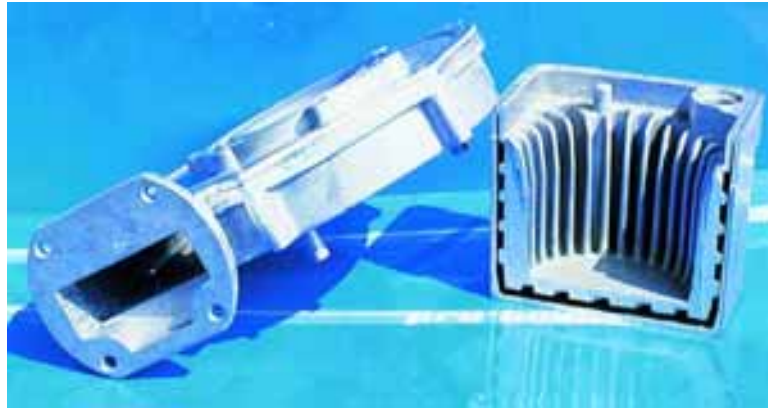

Fig. 47: Aluminium permits extraordinary narrow welds. Examples: 200 mm, 150 mm and 50 mm penetration.

Fig. 48: Heat exchanger fabricated from a pressure cast body and a wrought alloy lid.

Fig. 49: Pump casing (AlSi 12) and heat exchanger (AlSi 10 MgMn) EB welded from pressure cast aluminium.

The weldability of cast materials is dependent on the type of alloy (e.g. G-AlSi 12, G-AlSi 5 Mg,, G-Al MgSi and G-Al Cu 4 Ti) but more important on the casting method. Pressure cast aluminium is difficult to weld because of the inclusion hydrogen and oxygen as a mould release agent during the casting process. The solubility of the enclosed gases in metal increases with higher temperature, as a consequence the gases diffuse into the melt as it cools down. Finally if the gas content exceeds the limit of solubility, it produces pores and/or excess pressure that results in spatter. By welding with 3 overlaid weld beads one run, the gas escapes and porosity disappears. (Fig. 50)
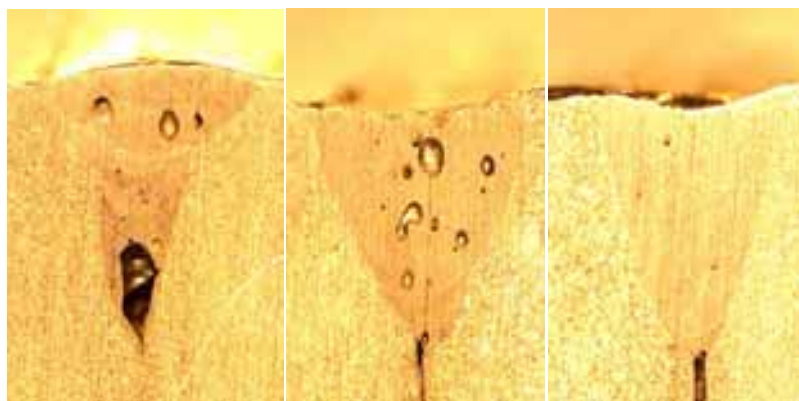
Fig. 50: 2 or 3 overlaid weld beads in one run can eliminate porosity in cast aluminium.
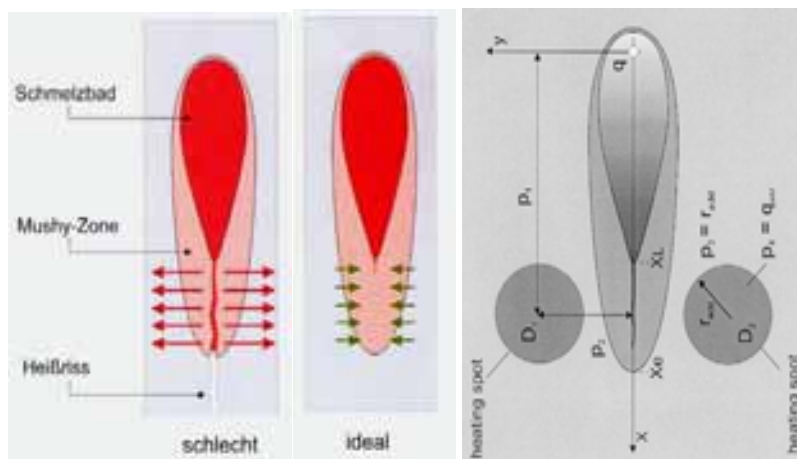
Figs. 51,52: By applying pressure points e.g. by lateral heat sources, cracking can be suppressed.

Fig. 53: Rim of a motorbike wheel made from pressure cast aluminium.

Fig. 54: Cross-section of the rim on which a cosmetic pass can be seen.

EB welding is critical in alloys which are sensitive to hard cracking (6000 series Al-Mg-Si) and alloys the elements of which boil at low temperature and pre-evaporate (5000 series Al-Mg-Mn and 7000 series Al-Zn) They produce a change in alloy composition that may influence the materials properties. Special attention has to be taken with hot cracking materials that, during re-solidification there is no tensile stress set up from restraints (Figs. 51, 52).

Fig. 55: Drive shaft, dia 80 mm, material AlMgSi 1.

*Fig. 56: Microweld in 0.7 mm thick aluminium sheet.*

Radial welds are therefore always preferred as they shrink freely. Surface impurities or oxidation produce adverse reactions especially with micro-welds. Cleaning just before welding improves flow behaviour and uniform wetting of the surface (Fig. 56). With an etched surface a more regular seam has been achieved with half the energy per length element compared one with oxidation.

Magnesium

Magnesium is significantly important as a light-weight material in the automotive and aerospace industry, it is also used widely as screening of high frequency fields in telecommunication. The most common application are as cast alloys and especially pressure castings, however hydrogen solubility is a problem. In both cases of cast and wrought material, the weldability decreases with the increase of alloy elements, because of the susceptibility for hot cracks. Alloys containing 6% to 9% of aluminium and up to 1% of zinc, are however readily weldable (e.g. AZ 91).
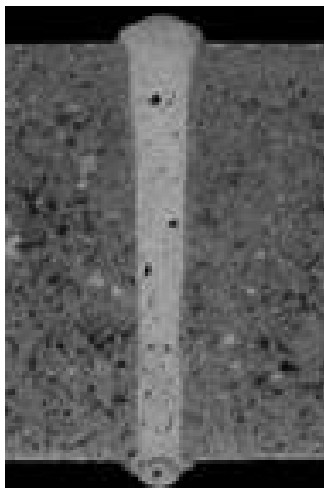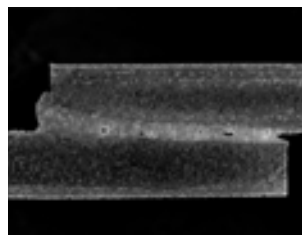

Fig. 57 (left): section through 5 mm thick AZ 91.

Fig. 58 (right): wave-guide for satellite antennas made from AZ 31. The access for internal machining has been sealed by EB welding.
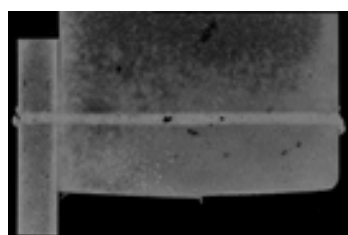
Beam

Figs. 59, 60: The good weldability of pressure cast AM 50 permits interesting design variations (weld depth 20 mm).

Alloys with a content of Zn > 3% (e.g. ZK 60) are not weldable, except the joint configuration can shrink freely. Under these conditions it is even possible to weld ZK 60 (Fig. 62).

Magnesium alloys with aluminium and manganese are weldable as wrought alloys. There is little reliable experience on AS cast alloys (aluminium-silicon) or AE cast alloys (aluminium-rare earths), however it would seem that they can be welded. Single-phase solidifying alloys are weldable, whereas

alloys with low melting additions tend to hot cracking. Magnesium can be EB welding by using multi-pool application similar to that for pressure cast aluminium. Multi-pool welding may also be applied to reduce porosity with magnesium. 80% - 95% of the tensile strength of the base material with reduced ductility is achieved with pressure cast magnesium alloys such as AM 50, AM 60, AZ 91, AS 21 and AE 42 and with the wrought alloys AZ 31 and AZ 61.

Fig. 61: Section through a forged rim of AZ 80 and a cover of ZK 60.

Fig. 62: Rim of a racing car wheel made of AZ 80, radial weld 25 mm deep.

Electron Beam Welding of Copper and Copper Alloys

Due to the high heat conductivity, copper absorbs a lot of energy from the weld zone. As the high power density within an electron beam produces just a small melt volume, this process is ideal for welding copper. In order to keep losses to a minimum, the welding speed has to be maximised. Counteracting high speed welding is the high gas content that mainly appears in electrolytic copper (O_2 and H_2 < 30ppm for weldability) whereas SE, SF and OFHC copper are readily weldable.

Figs. 63, 64: Section through SE-copper ring. Weld depth 35 mm.

Figs. 65, 66: Cooler fabricated from a profiled body and outer sleeve; welded on the end faces.

Fig. 67: Die for continuous steel casting.

Fig. 68: Die made from Cu Cr Zr, weld depth 40 mm.

Copper alloys with alloying elements vaporizing at low temperature such as brass (Cn Zn), nickel silver (Cu Ni Zn) and alpaka (Cu Ni Sn Pb) cannot be welded, but may be brazed with an electron beam. On the other hand, copper alloys such as nickel bronze, tin bronze, aluminium bronze or beryllium bronze are well suited for EB welding. Also copper with low alloying elements such as Cu Be 2.

Figs. 69, 70: There are more than 1000 EB welded clamps of Cu Be 2 in the ASDEX fusion reactor.
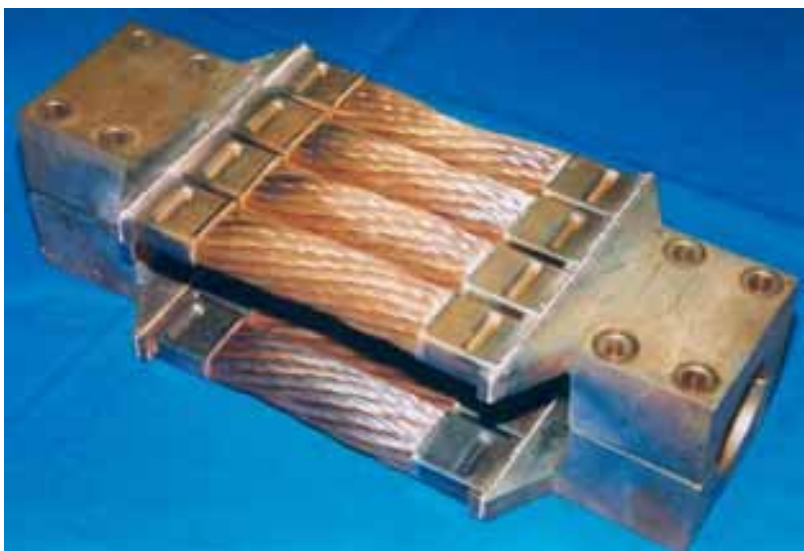
Fig. 71: High current flexible conductors for power distribution, fabricated from multiple copper laminates welded to silver coated connections.

Fig. 72: Detail of Fig. 71.

Fig. 73: High-current flexible conductors for power distribution, fabricated from compressed copper cable braids.

Fig. 74: Detail of Fig. 73.

Fig. 75: High-current conductors with internal cooling used for a tinning plant.

Fig 76: Detail of Fig. 75. Radial weld of a box section, 15 to 40 mm weld depth, CNC controlled.

Because of its good thermal capacity and electrical conductivity properties copper is the preferred material where these attributes can be utilized to the full i.e. high electrical current capacity and heat exchangers.

Fig. 77: Copper radiation absorber used in a solar power plant. Parabolic reflectors and a heat pipe produce super-heated steam to power a turbine.

Figs. 78, 79: Coolers used in experimental research.

Fig. 80: Brass connector with brazed interlayer and welded to copper.

Electron Beam Welding of Nickel- and Cobalt-Alloys

(often referred to as super alloys or high temperature alloys.)

Pure nickel and pure cobalt as well as many of their alloys like Ni Mn 2, Ni Cr 80 20, Ni Cu 30 Fe are readily EB weldable. With conventional welding, the high-alloyed precipitation hardenable nickel base super alloys (e.g. Inconel 718) tend for micro cracking caused by quenching of elements with different eutectic points. However the rapid temperature cycle combined with high chill rates that are typical of EB welding, and the reduced shrinkage due to narrow EB welds tends to counteract the cracking. In order to preserve the high creeping strength of transformation hardening nickel bases super alloys, like Inconel 625 the weld process must not lead to grain refinement. The low heat input with EB welding helps in this respect. Niobium stabilized alloys are sensitive to hot cracking.

Fig. 81: 6 mm deep weld in Nimonic 105.

Fig. 82: More than 400 nozzles made of Inconel 718 or X5 Cr Ni Nb 18 10 are welded into the injection plate of the Ariane rocket.
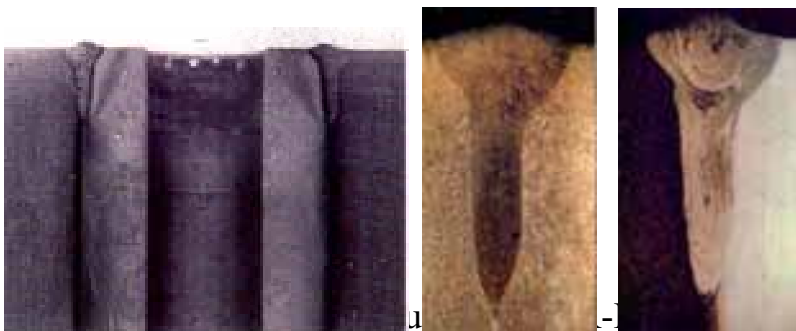
Figs. 83, 84, 85:
Left: weld layout,
centre: Inco 718 to Inco 718,
right: X5 CrNiNb 18 10 to Inco 718.

Heat resistant cobalt alloys (MAR-M 509) and corrosion resistant cobalt alloys (Vitallium, Protasul) are well suited to EB welding. The weldability of wear resistant cobalt alloys (Stellites) depends on their composition, whereas hard cementite metals with a high content of carbides in a cobalt matrix are not weldable.

Figs. 86, 87: Medical implants; pacemakers or hip joints may be fabricated from bio-compatible cobalt alloys.

Reactive and Refractory Materials

Reactive materials like titanium, zirconium, tantalum, vanadium or niobium exhibit a strong affinity to oxygen and hydrogen, especially at elevated temperatures. EB welding under vacuum provide the ideal environment for these materials. It is important, that the entire temperature cycle from melting to solidification and finally to normal temperature is completed under vacuum. Reactive materials in general are welded under hard vacuum conditions i.e.10 – 4 mbar. Niobium, when used as superconducting component in accelerators must be welded at 10 – 6 mbar, as single impurity atoms in the weld seam change the transition temperature of the super conductor, thus causing hot spots.

Fig. 88: Super conductive cavity of an accelerator made of Nb with up to 50 EB welds.

Alpha, near alpha and alpha-beta alloys (e.g. Ti 6 Al 4 V) are widely spread in aerospace industry for critical components. It is important that their

toughness properties are preserved when welding. Because of the low ductility of Ti alloys, residual stresses within the work piece must be avoided. This is achieved by design and by welding with full penetration in solution annealed condition. Impurities, both within the alloy and at the surface of the welding area may influence the seam properties and could produce cracks. Therefore, precise cleaning procedures for critical applications have been established (see specifications DVS 3213).
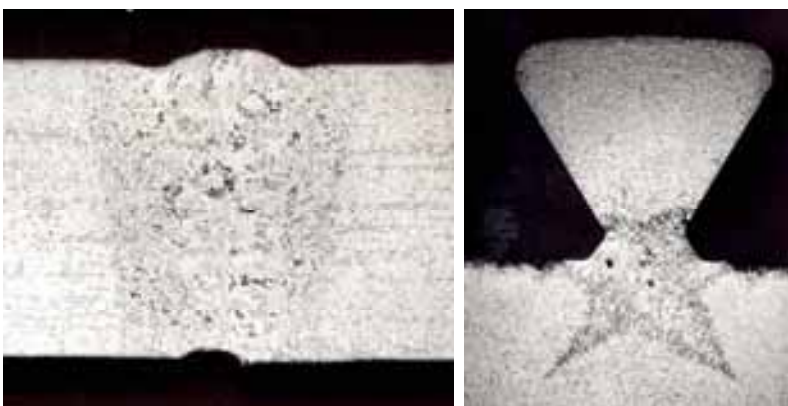

Fig. 89: Upper bead and weld root of a reaction chamber.

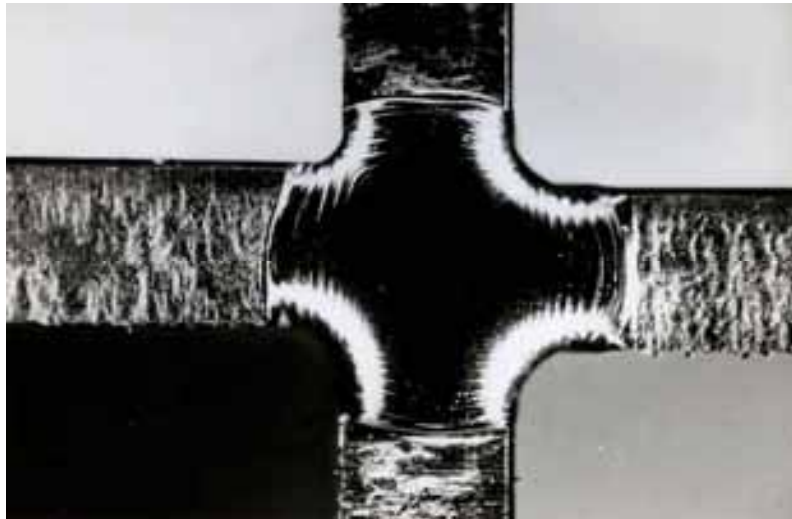*Fig. 90: Reaction chamber made of titanium.*

Fig. 91: Hip prostheses manufactured from titanium alloy.

Figs. 92, 93: Cross section in Ti 5 Al 2,5 Sn and section of a grid for equipment used in the chemical industry (2 fillet welds in Ti 6 Al 4V).
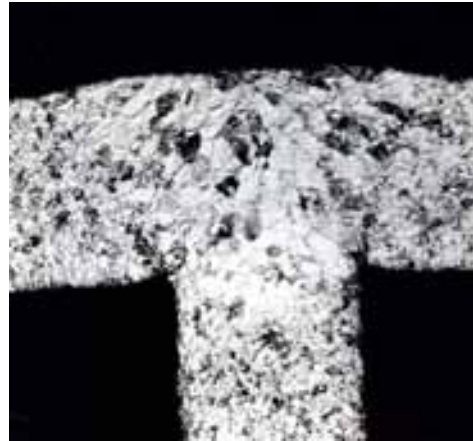
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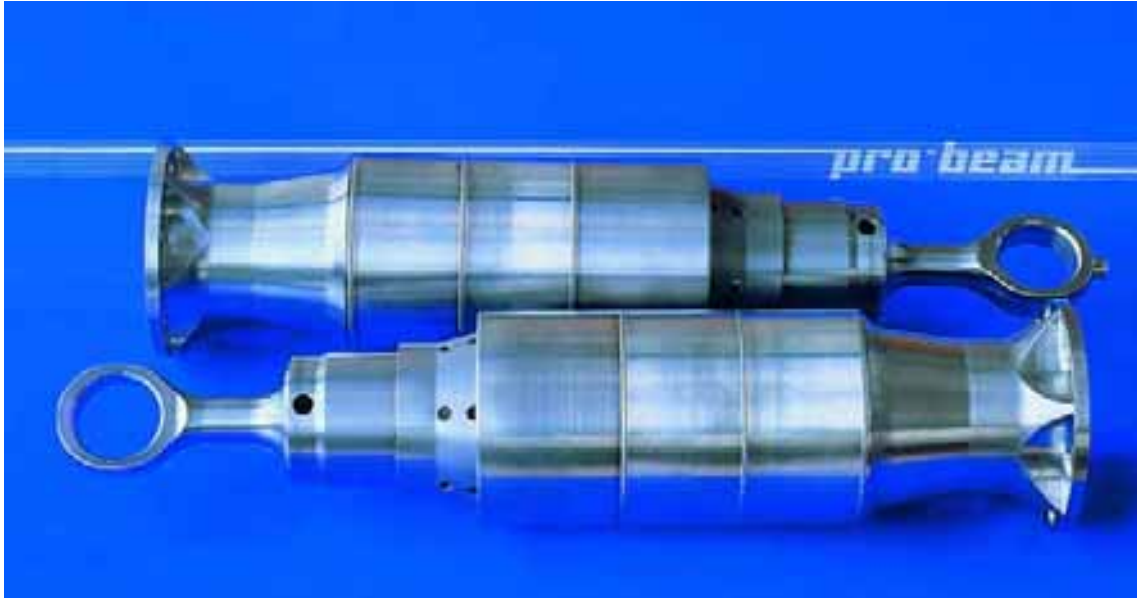
Fig. 94: Helicopter rotor-blade vibration dampers fabricated from 5 EB welded sections.

Fig. 95: Intersection of a fuel rod matrix spacer fabricated from Zr2.
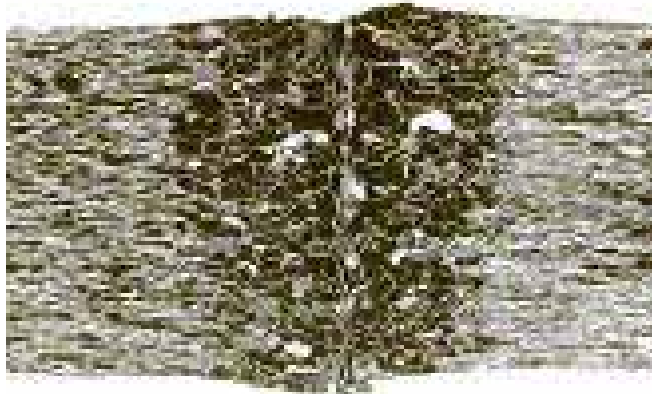

Fig. 96: Zircalloy fuel rod.

Fig. 97: Macro of Fig. 95

Refractory materials become very brittle due to coarse graining resulting from welding, however they may be welded if the thickness is reduced (Fig. 109).

Fig. 98: Tungsten "Flag", wire diameter and flag thickness 0,5 mm, welded with pulsed electron beam.

*Fig. 99: Cross section of a weld in tungsten. Thickness 3 mm.*

*Fig. 100: Cross section of a weld in molybdenum. Thickness 1 mm.*

EB-Welding of Dissimilar Materials

In principle it is possible to EB weld any dissimilar metals to each other, even if their melting points are far apart, but each case has to be individually investigated and tested to see whether resulting weld fulfils the service requirements. Only those metals, which alloy easily with each other are EB weldable without problems. In the case where they produce intermetallic brittle phases, the weld usually does not produce sufficient strength, however it is probably vacuum tight.

Fig. 101: Segment of a cold saw of S6-5-2 welded to Ck 45 in annealed condition. This saves 50% of the expensive high-speed steel.
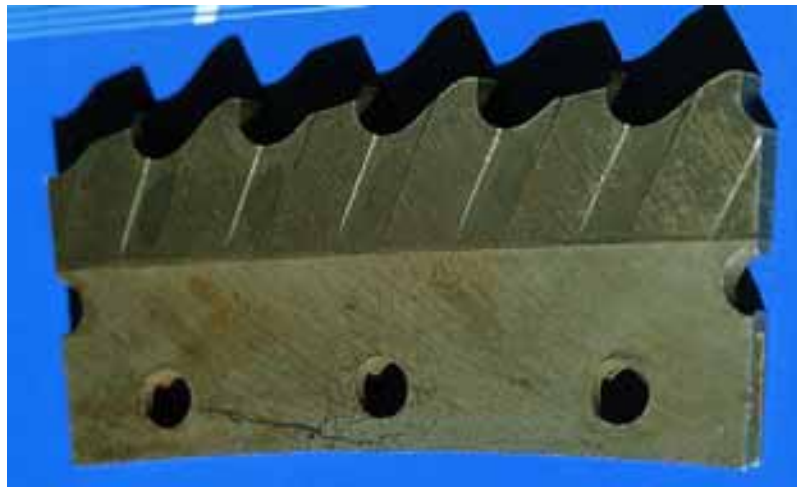
*Fig. 102: St 37 welded to X2 Ni Co Mo 18 9 5, 100 mm thick.*
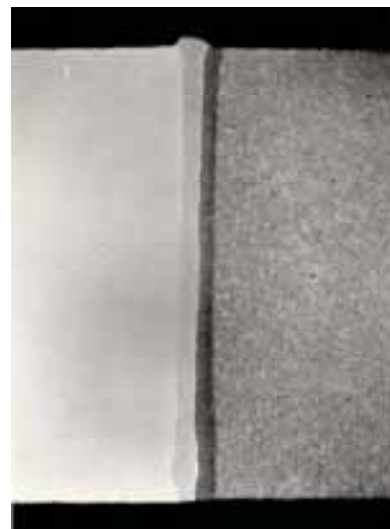
Fig. 103: X18 Cr Ni W welded to 17 Mo V, 14 mm weld depth.

Where there is only a limited solubility of the materials to join (e.g. 2% Fe in Al), it is theoretical possibility to melt 2% iron and 98 % aluminium by offsetting the beam, but a homogeneous mixture

cannot be achieved. There will always be a gradient of concentration towards the basic material, which if it does not fulfil the solubility requirements then will tend to crack. However such super saturated solid solutions often are the basis of improved properties of boundary layers in surface treatment.
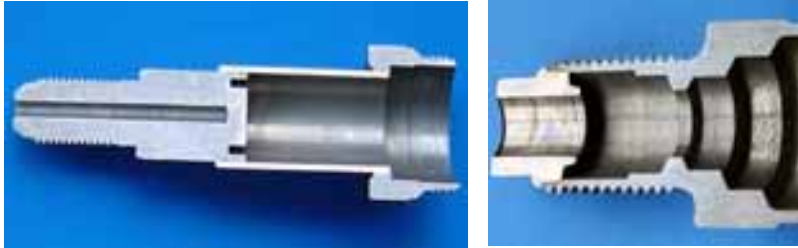
Figs. 104, 105: Typical applications for EB welding austenitic to martensitic steel (so called black and white joints) are solenoid valves.

When welding black and white joints, the low carbon content of the martensitic material suppresses chrome carbide formation. The weld shows good strength. The affected zone of the carbon steel may prove critical due to the temperature cycle annealing a small region and some loss of strength may result. What must be taken into account is that dissimilar materials usually have different thermal expansion coefficients. When the weld cools down, considerable longitudinal stresses (shear forces) will occur that may distort the work-piece. By asymmetric welding, the EB beam is positioned adjacent to the joint centreline, with this procedure distortion may be offset within certain limits.

The four above mentioned materials are usually known as un-weldable, however as dissimilar combinations acceptable EB welds are possible.
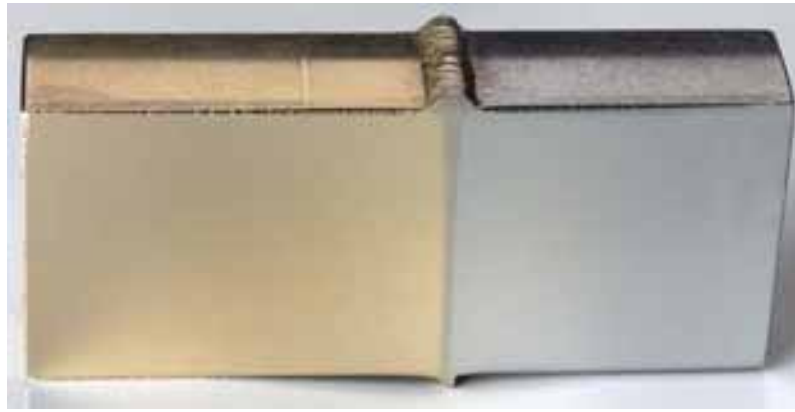
Fig. 106: Turbocharger fabricated from a free cutting steel shaft and an Inconel impeller.

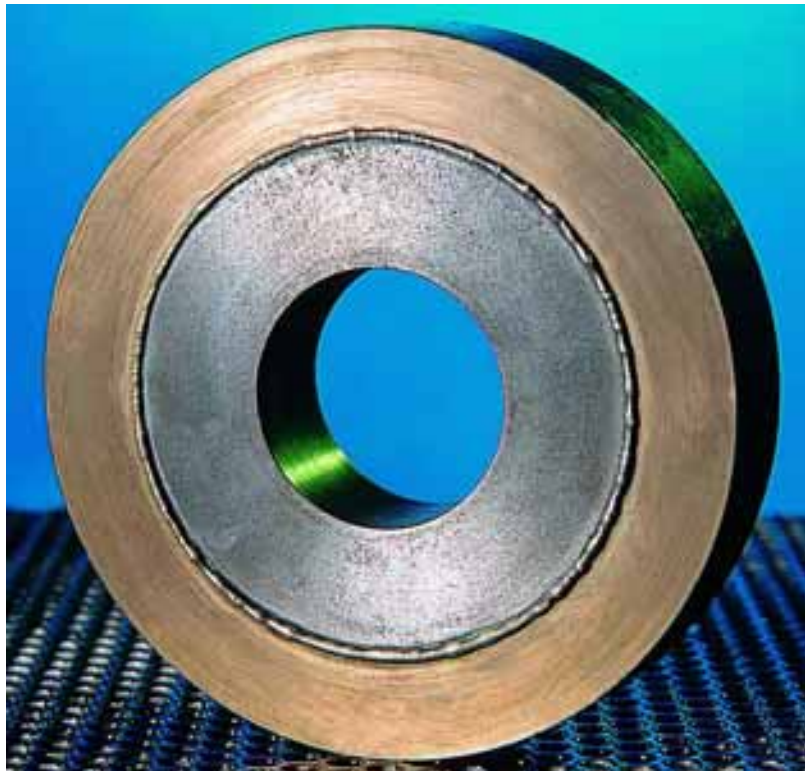*Fig. 107: Rocker lever made of 100 Cr 6 welded to Ck 60.*

Fig. 108: Combination of steel and bronze, 30 mm deep weld.

Fig. 109: Sacrificial cathode: Molybdenum housing with tungsten disc.

Fig. 110: Bronze-steel or bronze-cast iron combinations are an economic method to produce worm gears.

The use of a third material, either as filler metal or as intermediate layer, sometimes may solve a problem. By using a low carbon additive, hardening of carbon steels in the weld zone may be reduced to an acceptable value. With an intermediate layer of vanadium even titanium may be joined with steel.

Fig. 111: Guide rail made of case hardening steel, welded with a nickel filler foil to cast iron.

Degradation of corrosion properties may occur which then must be considered when combining dissimilar materials. Also during welding dissimilar materials thermal currents created by the thermo-couple currents may deflect the EB beam within the work piece by several degrees. This is also true for black and white joints.
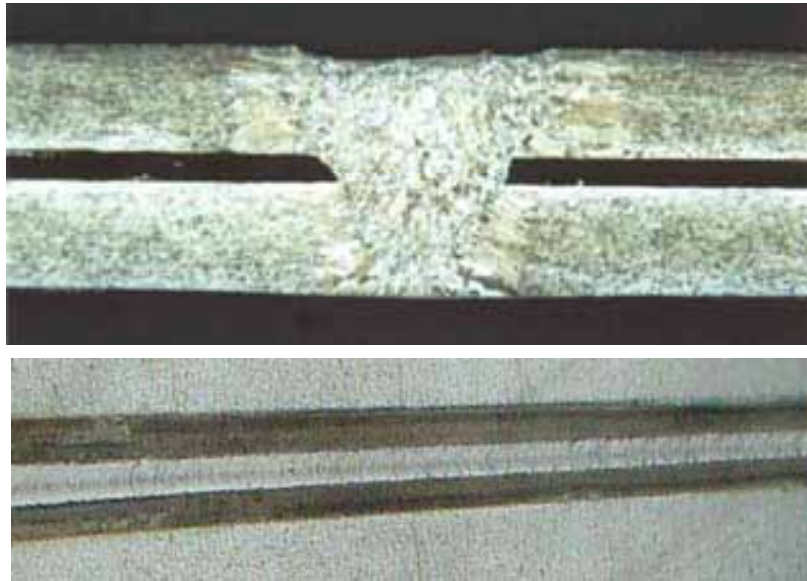
Figs. 112, 113: Nozzles welded of copper because of its good heat conductivity and steel for its wear resistance, are used in injection-moulding machines. The central bore is drilled after welding.
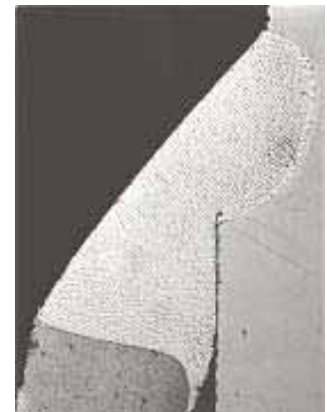
Figs. 114, 115, 116: Even steel to stellite (left) or copper to aluminium (centre and right) can be welded

Electron beam welding in general is not recommended, when the parts have a surface coating in the welding area and this coating evaporates at lower temperatures, e.g. galvanized sheet metal for car bodies. However if a constant gap of e.g. 0.2 mm can be maintained to allow for degassing good welds can be obtained.

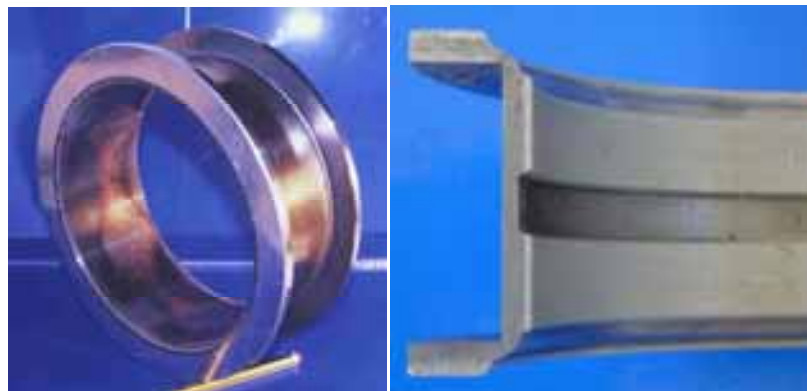*Figs. 117, 118: Zinc-coated automobile-body sheet of fine grain steel. Section and top view of the weld.*

Composite Materials

Joining of large areas of materials with different properties is achieved by rolling or explosion plating. Further processing of such composite materials poses the questions of how to join them. In the case of a sleeve bearing bushing of aluminium bronze on top of steel, only the steel is welded, because the alloy of the two materials does not produce good strength. The copper plated steel can be welded through the copper into the steel without noticeable intermixture. However, when welding through the steel into copper, porosity and cracks occur. An explanation may be due to the change of flow direction within the keyhole whilst welding.

Fig. 119: Steel-copper composite with imperfections in the transition zone.

*Figs. 120, 121: Sleeve bearings of composite steel and aluminium bronze.*

Electron Beam Brazing

In connection with joining of dissimilar materials we should return to brazing: during this process only the lower melting material becomes molten, which then creates a mixture of diffusion bonding, brazing and welding process, this then fuses with the high melting material.
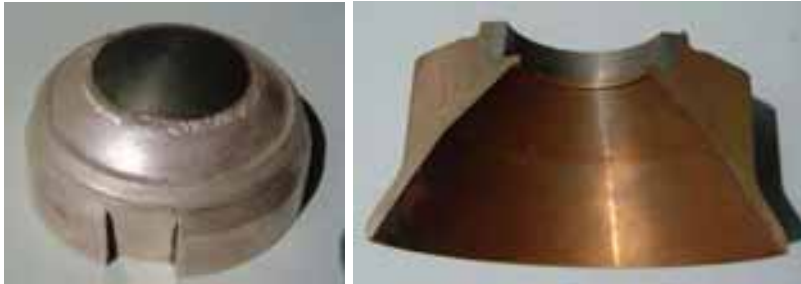
Figs. 122, 123: Tungsten, copper bonds produced without melting the tungsten.

This can either be achieved by heating the higher melting material up to the melting temperature point of the lower melting partner which then through good thermal contact and pressure fuses the two (e.g. W-Cu, steel-aluminium), or alternatively create a weld melt zone in the lower melting material adjacent to the joint interface. Under production conditions the latter can only be achieved with thin-walled parts, by maintaining a high degree of accuracy of beam position. With larger joint cross-section there is danger of not fusing the materials over the entire depth of the joint face or that the higher melting point material also liquefies. In the first case there will be a cold shut defect or a lack of fusion, in the second case, a brittle inter-metallic phase.

Fig. 126: Punching tool with steel body and hard metal ring.
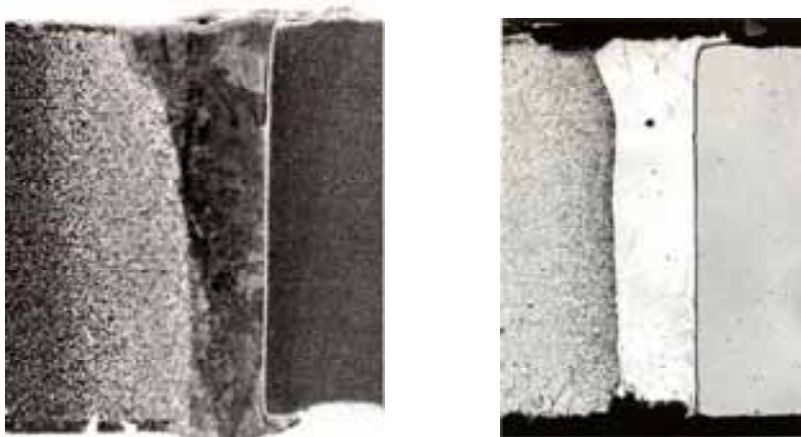
Figs. 124, 125: Brazing steel and hard metal, left without, right with cobalt filler.

Of course there is also the "standard" brazing, using the electron beam as heat source instead of a vacuum furnace. Brazing results from adding a third component, the melting point of which is lower than either of the other two base materials.
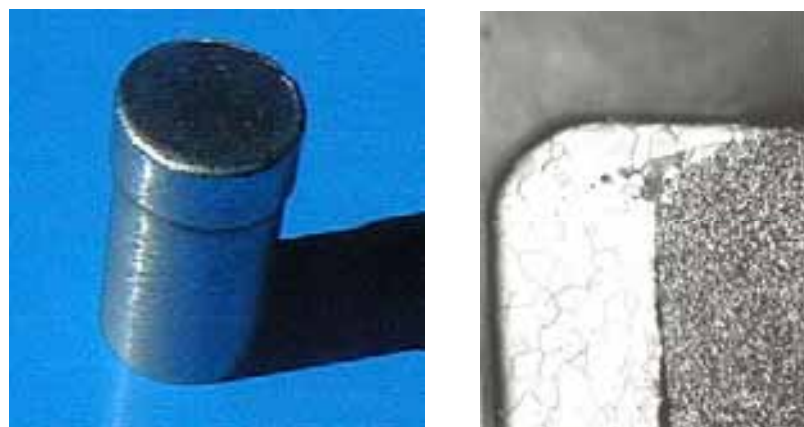
Figs. 127, 128: Brazing of copper to titanium with silver solder.

Fig. 129: Brass-copper joint with silver solder. The size of the fracture surface is used for quality control.

Lötfläche
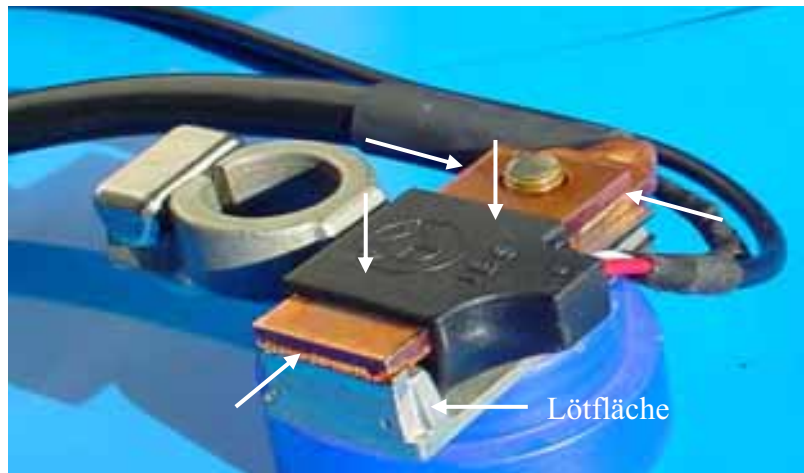
Fig. 130: Car battery cable with 5 EB welds and 1 EB brazed joint..

Figs. 131, 132: Cathode, molybdenum housing brazed to graphite disc.

Electron Beam Welding under Various Physical and Design Aspects

Low Heat Input

The most important attribute of EB welding is the low heat input when compared to other fusion welding processes and especially in comparison to laser beam welding. This results not only in reducing the thermal strain of the welded material but, as one of the most frequent applications, welding of parts containing temperature sensitive components close to the weld seam: e.g. encasing of electronic packages like pacemakers (Figs. 86 and 134) The temperature of these components is not permitted to exceed 100° C, or in pressure sensors, the strain gauge must not exceed 180° C, welding can as close as 4 mm from the component.

Fig. 133: Infrared cavity. The inner gold plating must not be overheated or coated with vapour. This has been achieved by reducing the wall thickness in the weld area.


Figs. 134., 135: Left - encapsulated pacemaker, right - data logger.
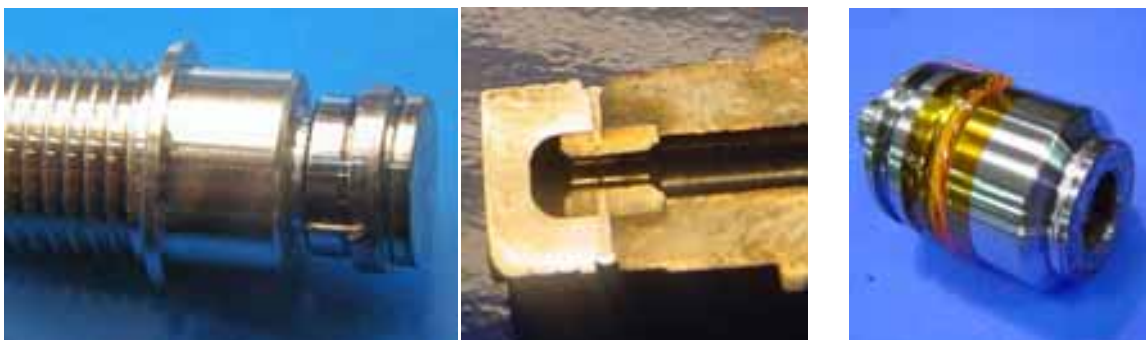
Figs. 136, 137, 138: Numerous types of pressure sensors from automotive injection systems to offshore applications are EB welded.

Other examples include commutators of electric motors with welds very close to temperature sensitive insulation (Figs. 139 and 140), or cold work-hardened copper which, despite of several welds, must not be heated above 120° C in order to preserve its strength (Fig. 141)
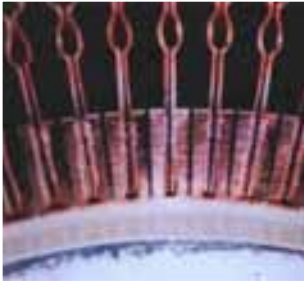
Fig. 139: Detail of Fig. 140.

Fig. 140: Commutators of electric motors with 8 mm deep welds (pulsed operation) very close to temperature sensitive insulation.

Fig. 141: Cold strain-hardened copper must not loose its hardness when welding four joints.


Figs. 142, 143: In order to avoid cracks due to the different thermal expansion between insulator and metal, the welds must be undertaken with minimum heat input.

Fig. 144: Helium leak-tight electrical vacuum feed-through.

Very narrow weld seams mean minimum heat input (Figs. 27, 32, 47) which, on the other hand, can introduce the risk of "lack of fusion" if the beam is not accurately positioned to the joint line. With beam oscillation or defocus techniques wide or even very wide weld seams can be achieved (Figs. 29 and 145) Although these applications are rare it is worth a mention. Where the beam power of the machine is insufficient to achieve the full weld width it is possible to create multiple weld seams adjacent (overlapping) to each other. (Figs. 146 and 147).
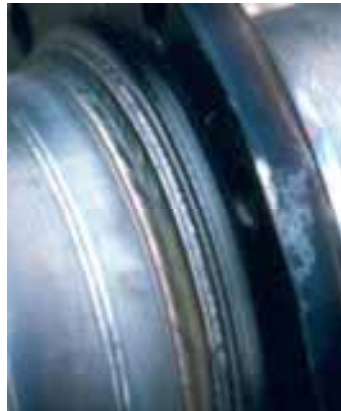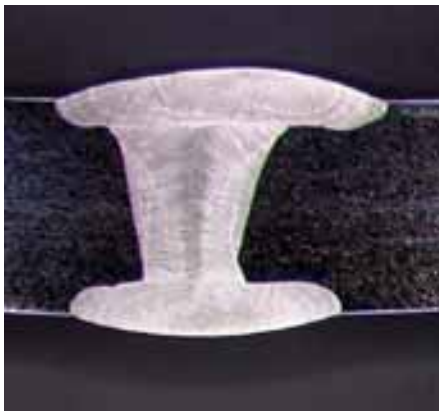

Figs. 145, 146: Examples requiring high heat input welds; left - tube welding with a upper and root reinforcement for corrosion protection. Right - rear axel with brake flange joined using 3 adjacent and overlapping EB welds.

Fig. 147: Truck axle, enlarge detail of Fig. 146.

Low Distortion

There are three distinct types of distortion; Angular deformation, longitudinal and transverse shrinkage. Parallel welds can be achieved with almost zero angular distortion because the molten pool solidification of fully penetrating welds creates uniform shrinkage. Transverse shrinkage is proportional to the width of the weld zone and is exactly reproducible when the geometry of the parts and the beam parameters remain constant.
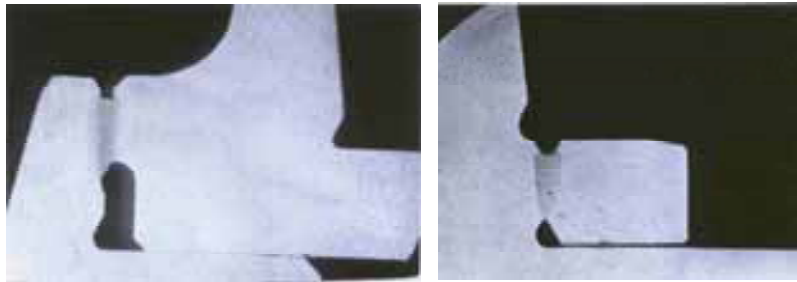
Figs. 148, 149: Left - Gear combination with fully penetrating parallel welds are without angular distortion. Right - Tapered weld demonstrates angular distortion.

Fig. 150: Even numerous parallel welds results only in minimal plate unevenness.

Consequently, the experimentally determined shrinkage value can be added to the original design in order to keep the finished part within close tolerances (Figs. 151 to 153). Longitudinal shrinkage, is in general, of miner importance.

Figs. 151, 152, 153: Tolerance rings exactly ground to size are welded from both sides, whereas the centre remains un-welded to maintain dimension.

Fig. 154: Styrofoam insulation moulders. Both roundness and angular distortion are required to exact tolerances.

Because of resulting shrinkage stresses, radial welds with full penetration are always preferred as they can shrink without restraint. Axial welds are always restrained against shrinkage, especially when not fully penetrating welds.

Figs. 155, 156: Pinion cage and driving gear fabricated with radial EB welds.

42

Fig. 157: Triple beam welding technique.

Nevertheless axial welds are preferred in gear fabrication design as the parts are more cost effective to produce. In order to achieve symmetric shrinkage and thus avoid offset of the axes, simultaneous welding with three symmetric beams is an innovative solution.

Figs. 158, 159: Indexing gear, EB welded with triple beam technique.

Figs. 160, 161: EB welding of all gears sizes is now accepted world-wide as the most frequent application for electron beam welding, mainly due to low distortion.

Fig. 162: The main drive spindles of machine tools are manufactured in two parts because of internal machining. After EB welding the run-out tolerance is within 0.05 mm / m.

In materials that become hard or brittle after welding, the accumulated internal stresses may result in cracks. Therefore especially narrow seams welded with low power and low speed are preferred.

Economic Machine Performance

It is the aim of this design concept is to fabricate parts from standard blanks, which are easy to machine or parts that are easily formed from sheet metal, e.g. by joining tubes of different diameter with an intermediate disc (Fig. 163), or by precisely joining a complex structure from machined plates instead of milling from solid.
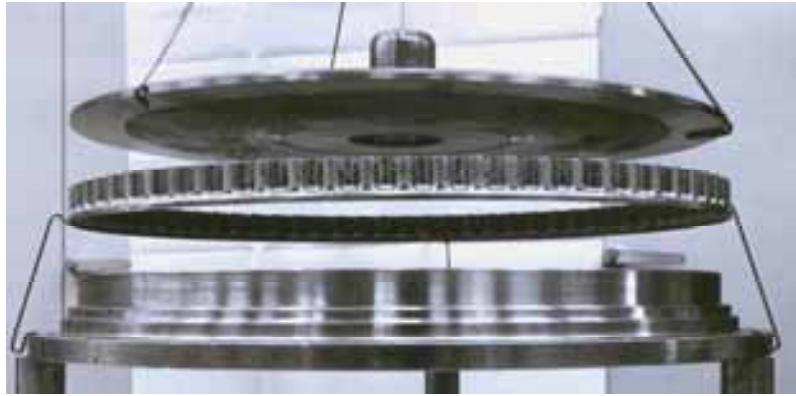

Fig. 163: Piston rod of a shock absorber, EB welded from two tubes and an intermediate disc.

Fig. 164: Microscope frame fabricated from aluminium plates rather than machining from solid.

Fig. 165: EB welded fabrication comprising turned plate, a crown gear and sheet metal formed hub.

Fig. 166: Hollow shafts fabricated from laser cut drawn tubes and end flanges – two radial and one axial EB welds.

Fig 167: Complicated construction fabricated from inner and outer rings and ring segments; all manufactured from turned parts. Left – completed fabrication, right - finish machined part.


Figs. 168, 169: Housing of a twin-screw-extruder. Both, the longitudinal welds and the figure-of-eight profile welds were achieved with EB.

Fig. 170: High current cathode fabricated from a copper casting with integral tungsten tip and EB welded to four legs stamped from copper plate.

A wide range of such design considerations can be found in gear manufacturing. Forged blanks are machined and welded, whereas machining from solid would require extra material to accommodate other machining processes such as milling or grinding. As a consequence the machined part would need to be larger (Fig. 173).
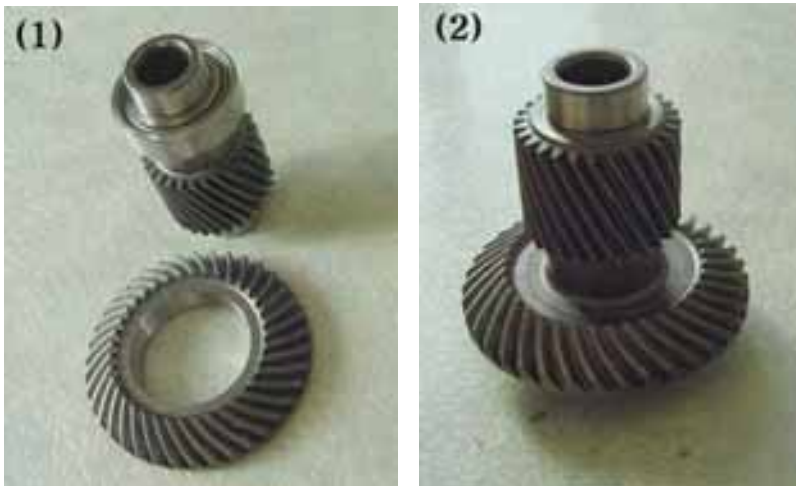
Figs. 171, 172: Fabrication of two forged gears.
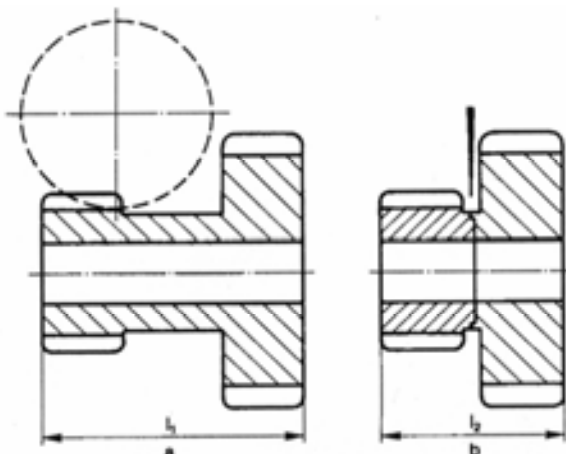
Fig. 173: Schematic drawing of weld designs referring to Figs. 158 to 161.

Fig. 174: Gear part fabricated from two splined tubes and ring.

Fig. 175: External view of Fig. 174.

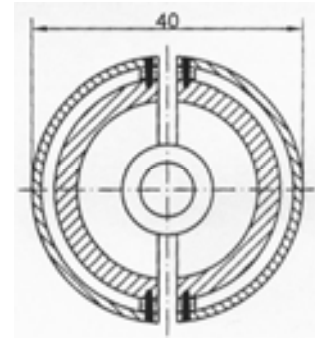Fig. 176: Gear combination fabricated of two thin discs.

Fig. 177: The same principle is used as in Fig. 167, with an additional tube.

Fabrication based designs can create curved or inverse taper components that cannot be produced by milling or even by spark erosion (Figs. 178 to 180). Even coreless casting or forging cannot create inverse tapers. The EB welded part is also economic to produce. (Fig. 182)
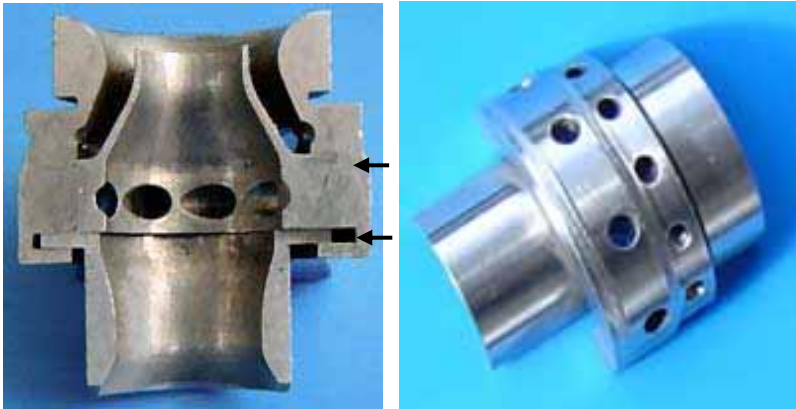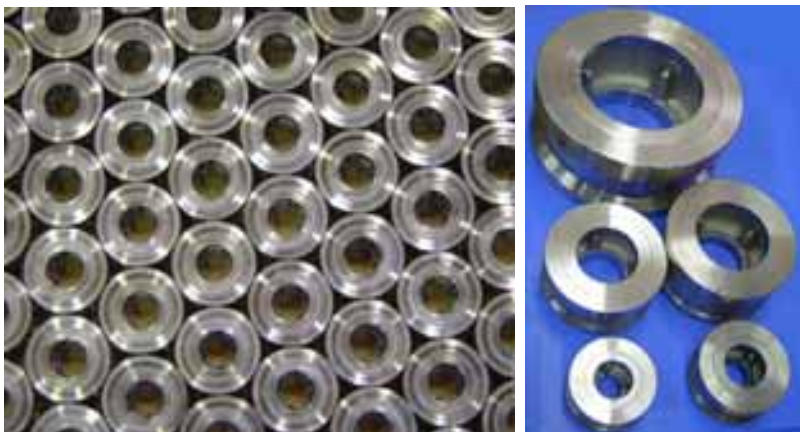
Fig. 179: Schematic drawing of Fig. 178.

Fig. 178: A further development of the principle used in Figs. 167 and 177 is the introduction of curved shapes. Additionally a flange and a tube have been added.

Figs. 180, 181: Mixer head, which can only be produced by joining parts with two radial EB welds.

Figs. 182, 183: Families of fittings made from investment cast stainless steel, EB welded with an insert ring, are produced more economically than lost-core casting.

Fig. 184: Section of Figs. 182 and 183.

Material Selection according to Function

There are numerous parts that are stressed by different loads. A typical example is the bimetal saw band. The teeth are required the be highly wear resistant are therefore made of high speed steel, whereas the backing strip has to flexible to bending loads and therefore is made of flexible spring steel. Earlier saw bands were made from high-speed steel only that not only required 80% more of the expensive HSS and broke earlier from heavy use but not from wear.
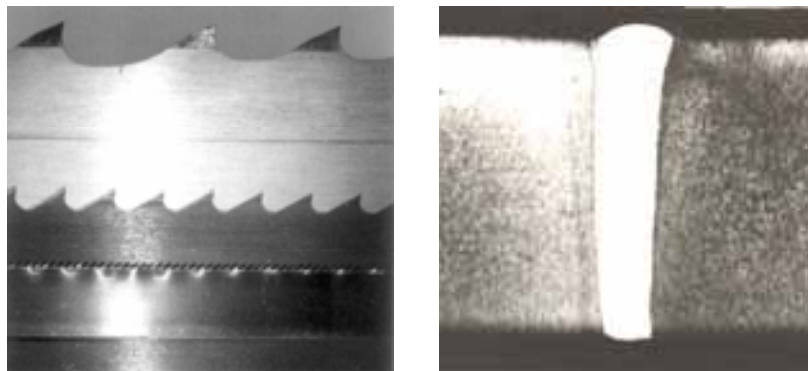
Figs. 185, 186: Saw blades EB weld of high-speed steel to spring steel. Macro 1 mm weld depth and less than 0,2 mm wide.

Another example is cold saws (Fig. 101). The usable volume of the HSS can be ground down as far as the fixing rivets. The lower half can be machined more easily from low cost carbon steel. A further example is rocker levers (Fig. 107). The surface wear resistant part is made of standard roller bearings (100 Cr 6) already with a finished surface that have been cut in half. The rocker arm is made of carbon steel.

Fig. 187: A weaver's shuttle with internal grippers.

A further example joins three materials with one weld in order to produce a loom shuttle. The nose is

of high-speed steel, the grippers of spring steel and the body of structural steel.

Worm gears represent a large segment of the market. The cog is made of bronze and the hub of steel or cast iron.

Figs. 188, 189: Bronze with good tribology properties is EB welded to low cost steel.

As bronze is much more expensive than steel, the thickness of the bronze ring is reduced to the absolute minimum as dictated by the bearing capacity. Hobbing is performed after welding (Fig. 110).
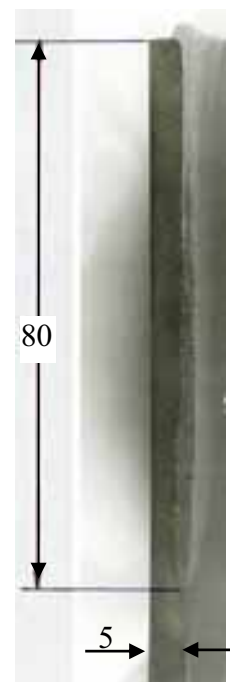
Figs. 190, 191: Section through the stator of a steam turbine. The welds are between 80 to 140 mm deep with a wall thickness of the cladding between 5 – 8 mm.

Fig. 192: 3D profile weld of a steam turbine vane, welded with simultaneous focus, beam current and welding speed control.

With large parts even small differences in steel prices can have economic consequences.

The surface of stator rings of steam turbines (Fig. 190) are subject to hot corrosion. Therefore two large rings of boilerplate steel are coated with 8 or 10% chromium steel by EB welding operations. As the vanes can be welded at the same time, there is a double advantage. The alternative process of welding drawn profiles to a forged base (Fig. 192) without undercuts is possible, but difficult to achieve.

Fig. 193: Copper injection nozzle, with steel tip.

Nozzles of plastic injection moulding machines are subject to highly erosive wear, whilst at the same time the design must ensure that the plastic does not cool significantly on its way to the mould resulting in clogging. This is overcome by EB welding an austenitic steel tip to the long copper tube (Figs. 112, 113, 193).

When switching a high current contactor, the resulting electric arc impinges on tungsten insert whilst the attached copper conducts both the current and heat away (Figs. 122, 123, 194).

The examples in this chapter "dissimilar materials" are described under materials aspects of are of course relevant topics according to functionality.

Fig. 194: Sintered copper-tungsten to copper connection; the solution to the demands of high current switching.

Accessibility for E-Beam and Tooling

There are weld designs, which have to be processed within narrow gaps. The small angle of aperture of an E-Beam of 0,6° allows welding solutions which cannot be achieved by other fusion welding processes. Sometimes it is necessary to slightly inclined the beam in order to weld at the foot of an upright part.
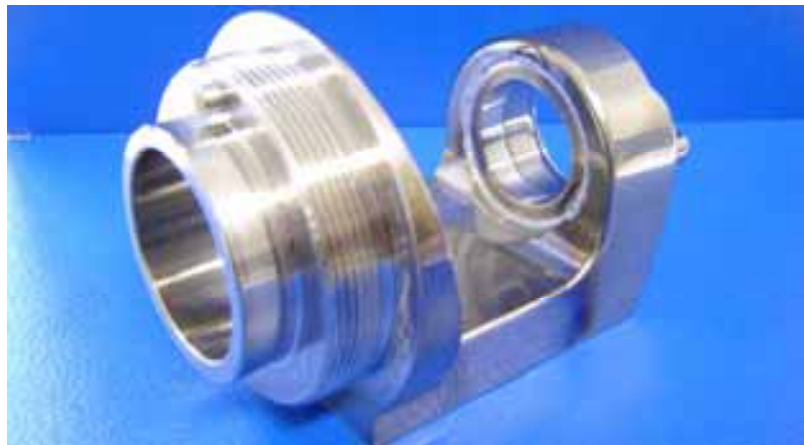

Figs. 195, 196: Gear combinations with difficult access to weld positions.

Figs. 197, 198: Because of the E-Beam narrow profile it is possible to weld the threaded tube of the safety airbag or to weld the inner seat of a valve housing.
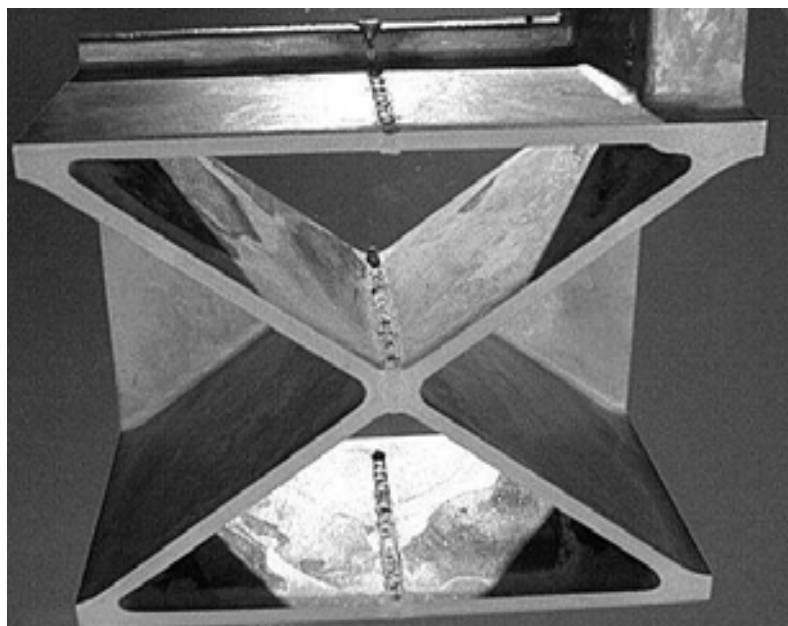

*Fig. 199: Welding of the support ring is carried out through the left opening.*

Completely inaccessible joints can be welded through successive layers without a noticeable broadening of the beam.

Fig. 200: The three welds, one upon another in magnesium are executed simultaneously in one run.

Another access problem by design is not related to the electron beam, but by mechanical tooling. By separating the parts by clever design, machining accessibility can be easily undertaken by turning or milling. As a final operation the profile is sealed with a stake weld (Fig. 201) or by inserting and welding a profiled cover. (Fig. 202).

These methods are used for numerous parts, especially to produce cooling channels are required (Figs. 48, 65, 150). Further examples; wave-guides for satellite antennas that require a perfectly smooth inner surface cannot be achieved by investment casting.
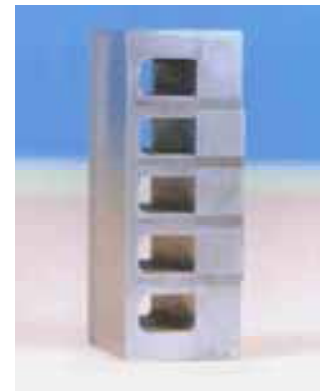
Fig. 201: Circular cooling channels are machined in the inner ring of an eddy current brake for engine testing that is then sealed by shrinking an outer ring and stake welding at each web.

Fig. 202: Access opening for internal machining that are sealed by EB welding.

An open profile is initially machined by milling, grinding and polishing, after which welding a attached lid seals the component.

Figs. 203, 204: Stake welds of cover plates of various contours.
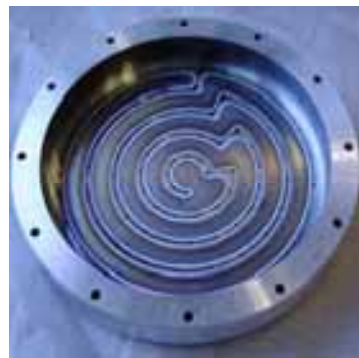

Fig. 205: Water jacket of a steam iron sloe plate.

Figs. 206, 207: A large variety of designs become possible by using stake welds.

Figs. 208, 209: Any free programmable contour may be milled in the body and sealed by lid attachments.


Figs. 210, 211: Spindles of large milling machines with internally machined profiles.

Spindles up to 6 m long for large milling machines with complex internal machining operations cannot be produced in one piece. Slotting machines for these lengths do not exist, therefore the spindle is fabricated from three parts that are finally EB welded with two circumferential welds.

Thick – Thin joints

Maybe the most impressive demonstration of a thick to thin joint is the EB weld of a razor blade edge to a solid disc made in the 1950's. This shows that the high energy density focused to a small spot melt both the thin edge and the massive block simultaneously. If heat sources with less power density were used then the thin part will melt away, whereas the thick one stays cold. The result is not a weld but a hole!
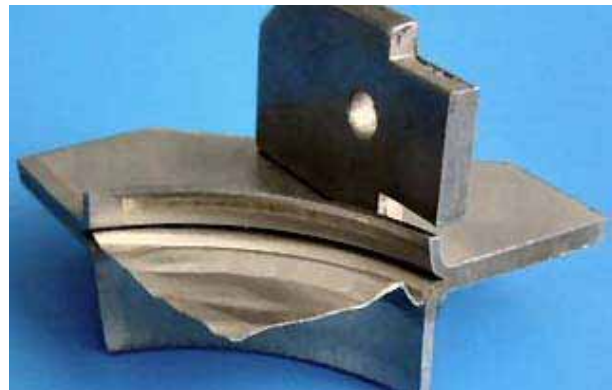

Figs. 212, 213, 214, 15: Welding of thin diaphragms for various applications is possible with electron beam welding.

Welding of such thick-thin joints, as well as of thin foils to each other without defects, is only possible if there is heat conductivity between them i.e. no gaps. In order to guarantee weld integrity the foil is often secured by a cover ring that is stake welded together. This design option is used for rupture membranes (Figs. 213, 216) or when attaching membranes for pressure or temperature measurement (Figs. 215, 217).
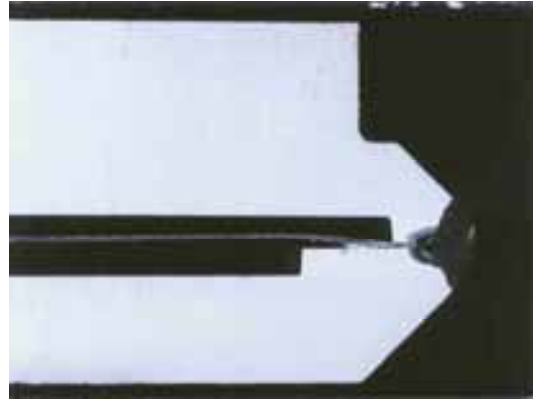
Figs. 216, 217: 20 µm thin rupture membranes or metering diaphragms are EB welded.
Figs. 218, 219: Preformed thin sheets are welded to produce pressure cells or bellows.
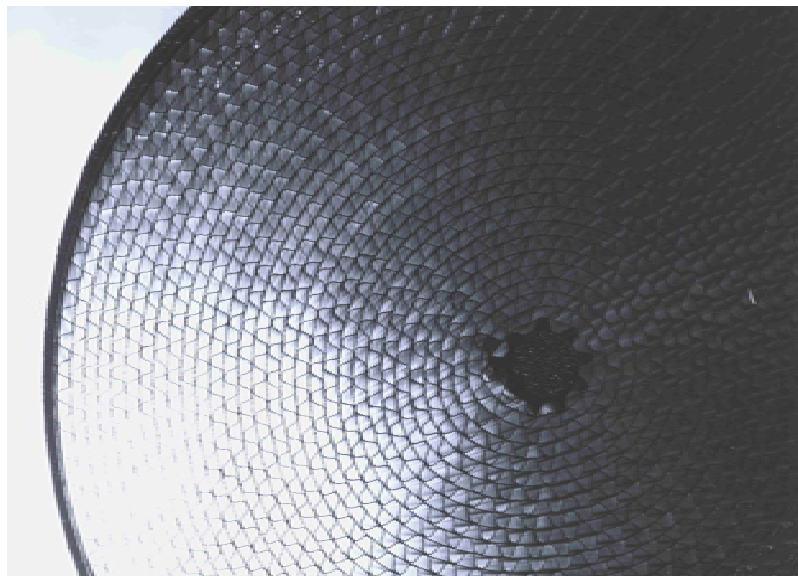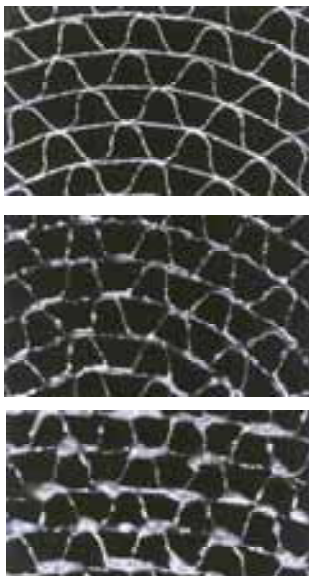
Figs. 220, 221, 222, 223: Exhaust catalyser EB welded with different beam powers.

Where irregular component geometries make it impossible programme each individual joint, it is possible raster a rapidly deflected beam in two axes over the entire surface with sufficient energy to melt all points. Approximately 3000 seams on a catalytic converter, made from 50 µm thick steel foils, are welded in three seconds (Fig. 223).

Fig. 224: Tension band, 30 µm thin, welded to an end terminal 70 µm thick.

Small Parts

Electron beam was instrumental in welding small parts the past; today it is widely superseded by laser beam welding.

Fig. 225: Filter capsule fabricated with three axial welds.

Only special requirements are of relative importance; such as low heat input, narrow welds (smaller than 0,2 mm) or with reactive materials, where vacuum is an advantage, is EB welding used.

Figs. 226, 227: Screw thread EB welded from the front side.

Fig. 228: Locking cam with four EB welds

Fig. 229: Macro of a sensor weld 0,2 mm wide.

Figs. 230, 231: Sensors are especially sensitive to temperature and distortion.

Further applications are of interest; where the precise beam positioning is achieved by seam tracking by means back scattered electrons detection. This process allows large volume production to be automated. In certain conditions (with small parts) both high speed and precise deflection of the electron beam is required; this can be performed beam deflection, thus eliminating the exact positioning by mechanical movement.

Fig. 232: Relay enclosure with heat sensitive glass feed-through.

Figs. 233, 234: Pinion and planetary gear of a hand-prosthesis with 17 EB welds.

Fig. 235: Eccentric fastener for a printed circuit board, 6 mm long.

Fig. 236: Longitudinal section through fastener Fig. 235.

Large Parts

EB welding become more economic as the wall thickness of the component increases. With other welding process the preparation time and cost for secondary operations e.g. chamfering become more costly. (Figs. 241, 242).

Fig. 237: Turbine shaft of a power plant. The individual segments can be machined on smaller machines.

In this way large shafts e.g. for marine propulsion or turbines are fabricated from individual segments. Big casings with one or two meters diameter for chemical processing industry are assembled from rolled sheets with longitudinal and circumferential welds, simply a drum is constructed by welding of a number of strips and finally flanges attached (Fig. 243).

Figs. 238, 239: High-pressure hydraulic cylinder operating up to 15.000 kN; weld depth 95 mm.

Fig. 240: Long piston rods fabricated by EB welding tube segments.

Figs. 241, 242: Comparison between a 150 mm EB weld and a submerged arc weld of same depth. It is evident, that EB welding is more cost effective due to the short welding time:

Welding time for a 1 m long EB welded seam 8,3 min (1 pass)
Welding time for a 1 m long submerged arc welded seam 314 min (152 passes and consuming 32 kg of filer wire).
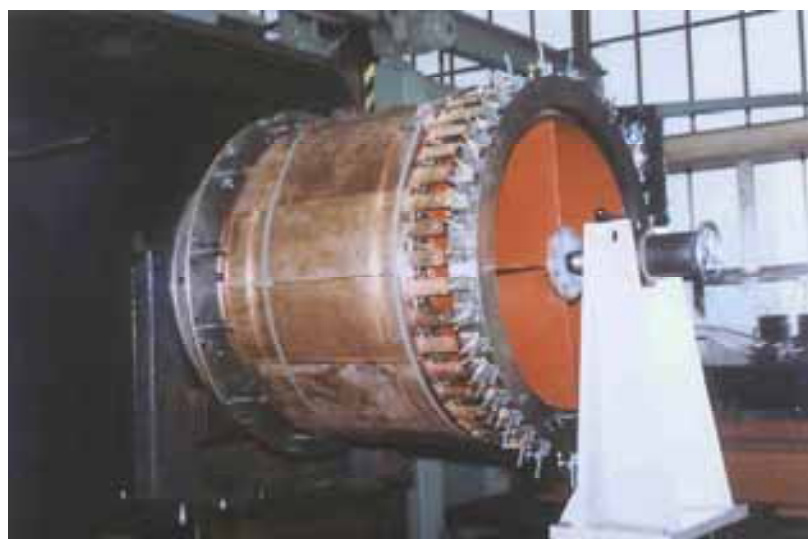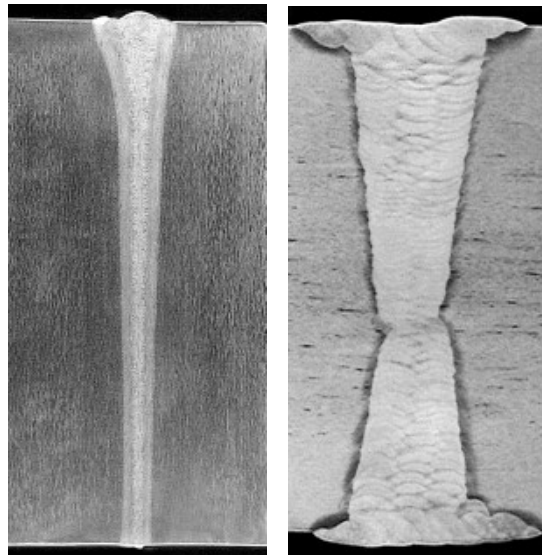
Fig. 243: Copper drum with contact bars; diameter 1,6 m.

Fig. 244, 245, 246: Furnace parts - EB welded in a 20 m³ chamber - used for the destruction of old ammunitions.

Fig. 247: EB welded "lifting lugs" for lifting marine engines weighing up to 140 ton.

Fig. 248: Lifting lug

Fig. 249: Welding seam on lifting lug, right - as welded, left - after grinding and x-ray
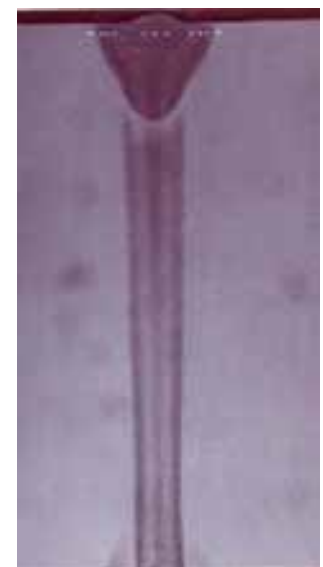
Fig. 250: Cross section of weld Fig. 249.

Repair Welding by Means of an Electron Beam

Because of the EB welding attributes and characteristics; low heat input, low distortion and ability to weld dissimilar metals, it is particularly adapted to repair welding. In most cases the parts that have worn out or are broken are critical and may paralyse the production of a whole factory. Fabrication of a new part could take weeks or months. Therefore repair employing some new parts can provide an economic and satisfactory solution.

Figs. 251, 252: A worn out valve body of 42 CrMo 4 was reconditioned by inserting a new sleeve. Weld depth 55 mm.

Figs. 253, 254: Repairing a broken electric motor rotor-shaft by welding on a new part.

Fig. 255: Worn out parts of a turbine rotor are exchanged with new ones.

Sometimes parts modifications produced in quantity is still preferred to a new production run on economic grounds. Finally there are applications, where even large parts are refitted by EB welding.

Fig. 256: Spark plugs from series production are modified for a special application by cutting apart and inserting a special ring.

Fig. 257: Detail of Fig. 258.

Fig. 258: Rotor of a gas turbine with a weight of 52 ton.

A huge rotor of a gas turbine shows wear around the circumference, This can be refitted by EB welding. The rotor is turned and new segments are welded in (Fig. 258).

The repair of quill bearing boxes involves recall of all parts as the original weld failed. The repair chosen saved the valuable cast casings of GS-16 Mn 5. On both ends new bearing journals are welded on. The weld quality and minimal distortion both to exacting standards were of equal importance.

Figs: 259 – 261: Repair of quill bearing boxes for locomotives.
Fig. 262: Weld underbead.

The angular position of the bearing journals relative to each other, the tolerance of the inner diameter of the bore for the bearings and the overall length after welding has to be within narrow tolerances. The design quill bearing boxes provided for final

machining after welding. By comparison; after EB repair welding the assembly require no further machining. (Figs. 263 and 264).

Figs. 263, 264: Assembled and installed after refitting the quill-bearing box.

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Subcontracting Electron Beam Welding of Series Production

Fig. 265: Washing plant.

Fig. 266: Automatic X-ray machine.

Fig. 267: Fatigue testing machine..

Series EB subcontract welding requires management changes in the job-shop, like establishing purchase and logistics, certification with training of QA staff and external audits. The requirement of supply contracts has expanded considerably since earlier times. It starts with purchasing of material including stock control and continues with cleaning, demagnetising and assembly. Series production working methods have to be planned, established and installed. EB welding follows with automatic parts loading and unloading from tooling. An important corner stone is an sensible, safe and traceable online quality control and backup in order to provide 100% traceability. Quite often, this includes post processes such as ultrasonic or x-ray inspection, where simple visual or camera viewing is not sufficient. For statistical control destructive tests are carried out, documented and the samples archived or returned to the customer. In certain circumstances the ancillary costs for the processes exceed those for welding.

Nozzle Guide Vanes

Nozzle guide vanes for helicopter or small airplane turbines are assembled loosely into an internal location ring of a substantial jig. An external ring with punched profile holes locates each vane precisely. The cast vanes are EB welded according a predetermined programme that distributes the heat uniformly controlling the shrinkage. As a first step the vanes, clamped by a ring, are tack welded by two circumferential seams, the clamping ring is then removed. The number of vanes is always a prime number e.g. 103 so that every 20th vane is welded, this creates the same distance between each weld, this cycle is repeated until all vanes have been tack welded. Full penetration welds are then performed on the other ends of the vane and completed with full penetration welding of the initial tacked end. This procedure

controls and equalises the shrinkage and stresses in all 309 welds. The complete welding cycle takes about 45 to 55 minutes, depending on the vane count, during this time the setter can load the next assembly. To complete the operation the welded stator ring is turned to create an inner hub and outer rim onto which flanges are welded.

Fig 268: Completed stator assembly with flanges attached.

Figs. 269 to 272: upper left – lower half of welding jig, upper right – blades located using a "blade punch", lower left – complete welding jig with stator in place, lower right – profiles of welded vanes.

Electron Beam Welding of Internally Hydro-formed Camshafts

Fig. 273: Assembly station with end-load measurement.

EB series production welding for the automotive industry and its suppliers is characterised by an integrated data acquisition and processing system of the individual process steps, so that the operator, material and welding data can be cross-referenced to each part via a data matrix code. Only by this method can 100% traceability be guaranteed as demanded by automotive industry. The welding positions are located within the bearing mounts that have to be ground as a final operation. The resulting surfaces must be fault free. Whilst using EB welding the defect rate is kept below 50 ppm (parts per million).

Fig. 274: Camshaft are supplied with engraved data matrix code and plain text.

Figs. 275, 276: A laser scanner determines identifies each shaft on each workstation before processing.

The process starts with the part being washed followed by laser scanning the data matrix code. After it is loaded the end-load and length are recorded. After welding the parts with a 5-spindle rotary device on a load-lock-shuttle-machine, using automatic seam tracking, quality control checks the part run-out. At each station the code confirmed. Finally the parts are packed and shipped.

Outsourcing volume production to a job-shop is of special interest to automotive industry and their sub-

suppliers because of high quality assurance aspects, the sub-contractor is more flexible when one machine fails he has alternate machines he can use. This arrangement can also cope with production volume peaks as they occur.

Fig. 277: Mounting and welding on a load-lock-shuttle machine.

Fig. 278: Automated exchange of the 5-spindle work piece fixtures.

Figs. 279, 280: Camshafts after welding (top) and finish ground (bottom)

Fig. 281: Checking for run-out after welding and data protocol production.

Fig. 282: Dispatch.

Fig. 283: Packing.

Final Remark:

Already before going to press this booklet has got its nickname:
"the electron beam welders stamp collection".

My hope is that this book is the start of your collection and that you continually add your own applications.

Acknowledgement