ELECTRON BEAM WELDING

A Key Technology to Construct Vehicles for Road, Rail, Sea, Air and Space

Dietrich v. Dobeneck

pro beam

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Introduction

The ever increasing pressure from international competition to produce higher quality at lower prices in shorter times leads to the use of specialized processes, wherever a little advantage may be detected. This is true for a large variety of manufacturing technologies including welding. As a lot of those processes need very specific and detailed know-how, usually not available at the manufacturing companies, outsourcing becomes a popular solution. Another reason for outsourcing is the initial high investment for some of the processes. And last but not least, in order to be cost effective, high-cost equipment has to be productive around the clock. As the volume of a certain production usually does not exactly fit the capacity of one specific machine, time-sharing of equipment with other requiring companies is an adequate solution.

Fig. 1:
High productive load-lock shuttle-machine for EB welding of pressure sensors. Automated loading and unloading with a gantry under clean room conditions.

Adapting this philosophy to electron beam welding (EBW), there is another reason for sharing machine capacity: as size, power, control possibilities and work piece handling have to fit the requirements of each application, only contractors with a selection of different equipments and a strong financial background to bridge the time gap between product evaluation and start of production can meet these needs. The contractor in turn tries to use equipment which is as flexible as possible, in order to use it for other applications in the future. The new generation of load-lock machines fulfils all these requirements in the area of EB welding. They are three to four times more productive compared to the former generation of chamber machines and they can be used with work piece carriers for any kind of single or multiple work piece manipulations. In this respect they are much more flexible than the drop-bottom cycle-machines (Fig. page 1) generally in use in the automotive industry.
The perfect reproducibility of process parameters and improved methods for online process controls allow to produce highest quality standards, including documentation at reasonable cost.

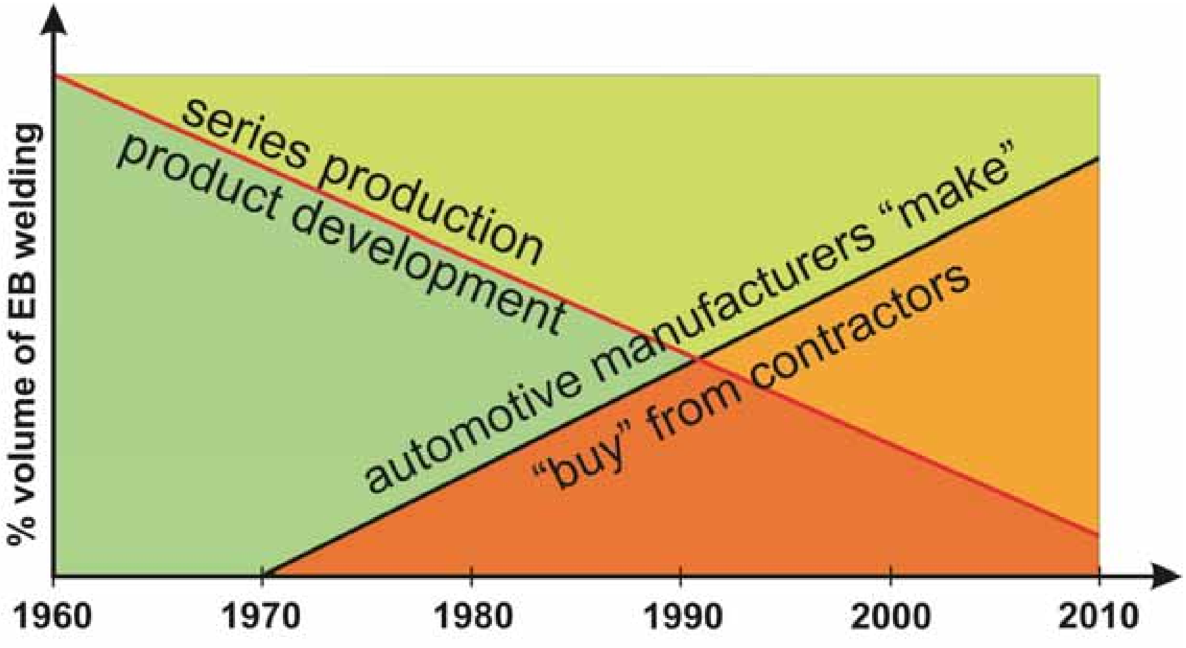


Fig. 2:
While series production and subcontracting grows, automotive industry reduces own EB development and related production.

Today’s requirements in the area of Quality Management based on ISO 9000, ISO 9100 or TS 16949 are more or less the same throughout different branches of industries, but still there are some slight modifications. Aeronautics industry usually applies an intermediate control after each step of production, as the work pieces are extremely expensive, whereas the automotive industry, with high volume production, tries to optimize between expenses for intermediate controls and cost for eventually scrappable parts. At the end all groups insist to be supplied with zero defect parts, independent whether the failures are detected and sorted out in between or only at the end of the manufacturing chain. Using the “intelligence” of an electron beam, some online control capabilities may be used to adjust the beam or sort out parts just before welding and thus save parts within fractions of a second.

Fig. 3:
Weld documentation.

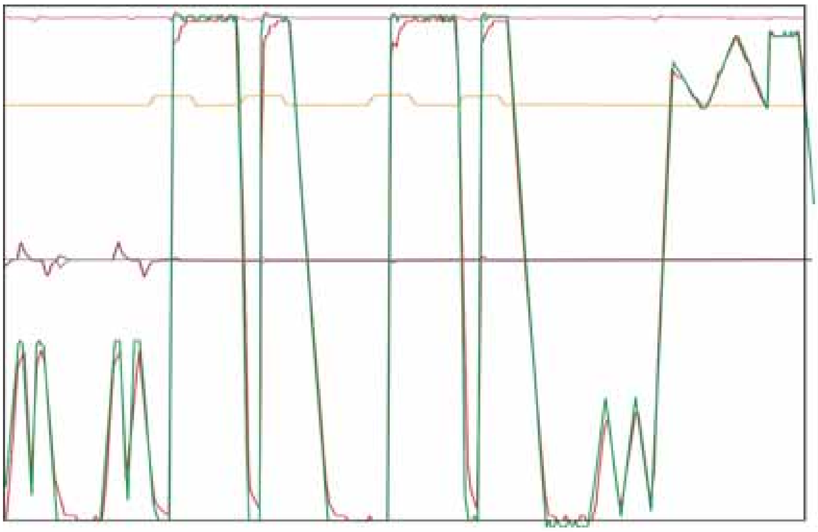
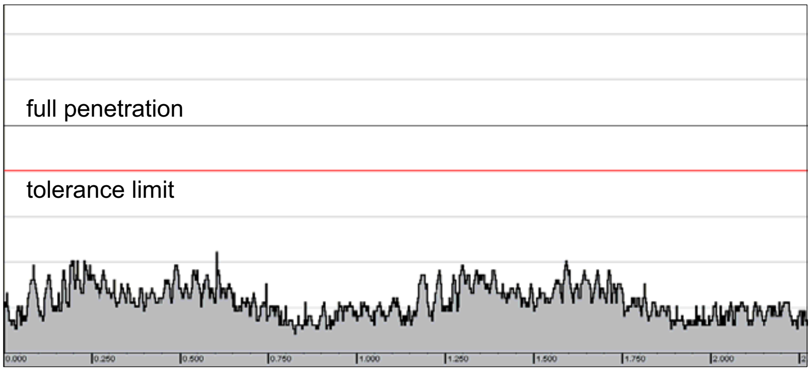


Fig. 4:
Ultrasonic inspection of root spiking of an EB weld.

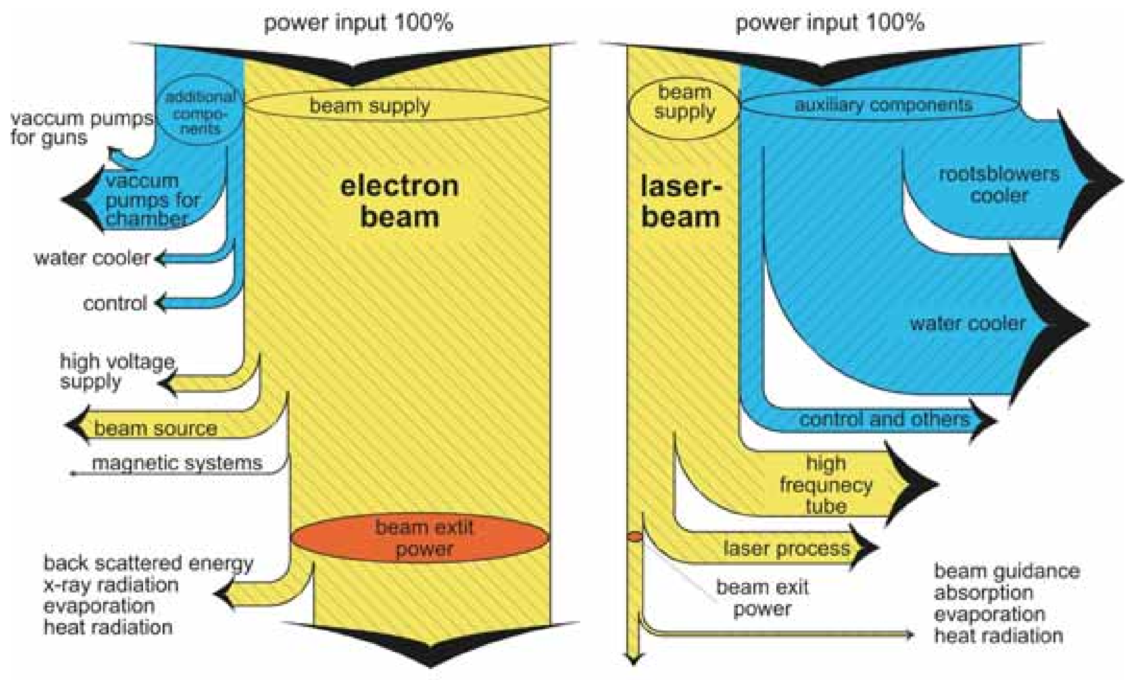


As there is still good potential for further development of EB technology towards higher productivity, which results in lower cost, and towards better or new processes, the trend to outsource production to strong contractors will continue. At the time being, the automotive industry is reluctant to invest own money and thus paves a way for subcontracting EB welding, which is equally to the advantage of all other industries.
By outsourcing their production the connected technical and economic risks, however, are transferred from the OEM to the prime contractor or even to the 2nd tier supplier.

Electron beam machines have a nearly unlimited life. Only in case of a lack of spare parts after 30 or 40 years of use, the machines may be scrapped. The principle: “never change a running system”, however, is sometimes counterproductive in two directions: the users of old machines do not share the economic benefit of new developments, e.g. of highly automated and faster equipment, which counts for themselfs. Secondly, the impression to outside people is more that of an oldfashioned technique than of a highly sophisticated and modern production tool. Young engineers prefer to be in attractive surroundings with up-to-date equipment. This should be kept in mind in order to attract qualified and motivated personnel.

The importance of automotive industry for promoting electron beam welding is demonstrated by the fact that two thirds of the 590 EB welding machines sold during the last five years were purchased by automotive industry, mainly by suppliers of aggregates or components. It is equally remarkable that more than fifty percent of these machines were invested in Asia. This has a simple reason: cost for electricity is, mainly in Japan, much higher than in Europe or America.

Due to the much lower energy consumption of EB machines, including vacuum generation, compared to a 4 kW solid state laser, savings of more than € 50.000 per year are achieved in Europe and twice as much in Japan, disregarding additional cost for shielding gases, necessary with lasers. That is why EB welding dominates mainly in gear welding in Asian countries with applications where both beam technologies compete.



Source: ISF

Fig. 5:
Comparing the efficiency of an electron beam and a laser beam source, it is obvious that furthermore the running costs of lasers are by far higher than that of EB.
Weld penetration with EB is twice as deep as with lasers of the same beam power and vacuum is cheaper than shielding gas. Recent developments like disk and fiber laser are improving in this respect.

A statistic of world distribution of electron beam machines and their age, covering the last 50 years, demonstrates clearly the shift of electron beam use from the old industrialised countries to the emerging markets in Asia. There are few informations on the former COMECON area.

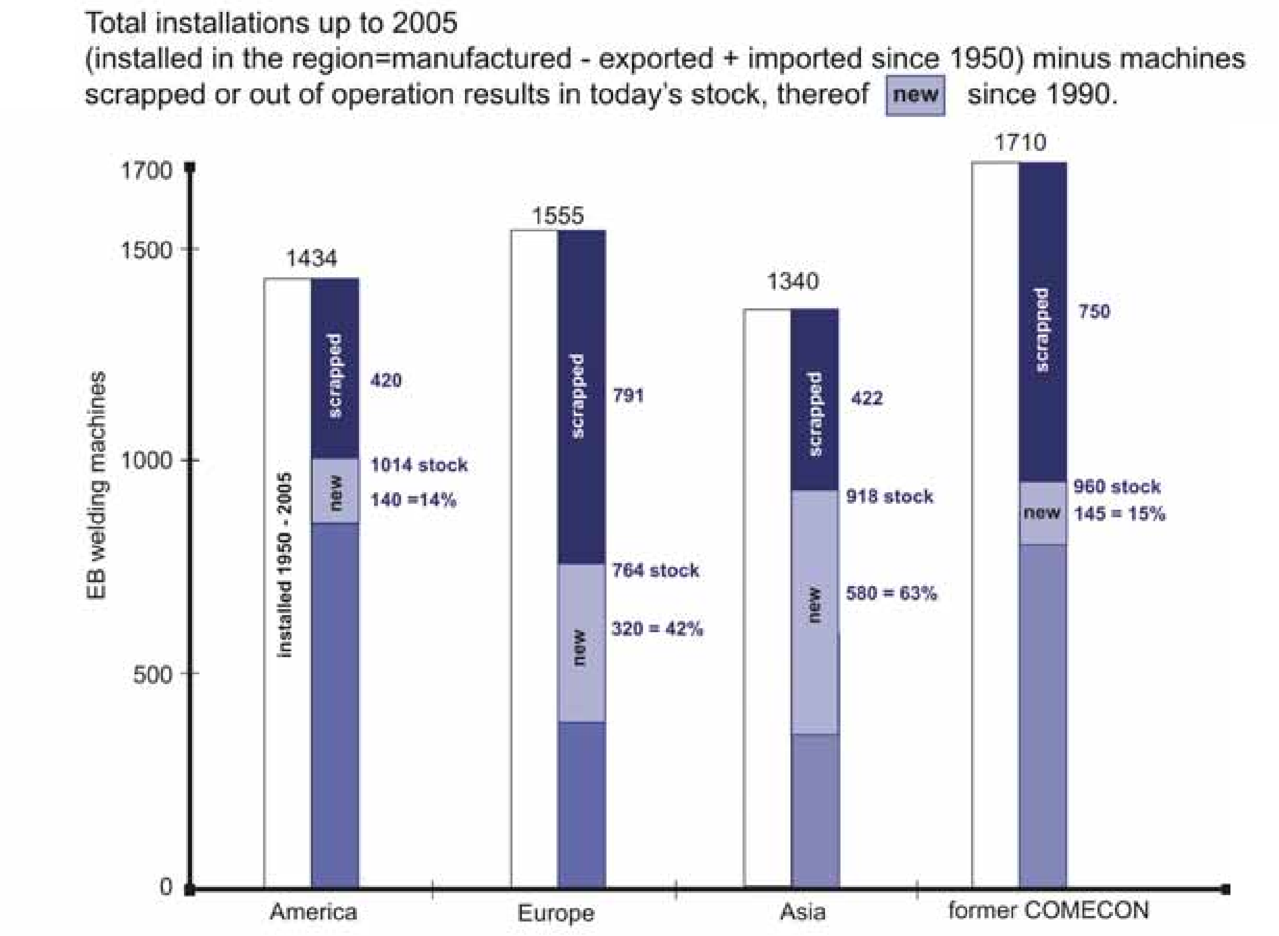


Fig. 6:
The market for electron beam equipment shifts from America to Asia.

For the future of high volume EB welding, the basic question which will have to be answered is whether it is more effective to run e.g. 5 identical low-cost machines for a high volume application, 4 to fit the required capacity and 1 in standby for peak capacity, for maintenance or security purposes, as it was in use in US gear manufacturing companies in the 1970ies, or whether 2 highly productive (and of course more expensive per unit) machines shall be invested?
There is still more space, more energy consumption, more spare parts and more service to be considered against production security with more machines.

Automotive Industry

All applications of electron beam welding in automotive industry are part of the chassis, the power train, the gear box or the engine and a number of auxiliary components, such as electrical parts and sensors, heat exchangers and so on. None is in the field of the car body, which is the domain of laser beam welding.

Fig. 7:
EB welding is intensively being used in automotive industry, both for series production as well as for racing applications.

A reason why electron beam welding is being used instead of other joining techniques is the high productivity and readiness for automation for series production combined with the control capabilities of process parameters as well as the high flexibility for manufacturing of prototypes.

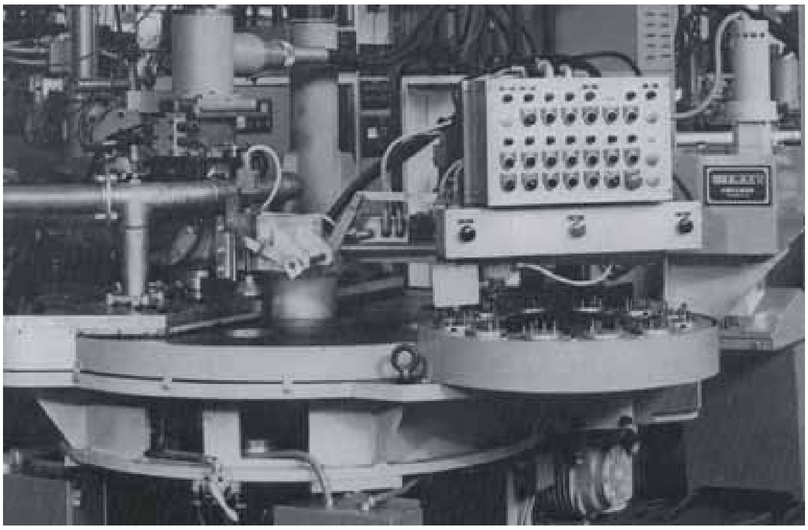


Fig. 8:
The old generation of dial feed indexing tables is no longer in use, despite of its high productivity.
This machine once welded 1100 ignition distributor fingers per hour.

Already in the 1970ies welding machines were in use which were able to weld 1000 parts per hour. It is surprising why today's automotive industry is so reluctant to make use of these potentials, or at least, why it is the last alternative of choosing a production technology? Several times EB machines were only bought after few years of experimental work with lasers, which failed. Only in the last minute before production had to start, EB welding has been considered. The capability of pro-beam job-shops to guarantee full production over the period until a new machine could be designed, manufactured and supplied, brought EB into business again.

Sometimes it was too late, as investment in a less suitable process was had been done already. Which employee in such a situation will ever go to his boss and confess: I found a better process, we will have to re-invest and lay-off the just purchased equipment? Most of the European and American automotive companies are so much focused on lasers that they employ large groups of laser specialists including good laboratory facilities and have not a single expert to promote, or at least to have a look at EB capabilities.

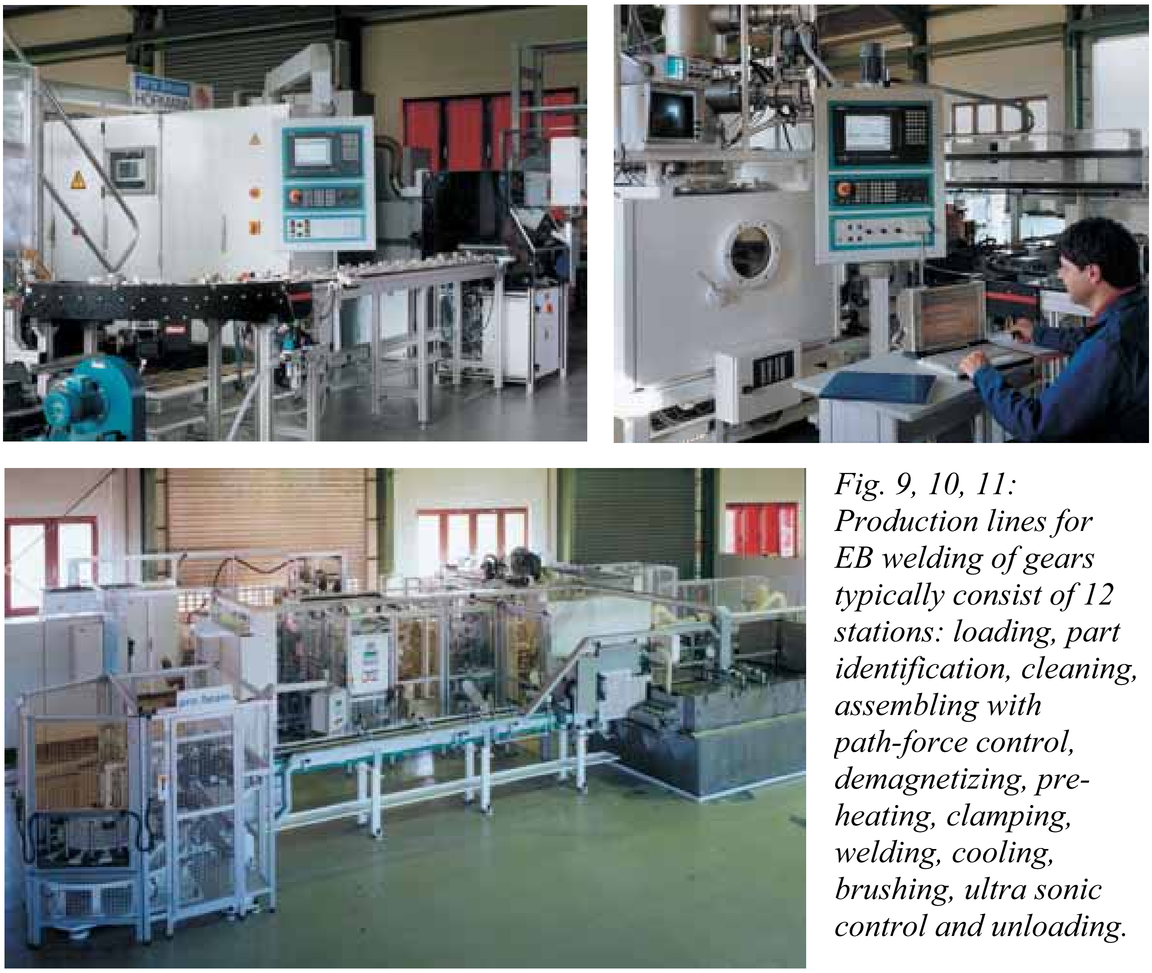


Fig. 9, 10, 11: Production lines for EB welding of gears typically consist of 12 stations: loading, part identification, cleaning, assembling with path-force control, demagnetizing, preheating, clamping, welding, cooling, brushing, ultra sonic control and unloading.

Contrary to Asian companies, many of our European design engineers and production managers are not up to date of ongoing EB developments, which might be helpful to solve their joining problems. In other words: the lack of “sex appeal” of the electron beam is confronted with the exaggerated enthusiasm regarding the laser beam. Even experts are not really aware of the fact that a typical European car has something like 20 to 25 EB welds, one luxury SUV has 120 EB welds. The reasons why and when electron beam welding is used instead of other joining techniques are so manifold that they can be explained best by using examples of applications:

Engines and Engine Components

Three different fields of EB welding are being observed on car engines made of aluminium alloys: improved cooling necessary for increasing engine power, a welded closed deck design to ease casting and improve stiffness and the use of dissimilar materials according to function.

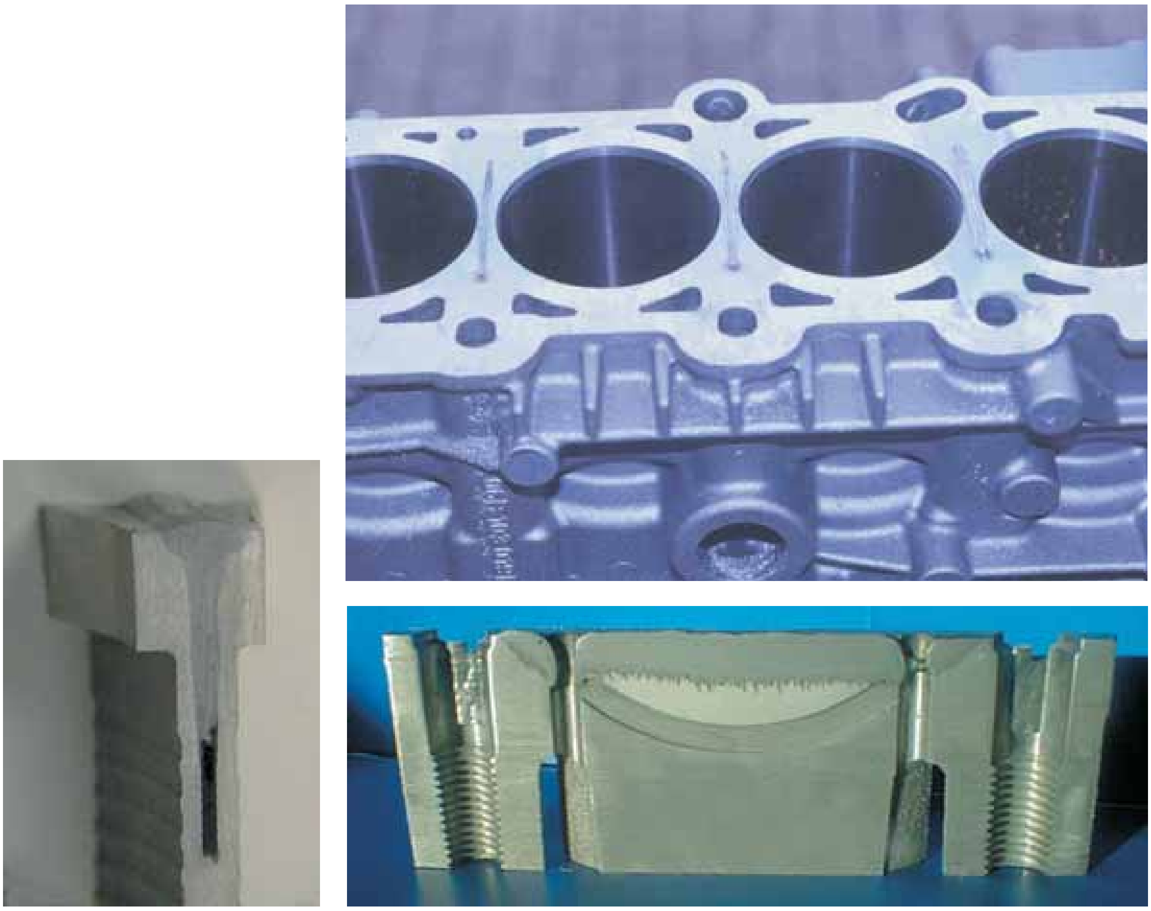


Fig. 12, 13, 14:
Cutting a slot for cooling between liners and covering it with an insert, sealed by two EB welds. Cross and longitudinal section of the slot.

In case one there is the basic idea to increase the cylinder volume of an existing engine without changing the distance of the cylinder axes. This results in a reduction of the web thickness between the cylinder liners and, as a consequence, it requires an increased performance of cooling. A slot of 0.8 mm is milled into the remaining 2.3 mm wall of aluminium next to the cast iron liners. The slot is covered with a sheet metal segment. This has to be welded with 2 EB welds on both sides, 6 mm deep. If the welds touch the cast iron, intermetallic phases are produced, including cracks which lead to leakage and finally cooling water mixes with oil. The problem involved is, that the tolerances in casting are much larger than can be accepted by welding. Therefore an automatic seam tracking has been introduced. The job has been performed with load-lock transfer-machines with a cycle time of 49 seconds for the 4-cylinder engine with 6 EB welds and of 52 seconds for the 6-cylinder engine with 8 EB welds.

Fig. 15: The main welding problem results from offset of the slot due to large tolerances in the castings.

Fig. 16: Load-lock transfer-machine for EB welding of 4 cylinder motor blocks.

From time to time during the last 15 years ideas came up to produce closed deck motor blocks, using coreless molds for casting and then insert a contoured deck which is sealed with a CNC controlled EB weld. Precision casting and even pressure diecasting of aluminium in conjunction with EB welding is being tested.

Fig. 17, 18: Closed deck motor blocks. Left: open; right: closed with contour welds.

With increasing power of the engines it became obvious that the best suited alloy for the liners is not good for the crankcase and vice versa. Therefore a lot of experimental work is going on to modify the metallurgical structure or the mechanical surface of cylinder liners, either by heat treatment or by alloying. Sometimes it is difficult to do this with the entire crankcase. E.g. it may be much more convenient to rotate just the liner in order to perform an inner surface treatment and then weld it to the motor block, or even more effective, use a liner material with the required properties.

As aluminium alloys with a high content of silicon show good tribological and wear resistant properties, they are well adapted to be used as cylinder liners. However these hypereutectic alloys do not meet the requirements regarding stiffness and strength, necessary for a crankcase of a high-powered engine. Therefore dissimilar alloys are being joined by EB welding, just welding the liner into the motor block on the bottom as well as on the top side.

Fig. 19, 20, 21, 22:
Motor blocks with EB welded inserted liners, closed deck (above) and open deck (below).

A curiosity with respect to prototype manufacturing was the request to produce an 18-cylinder engine for Bugatti. The car should drive with its own engine at the Geneva Auto Saloon. Cutting one cylinder off standard 4-cylinder motors and EB weld them to a 6-cylinder in-line motor was the first step. Three of such motors were then assembled in the shape of a W-motor. The job was successful; the engine had a wonderful roaring sound.

Fig. 23:
The unique 18 cylinder engine for Bugatti assembled with spacer plates.

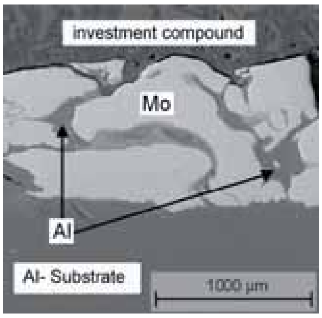


Fig. 24: Structure of molybdenum dispersed in aluminium.

An interesting and novel technology is “dispersion alloying” on the inner surface of liners by spraying molybdenum or tungsten droplets via centrifugal forces. A rod of Mo or W is rotated in the center of a cylinder with 5.000 to 40.000 rpm and at the same time heated by an intense electron beam above melting temperature. The particle size of the liquid heavy material at temperatures twice as high as the melting point of aluminium depends on the rotational speed. The droplets penetrate deeply into the liner. After honing the surface is hard and wear resistant.

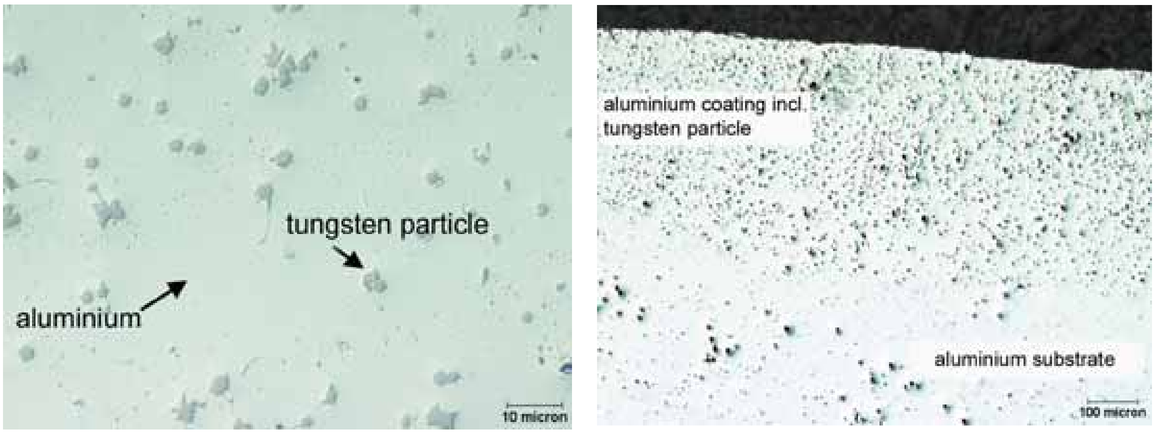


Fig. 25, 26: Dispersion alloyed structures.

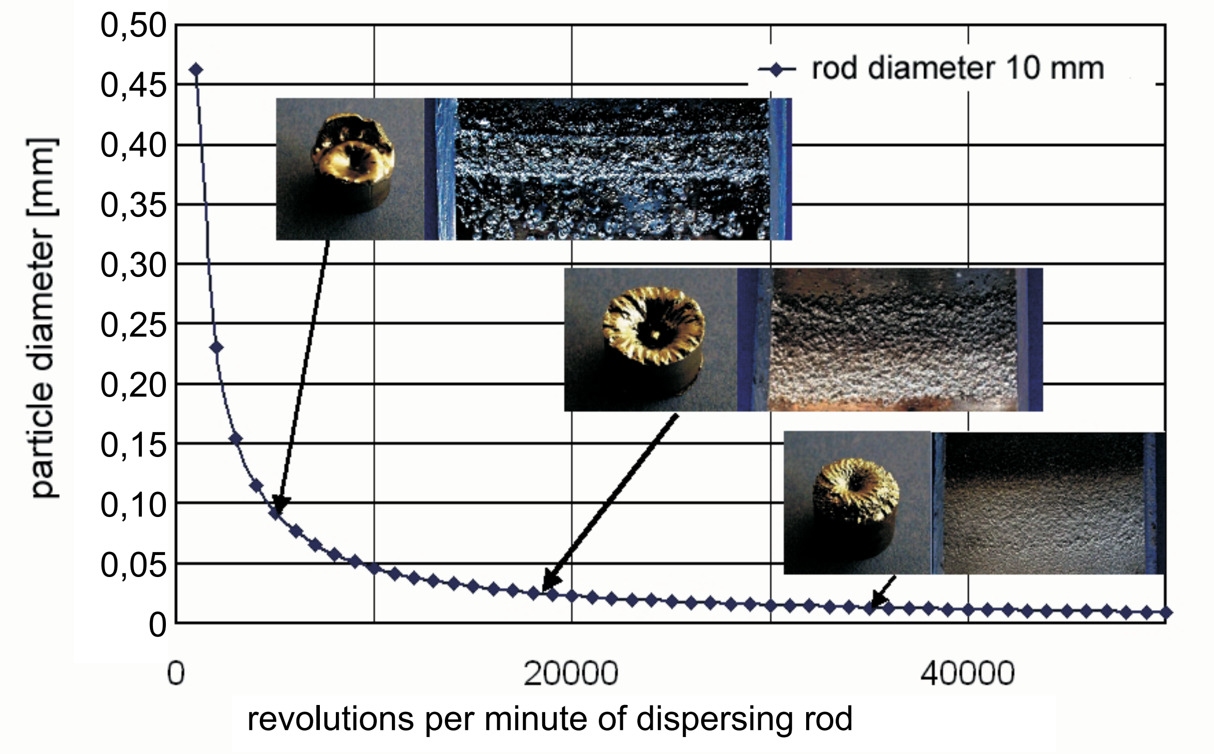


Fig. 27: Particle size depends on rotation speed and resulting surfaces.

Fig. 28:
Liner of hypereutectic aluminium alloy EB welded to dissimilar alloy with better stiffness.

Many pistons are made of aluminium silicon alloys. The bottom being cast because the steel support ring for the sealing ring has to be melted in, the rest is a forged alloy. Using EB welding to join the two parts, it is possible to simultaneously produce the cooling ring channel. In this case, adapted to larger motors for trucks or ships, the circumferential weld is executed first, allowing free shrinkage with reduced stresses. The second axial weld has to be as narrow as possible, because the alloys in question have limited ductility and therefore are susceptible to strain cracking. A subsequent heat treatment is necessary. For smaller pistons, two parallel axial welds are designed because they can be performed in the same fixture and operation within the welding machine and thus reduce cost compared to 2 welds in different directions.

Fig. 29:
Slender EB welds allow to produce a cooling channel without a lost core for casting.

Fig. 30: The cooling channel on smaller pistons is welded with 2 parallel seams.

Fig. 31, 32:
Pistons built from wrought and cast alloy make use of the design capability of EBW.

Camshafts are being EB treated in two different ways: the cam surfaces of those made of grey cast iron are either fusion treated by remelting a surface layer of about 1 mm thickness with self quenching and subsequently ground, or they are just transformation hardened at a depth of 0.7 mm. Depending on the number of cams to be treated, the cycle time in a twin chamber machine is 35 to 55 seconds.

Fig. 33, 34: Various designs of cam shafts with 6 to 12 cams.

Fig. 35: Twin chamber machines for surface treatment of cams.

The newer types of camshafts are of a light weight design. A tube is shaped by internal hydroforming and at the same time the excentric camrings, made of case hardening steel, are fixed in position. The two open ends of the tube have to be closed by EB welding of end pieces.

Fig. 36:
Hollow camshaft with EB welded endpieces.

Fig. 37:
Production line for EBW of camshafts with pre- and post-processes.

A curiosity for weight saving was the trial to EB weld a crankshaft of a truck. At each bearing seat the piece was split and the inner material was removed down to the required wall thickness before being rewelded by means of an electron beam. Using internal hydroforming, this idea may eventually revive somewhen.
EB hardening of crankshafts may be in series production much earlier. The challenge is the access to the radii under flat angles and to achieving sufficient depths of hardness.

Fig. 38:
Experiment for weight saving on a crankshaft.

Fig. 39:
EB hardening of crankshafts.

Viscous vibration dampers in various sizes up to ∅ 800 mm have been EB welded since nearly 4 decades. As there is a big production volume and each damper has two relatively long welds, they would be welded most economically in a load-lock transfer-machine with an idle time of less than 15 seconds for work piece exchange, however drop bottom machines are the state of the art today with an idle time close to 60 seconds. From the material side, grey cast iron in combination with a mild steel cover requires welding with a relatively slow speed, therefore the key to economy is suppressing idle time.

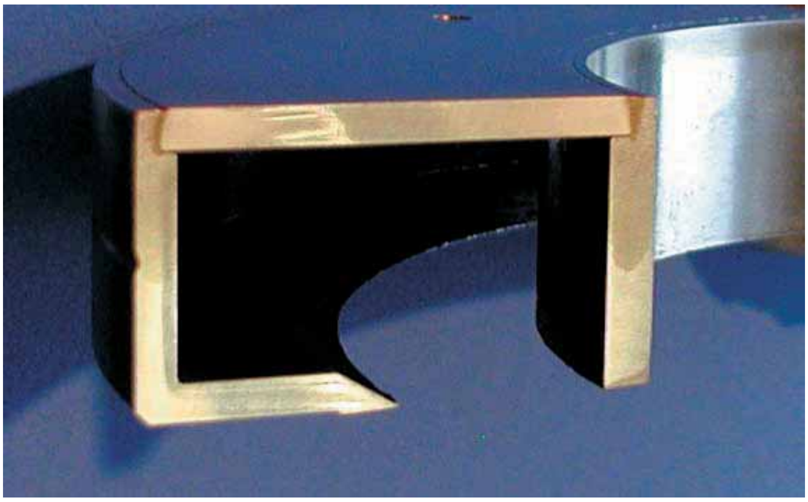


Fig. 40, 41:
Viscous vibration damper, top view and cross section of the 2 welds of a different type.

Fig. 42:
Hollow piston rods.

Fig. 43:
Shortened piston rod.

EB welding offers great flexibility for experimental work and for manufacturing of prototypes. The designer can easily transfer his ideas due to free programmability of any weld contours or beam parameters.
For racing cars some designs have been tried to produce hollow piston rods of a titanium alloy, but failed. The stress free design with two longitudinally split symmetric halves of an annealed titanium alloy is still waiting to be tested.
Sometimes piston rods have to be adapted in length for experimental purposes by using series parts.

High performance engines, especially for racing purposes, use hollow, sodium filled valves for improved heat dissipation at the valve head. Using EB welding to close the lid has the advantage, that there is vacuum inside the valve, which protects the sodium from contamination.

Fig. 44:
Valves cooled by a heat pipe system.

Fig. 45:
Standard light-weight valve with hollow interior and fusion treated sealing edge.

Fuel and Combustion Management

Many auxiliary aggregates to the engine are EB welded as well. Pressure sensors for common rail injection systems require deep penetration welds for pressures up to 2000 bars. At the same time the heat input has to be minimized due to heat sensitive semiconductor surfaces close to the weld. The only solution to meet these contradicting requirements is a very narrow weld seam. An aspect ratio depth to width of twelve is achieved.

Fig. 46:
Pressure sensor for common rail injection systems.

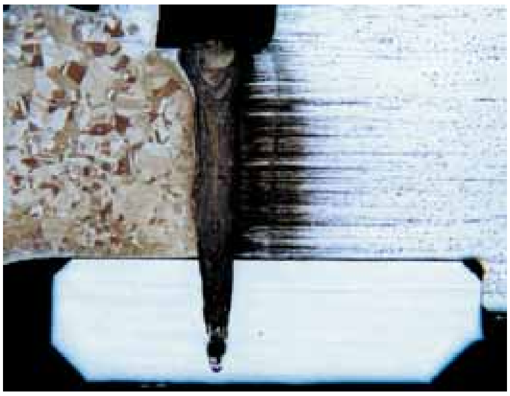


Fig. 47:
Microsection of sensor weld 0.2 mm wide, 2.3 mm deep. Dissimilar materials.

Another request is, that parts which are (miss) assembled with a run out or a face out, or which are wrongly loaded in the welding fixture, must not be welded. This is achieved by a quality control method, using the analysis of back scattered electrons. One full revolution of each part is done for seam tracking prior to welding. Using 20 scans per revolution, the projection into plane has to be a straight line showing that parts are well assembled. If deviation from straight is more than ±10 µm the parts are not welded and can be reassembled, thus saving the expensive semiconductor. The pressure sensors are produced in load-lock shuttle-machines (Fig. 1) with a gantry for automatic loading and unloading of a 20 spindle rotary device. Total cycle time is 1.5 min for 20 parts.

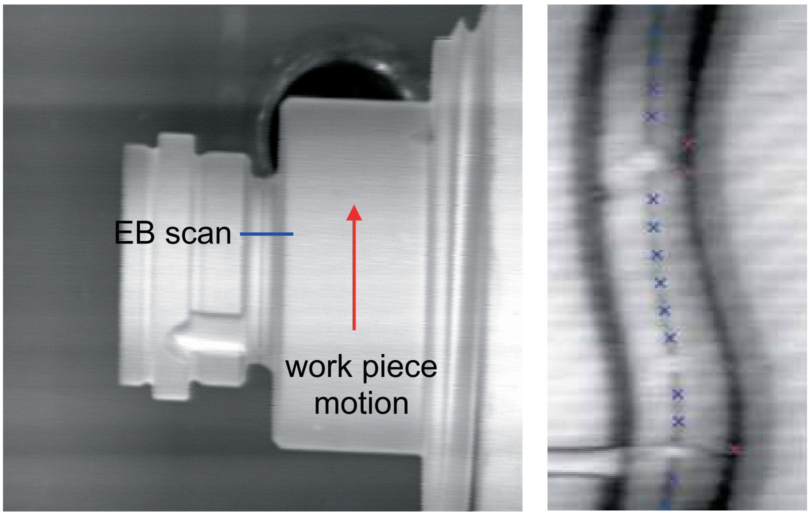


Fig. 48, 49: left: Pressure sensor monitored by back scattered electrons and right: projection into plane of the weld joint. A good assembly shows dots in a straight line with no deviation.

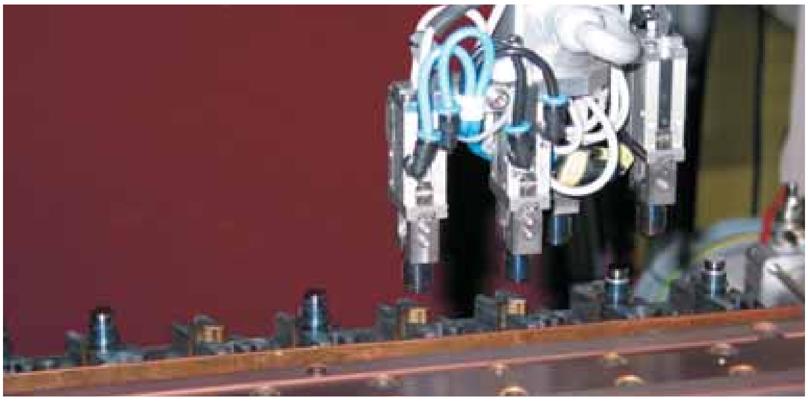


Fig. 50: Loading and unloading with a 4 claw gantry system.

Fig. 51, 52: For special size sensors a different tooling is being used.

Fig. 53: Production tool for welding injectors.

Fig. 54: Solenoid direct injector.

Recently developed solenoid direct injectors (SDI) show reduced CO_2 emission and an improved cold start behaviour. Three tube shaped parts are centered one in another and are being EB welded with two welds at a small angle. The work piece carriers are 8-spindle rotary devices, each carrying one injector. With the pointed angle of beam impingement a run out of the parts results in 3 times the deviation in weld position and this in return in less beam penetration. In order to achieve consistent weld quality, an automatic beam alignment is introduced, which detects the exact joint position in 2 different vertical levels. Loading and unloading of the work piece carriers is manual. For quality control a helium leak test at a pressure of 120 bars and a run out test has been adapted.

The fuel injector pipe, manufactured by internal hydro forming, is joined to a tube with a circumferential weld which requires high integrity.

Fig. 55: Fuel injector pipe.

Less spectacular components are impellers for turbo chargers, as they have been EB welded since 3 decades. But of course there are improvements, mainly in materials selection. As the trend for the impeller goes to materials with higher fatigue resistance at more elevated temperatures and the shaft material to tougher and harder steels, the material selection is limited by its readiness for welding. Super alloys of nickel- or cobalt-basis with exceeding titanium and aluminium content use to produce cracks which may propagate during use. Therefore special care is necessary to avoid such cracks.

Fig. 56: Turbocharger: Impeller made from a superalloy, shaft of case hardening steel.

Another automotive application, which requires EB welding due to materials selection, are valve heads of turbo chargers. The material is a high temperature alloy, which tends to hot cracking. The circular weld with a diameter of 8 mm and a penetration of 5 mm is restrained from shrinkage. Therefore a very narrow weld has to be applied in order to minimize stresses. A weld with an average width of 0,5 mm requires a position tolerance of 0,05 mm of the beam at the joint. With a larger tolerance, there might be a lack of fusion at the weld root. Using the capability of a scanning EB to monitor an image of the work piece edges by back scattered electrons, the exact positioning of the beam at the joint can be achieved fully automized, which, as a consequence, allows man-less welding. As there is no way for a non-destructive testing with the existing part shape, one has to rely on the exact reproducibility of the welding process. The production is being performed with work piece

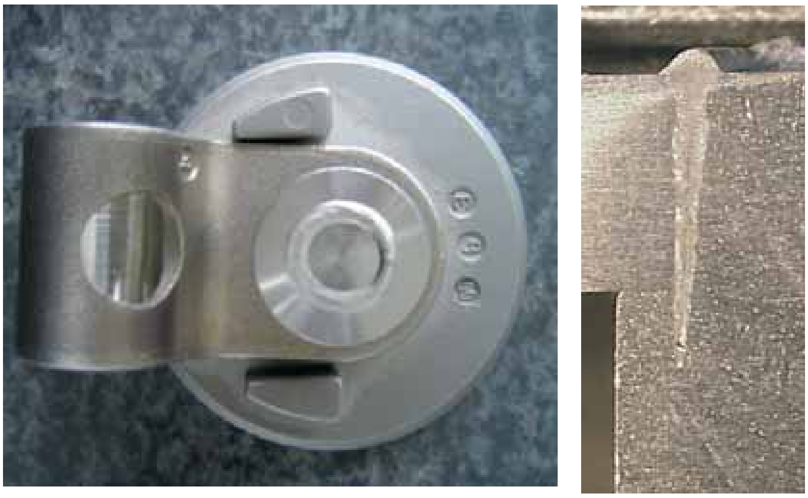


Fig. 57, 58:
Valve head (flap) and related cross section of the weld.

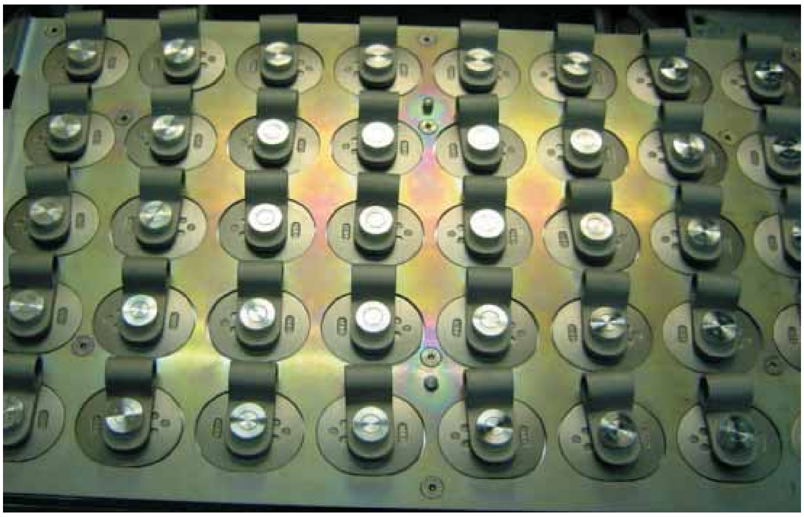


Fig. 59: Multiple tool for welding valve heads.

carriers, holding up to 50 pieces each (depending on size) and being processed in a load-lock shuttle-machine. The energy consumption of the entire system is less than 25 kWh per 1000 parts.

The adjustable tail ring of a turbo charger is made of high temperature alloys and today they use to be welded with TIG or plasma. Assembling in a fixture so that all tails are exactly in right position was as time consuming as todays welding.

EB welding with a multi beam flash technology in combination with automatic monitoring of the weld joint positions is a way to accelerate production speed considerably.

Fig. 60, 61: Control ring for turbo chargers. Front and reverse side with 11 circular EB welds.

Along exhaust pipes, an EB welded catalytic converter or a particle filter may be inserted, depending on kind of engine. The steel carriers with the large surface for the catalyzer are sometimes made of corrugated stainless steel. As the positions where the foils touch each other are irregular, welding is performed with a beam, scanned with high frequency in two axes. Thus every joint is welded.

Contrary, welding of particle filters may be performed with a precise jumping of the beam to the joints of the 60 filter pockets at a frequency of 60 kHz, so that all 60 welds are produced simultaneously at a relatively low welding speed. The low speed is necessary, as the wire mesh, carrying the catalyzer, does not melt and flow smoothly at higher speeds, but produces intense sparkling and spattering. In order to maintain productivity, simultaneous welding of all joints is an attractive solution. The overall time is 16 sec per part compared to 16 min with TIG welding.

Fig. 62:
Catalyzer welded with a scanning beam within 3 seconds.

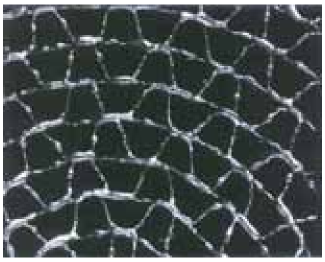


Fig. 63:
Detail of Fig. 62.

Fig. 64:
Particle filter with simultaneous welding of 60 filter pockets in order to improve production speed.

Fig. 65:
Cross section through 4 layer edge weld of the particle filter.

Power Train

From the drive shaft the power is transmitted via a cardan shaft, in racing cars made of titanium, to the differential gear. The differential gear is one of the actual welding challenges as joining dissimilar materials like grey cast iron to case hardening steel without pre-heating and without interlayer material is not easy. When welding grey cast iron with a carbon content of more than 4%, combined with a typical gear steel such as 16MnCr5, even with the case layer being removed, results in an extremely hard and brittle fusion - and heat affected zone. At a weld depth of 25 mm the weld is 1 mm wide at a minimum. When cooling down the stress from shrinking is released by micro cracks. These are smaller than the size of carbon lamellas so that there should be no danger. A post heat treatment is not possible as the gears are already finished and hardened. Up to now the use of interlayer material and local preheating is the solution. Electron beam welding offers good potential to solve this problem without these precautions.

Fig. 66:
Driveshaft of a SUV. The weld with 35 mm penetration has to carry a torque of 750 Nm (see fig. 135, 136).

Fig. 67:
EB welded cardan shaft made of titanium.

Fig. 68: Differential gear combines grey cast iron and case hardening steel.

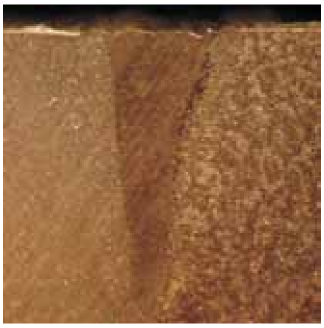


Fig. 69, 70: The problem could be solved by limiting weld depth. Welding with case layer and without interlayer material is feasible.

Chassis

Electron beam welding of axes, both for trucks and passenger cars is performed under various design aspects. There are two half shells with full length of the axle including the differential gear housing which are welded longitudinally with two EB guns. The guns are mounted under an angle so that they do not destroy each other in case of a weld run without work piece. In another design there is an axe extension. A stub shaft is welded to the tube, sometimes including the break-shoe carrier.

Fig. 71:
Two half shells of a truck axle (dummy for experiments).

Fig. 72:
Axles for trailers.

Fig. 73, 74:
Stub shaft of a truck axle is welded to the axle (upper weld). The break-shoe carrier is EB welded with several weld runs to increase weld width.

These applications are also simultaneously welded with two EB guns, as is the following wheel suspension of an SUV vehicle .

Fig. 75: SUV axle joined from 2 forgings and a preformed tube.

There are a number of different designs for car rims, all using aluminium or magnesium for weight saving of not spring relieved masses. Sometimes it is a circumferential radial or axial weld; in other cases spoke contours have to be welded according to NC programs. In any case the welds are safety relevant and have to be leak tight for tubeless tires. These rims are used for motorbikes, trikes, cars and race cars.

Fig. 76: Rim of a motorbike made of pressure diecast aluminium.

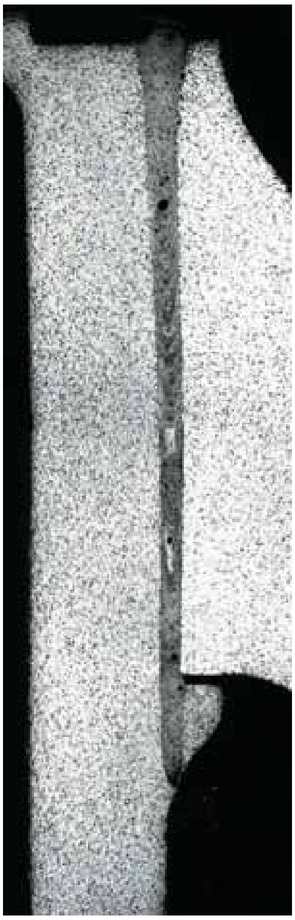


Fig. 77, 78, 79: Rims for race cars welded from forged magnesium alloys. Weld depth 20 mm.

Fig. 80: (left) Magnesium rim with contour welded spokes.

EB welding of shock absorbers seems to be a simple job, however there is a number of separate operations, which have to be done precisely. As always with EB welding, careful cleaning is essential to avoid porosity or blow outs where residual dirt or e.g. cooling lubricant from machining is left. The assembly has to take care that there is no gap remaining, which would lead to an undercut and that there is no tilt between the 2 parts, which would result in a run out.

To detect such defects, quality control in weld position is introduced by scanning the joint circumference with the electron beam. If the run out is found to be good, there is subsequent local preheating with EB at the automatically detected joint position, EB welding and EB marking for trace back of production data. This is followed by a run out measurement after welding and an ultra sonic control for porosity and lack of fusion. All data can continuously be recorded to an integrated data processing system.

Fig. 81:
Piston rod of a shock absorber with weld and identification by EB marking.

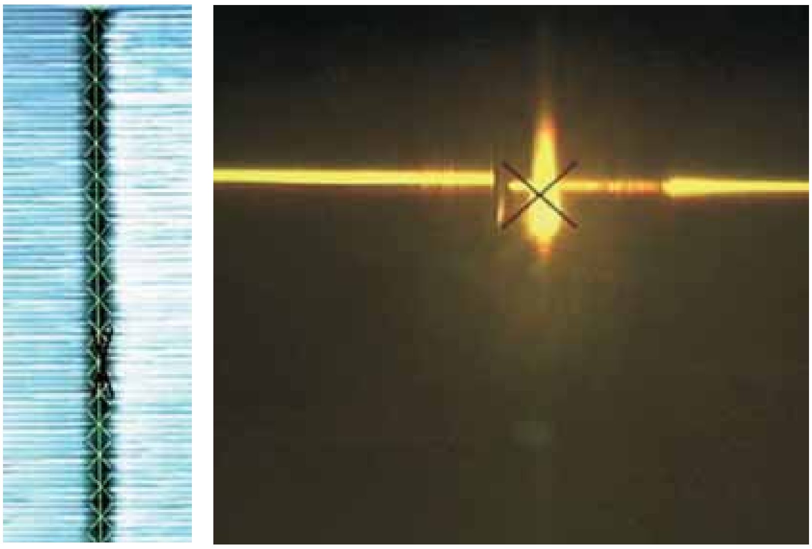


Fig. 82, 83:
An EB scan checks run out for correct assembly (left) before welding (right).

Components:

A product of high volume where EB welding is applied are hydraulic diaphragm tanks of various designs. They have in common that close to the weld there is a rubber membrane fixed to a suspension ring, which has to be sealed pressure tight with the same weld run as the one joining the two half shells. This means that the butt weld between the half shells has to resist high pressure and the overlap weld with the ring at the root of the butt weld has to be leak tight. At the same time heat input has to be small enough not to melt the rubber membrane.

Fig. 84: Diaphragm hydraulic accumulator.

Fig. 85: Weld root at the suspension ring.

Steering columns have been EB welded in large volumes already 40 years ago. Of more recent application is the steering wheel lock which needed some reinforcement on the steering column. A sleeve was EB welded to the column.

Fig. 86:
Steering column with reinforcement for lock.

Designs for racing cars change very rapidly and the parts to be welded are typically unique. So are the shifter rods and gear shift bars made from titanium for a formula-1 racing car.

Fig. 87: Shifter rods.

The adjustable back rest support for the driver and the passenger seat exists in so many different designs regarding the seat bracket, whereas the wobble plate for adjusting stays always the same. Therefore it makes sense to make the stampings on a small machine in high volume with a simple tool and join the brackets in their manifold of shapes by EB welding.

Fig. 88:
Back rest adjusting for passenger cars.

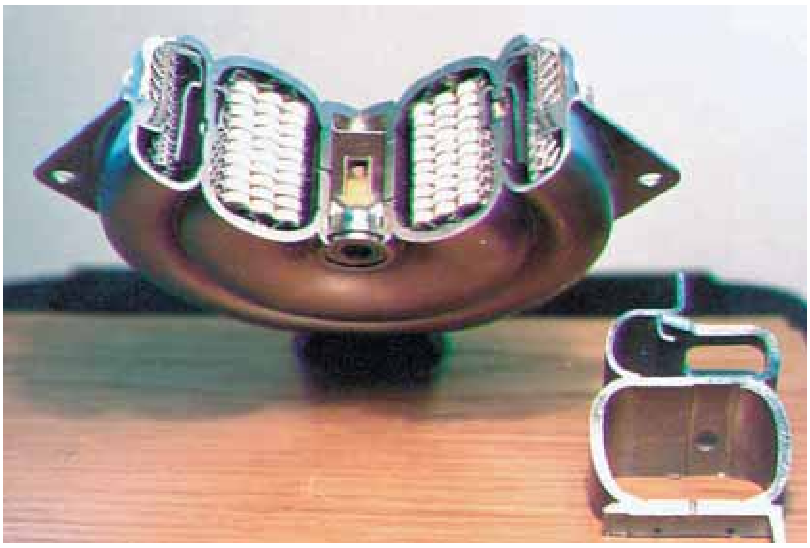


Fig. 89:
Gas generators for driver airbags with 5 concentric EB welds.

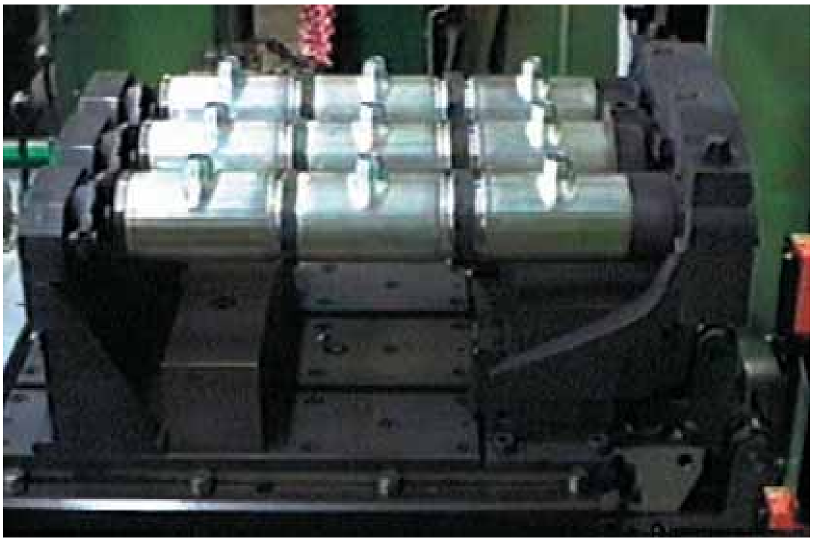


Fig. 90:
Gas generators for passenger airbags with 1 axial and 2 radial EB welds.

Electron beam welding of gas generators for driver and passenger airbags has been in use since long. The reason for EB welding is low heat input, as the final welds are done with the explosive inside. The airbag generators would ignite when overheated or when the beam, directly or via spatter, would hit the explosive.

Now new laws request that the pressure within the balloon is adapted to the weight and the seat position of the passenger. The seat is mounted on 4 power sensors, which signal whether a child or a heavy person is sitting close or far from the front window and control the gas flow into the balloon accordingly. There are 3 welds on the spring and another 8 tack welds to fix a cover for the sensor. As the welds are security relevant and as the material is sensitive to strain cracking, intensive control is applied. Each sensor is identified by a data matrix code. After cleaning the 3 parts housing, spring and screw are assembled, clamped in a fixture and EB welded. In a second run the lid is mounted and welded. Then a 100% bending control and a 100% X-ray control is applied. The bending improves, by cold forming, the strength characteristics of the material.

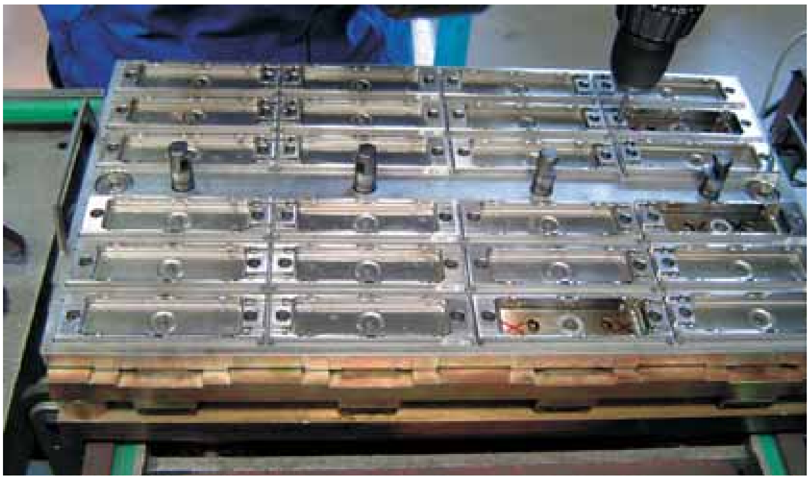


Fig. 91, 92:
Sensor to register seat position and weight of car driver and passenger. Clamping tool for production of 24 parts.

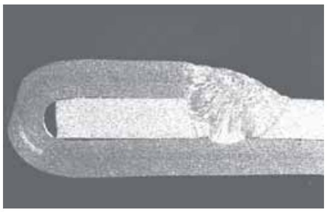
An auxiliary heater, for gasoline and diesel engines, warms up the engine following a preset time. The necessary fuel, according to regulations, must not be taken from the tank, but out of an additional container with limited size. This is made of pressure diecast aluminium and has to be helium leak tight. Therefore no porosity is accepted in the weld. It can be achieved by multi beam welding, e.g. 3 beams following simultaneously one after another at a distance of a few millimeters. The related heat exchangers, also used in Diesel engines for addition heating, are hermetically sealed by EB-welding.

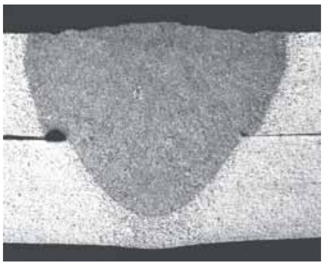
Fig. 93:
Fuel container and heat exchanger of an auxiliary car heater.

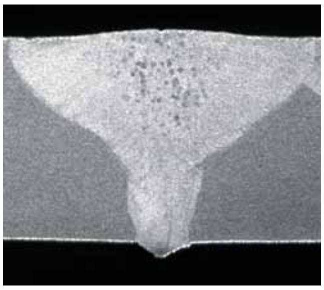
There are only a few, but sometimes important, EB welds in automobile electric. The contact terminal of a car battery controls the state of charge and current flow by means of a shunt and an electronic chip. It incorporates 5 EB welding and one EB brazing operation.
Heat sensitive electric components which have to be placed in the motor region need cooling and protection from dirt and oil. Therefore they are embedded in an aluminium housing with good heat conductivity and sealed by EB welding.

Fig. 94: Battery cable contact clamp.

Fig. 95: Housing for electronic board.







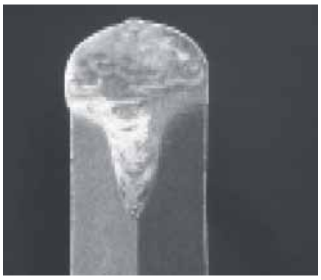


Fig. 96, 97, 98, 99:
EB seams welded at a distance of 2.5 m by beam deflection: Fillet weld, overlap weld, butt weld and edge weld.

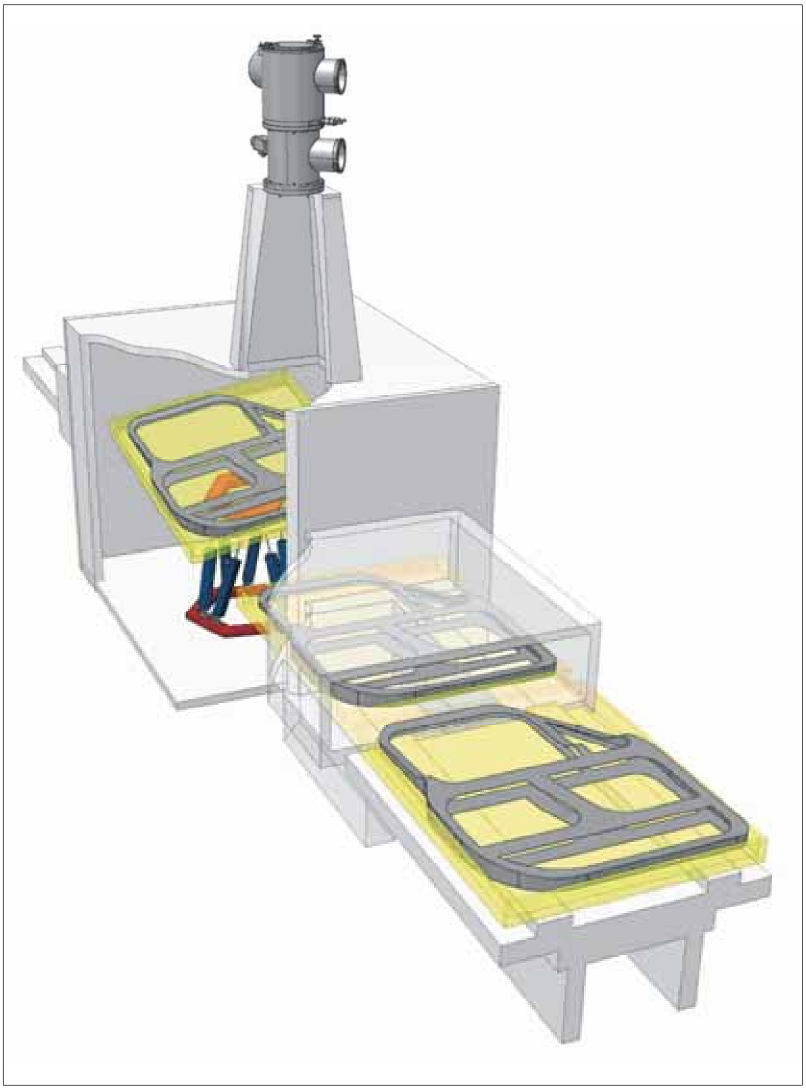


Fig. 100:
Principle of remote welding of a car door using a load-lock shuttle-machine and table swing.

In the preface to this chapter it is mentioned, that EB welding is not applied to the car body. Yet the potential for remote welding of sheet metal is quite good, both for tin coated steel as well as for light metals like aluminium or magnesium. The weld seam is smooth without undercuts and optically perfect. The welds were made only by beam deflection at a remote distance of 2.5 m. The main advantage, compared to laser beam welding, is the vacuum as application of shielding gas is, where required, a problem for remote welding. Exact clamping is essential though. Using load-lock machines the cycle time for a 4 m long weld on a car door will take about 1 min.

Fig. 101:
Tailored blank as support for a shock absorber. A 2 mm thick disk is EB welded into the 1 mm thick wheel box and subsequently deformed.

Transmissions and Gears

Gear welding is the application within automotive industry which occupies most of the electron-beam welding machines. It is the possibility to join ready machined gears, or gears to shafts or flanges as a final operation, which makes EB welding attractive. The shrinkage resulting from cool down of the melt pool is so small that the final part is within the required tolerances. The residual eccentricity is within hundredth of a millimeter and does not influence the

Fig. 102:
The synchronizing ring with low mass and the gear with high mass warm up and expand at different speed. This is the typical weld situation when welding gears.

function of the gearbox. However the noise level is also influenced by eccentricity and therefore a symmetric heat input with a multiple of electron beams, welding simultaneously, can be used to keep the shrinkage symmetric. This avoids a set off between the axes of the components. In addition some cost reduction, due to shorter cycle times, is a positive aspect, besides noise reduction. Gears to be welded may already be hardened, but it is necessary to remove the case within the welding area.

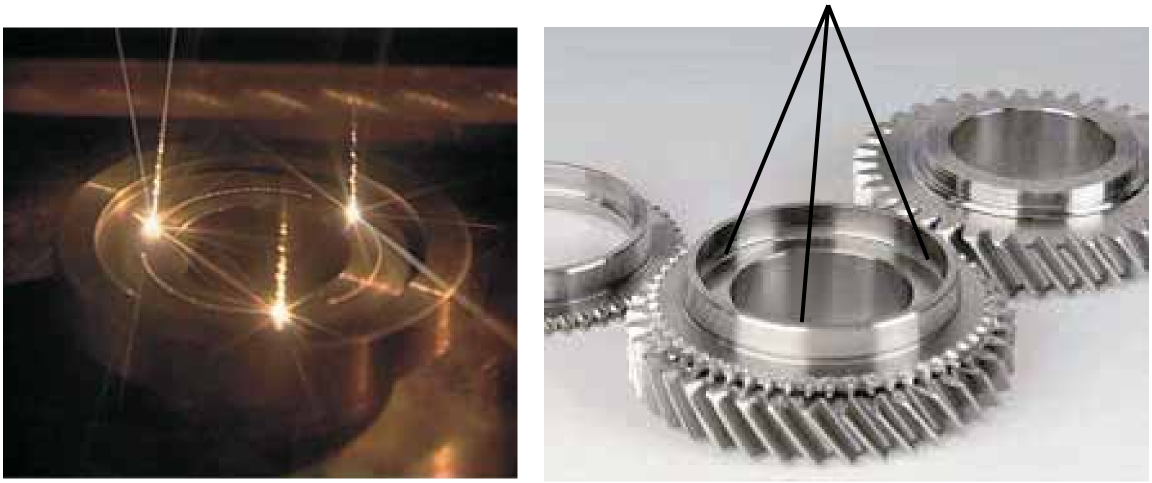


Fig. 103, 104: Triple beam welding of synchronizing gears prevents axis offset.

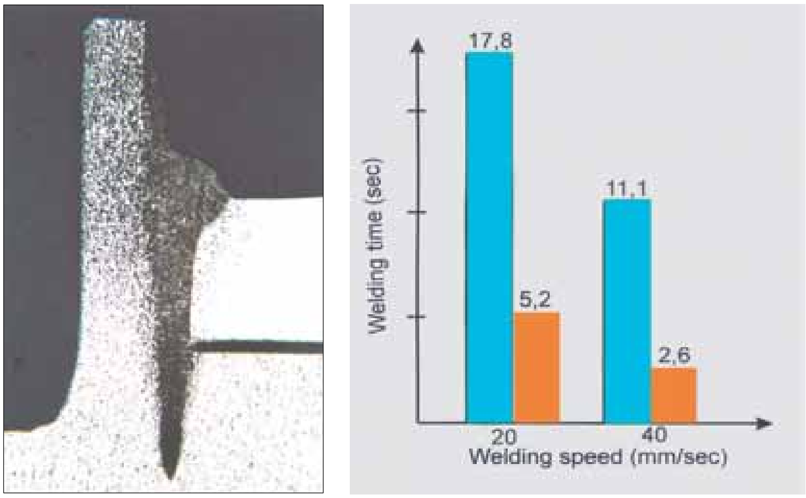


Fig. 105, 106:
Series production of gears is being improved by multi beam technique: reduction of distortion by symmetric heat input and narrow welds; right: reduction of welding time by elimination of tack-weld and reduction of weld length for each beam.

Fig. 107, 108, 109, 110: A selection of gear combinations for automotive applications.

Fig. 111, 112:
Bevel gears and triple gears are manufactured to advantage by machining each part individually. Subsequent joining requires a process with minimum heat input, as the parts are already hardened and minimum distortion to meet the tolerance specifications.

The basic idea in designing EB welded gear assemblies is to ease forging and machining, which is obviously much simpler and more economic with separate components compared to a monobloc design. As tools for cutting teeth need space for run out, a monoblock gear combination is always much larger than a joined one. This, in return, reduces not only the weight of the gear assembly but also of the shafts and the entire gear box. The dense and stiff packaging also reduces vibrations. And last but not least, EB welding opened the way to introduce sheet metal and powder metallurgical designs, which are most successful in automatic shifted transmissions.

Fig. 113: Sintered clutch drum welded to a deformed gear disk and a shaft.

*Fig. 114:
Joining of forged and machined gear blanks.*

Fig. 115: Radial EB welds between flanges and gears.

Fig. 116: Deep drawn sheet metal part with hollow shaft of a clutch.

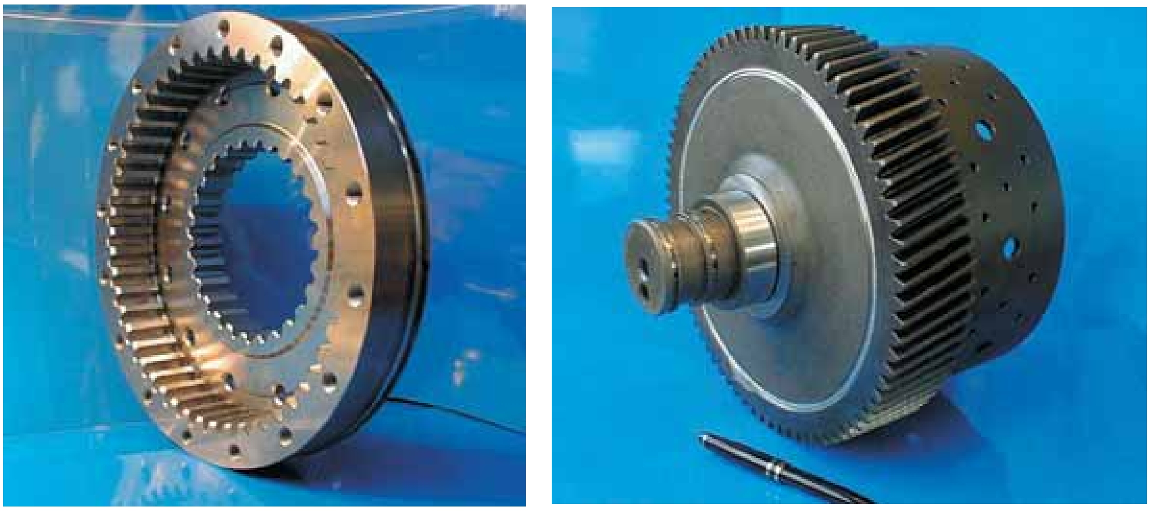


Fig. 117, 118: *Gears with radial and axial EB welds.*

Fig. 119, 120, 121: *Gear unit for a wheel loader.*

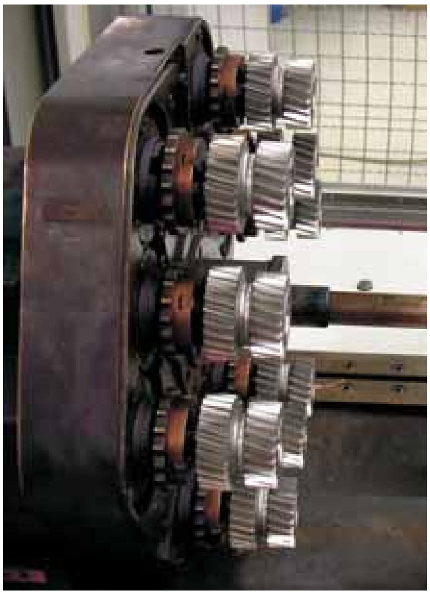


Fig. 122: *Multi spindle unit for economic welding of gears on small volume production.*

Fig. 123: *Weld detail of construction of Fig. 122.*

The cage of planetary gears is another typical example for electron beam welding. The cages may be made from forgings for trucks or from deformed sheet metal for passenger cars. Both, the continuous variable transmission (CVT) for longitudinal installation in the car and the dual clutch transmission (DCT) for transverse installation use complete production lines for man-less automatic EB welding.

Fig. 124, 125:
The triangular cross section of a truck planetary pignon cage has to be welded across the full profile.

Fig. 126:
Stub shaft of a homokinetic transmission.

Fig. 127:
Chain drive for camshaft.

Fig. 128, 129, 130, 131: Planetary pignon cage with 3 radial welds (top) and drive gear, welded through the upper orfice. The part belongs to a CVT transmission.

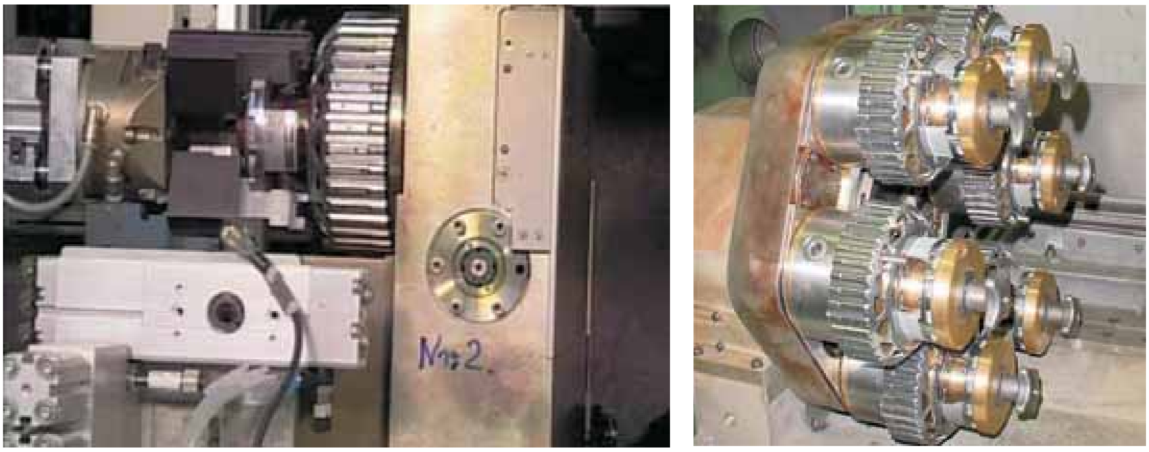


Fig. 132, 133: Robot assisted loading for man-less production welding machine (left) and manually loaded multi spindle tool for smaller volume production of above CVT.

Another reason for EB welding of gears is the accessibility of the extremely slender beam to the joint. A further aspect is the capability of the electron beam for deep penetration in combination with the parallel weld bead, even close to an edge. This allows to weld gears, which have to transmit high torque.

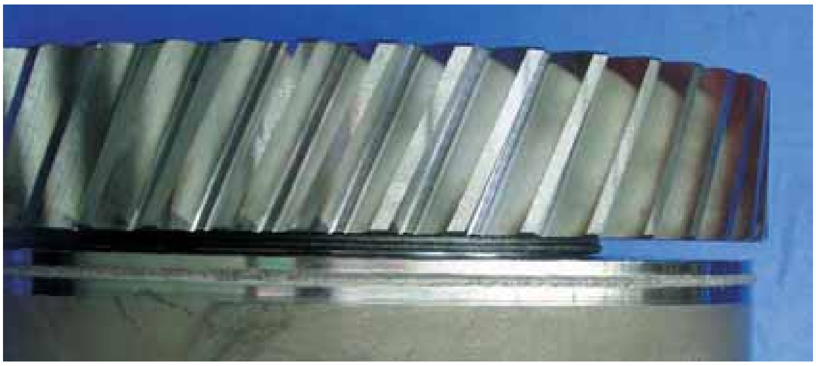


Fig. 134: Gear design with difficult access to the weld at the bottom of the slot, besides the one close to the slot edge.

Fig. 135, 136: Cross section of drive shaft with 35 mm weld depth for high torque transmission. Weld position close to the shaft.

Actual developments for new automotive applications like starter generators, fuel cells, or hydrogen tanks are in progress. Results are promising, however still confidential.

Resuming this selection of typical automotive applications of EB welding, it is evident that the designer must be aware of the typical capabilities and possibilities of EB welding. These are: minimum heat input compared to all fusion welding processes, resulting in little shrinkage and low distortion. By applying dissimilar materials according to function, cost savings can be important and performance may be improved. Lightweight design is being assisted by EB welding from the engine to rims, from the transmission to auxiliary units. With increasing costs for material and energy and falling costs per part for welding, the attractiveness of EB welding will continuously grow.

Aeronautics and Space Industry

Fig. 137:
There are numerous EB welds on the Ariane rocket.

The Aircraft and space industries have already started in the mid 60ies to use electron beam welding, as at that time the shielding gases necessary to weld reactive materials like titanium and its alloys, were not clean enough to perform sound welds. Hydrogen embrittlement was the main problem, besides oxygen or nitrogen contamination. As more or less all high-strength materials are sensitive to change in structure, caused by welding, a welding process with minimum heat input and reduced heat affected zone, is preferred in order to minimize the detrimental influences in the parent materials, such as distortion, heat affection or residual stresses. Electron beam welding is the preferred process for joining nickel-base super alloys or titanium alloy components and even steel or aluminium aircraft structures are welded with excellent results. Moreover, the narrow and parallel weld geometry is well adapted to a non destructive weld inspection, thus eliminating concerns about weld structure integrity. As some of the components to be welded were quite large, e.g. the wing box of aircrafts such as for MRCA or the nacelle doors of the supersonic Concorde, huge machines have been designed, like the famous clamshell or tunnel machines, some of which are still in use. The three main criteria for airframe design which are closely related to material selection and weld process capabilities, are static strength, aero elasticity and fatigue life.

Aircraft Structures and Components

Fig. 138:
A safety critical part is the assembly of four forged Titanium segments by 4 EB welds to a hub which carries the rotor blades of the Cheyenne helicopter.

Fig. 139: Wing box of MRCA plane.

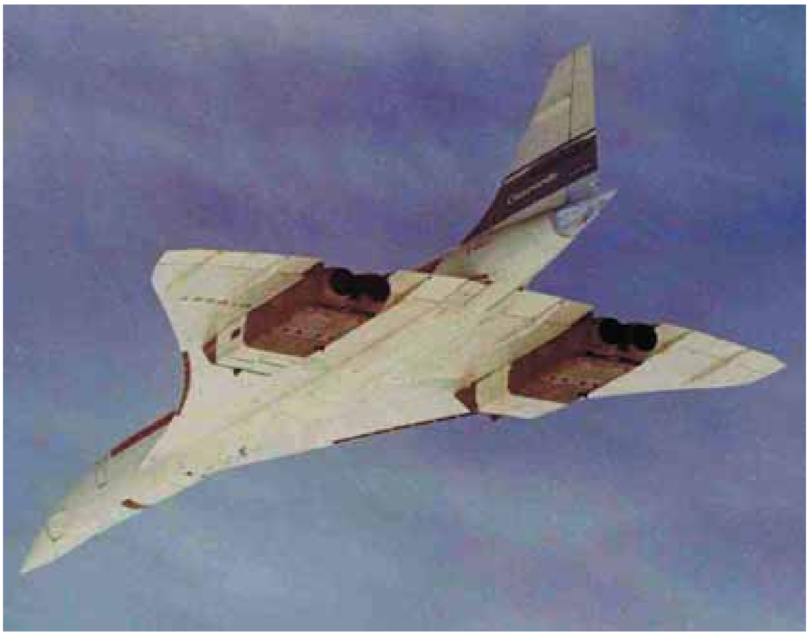


Fig. 140: The supersonic Concorde with the nacelle doors covering the engines.

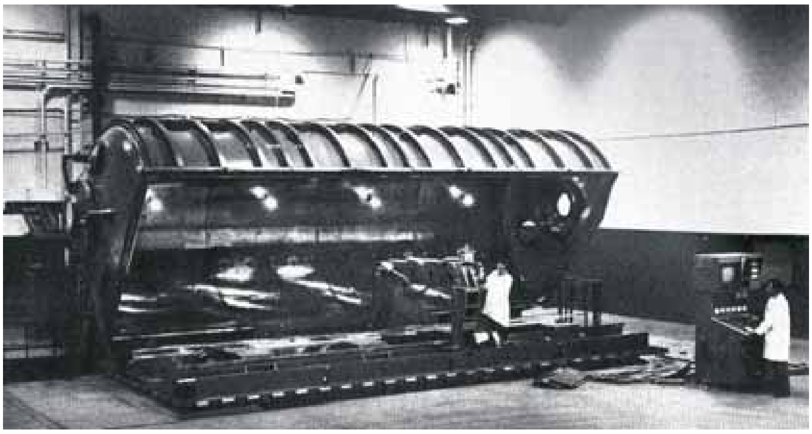


Fig. 141:
The clamshell was the largest EB welding machine in the 1970ies with a volume of nearly 100 m³.

Design studies for the nacelle doors as stable self supporting structures were carried out. The corrugated stiffener ribs were brazed to a string and then EB welded at a working distance up to 2.3 meters to the Titanium inner and outer skin.

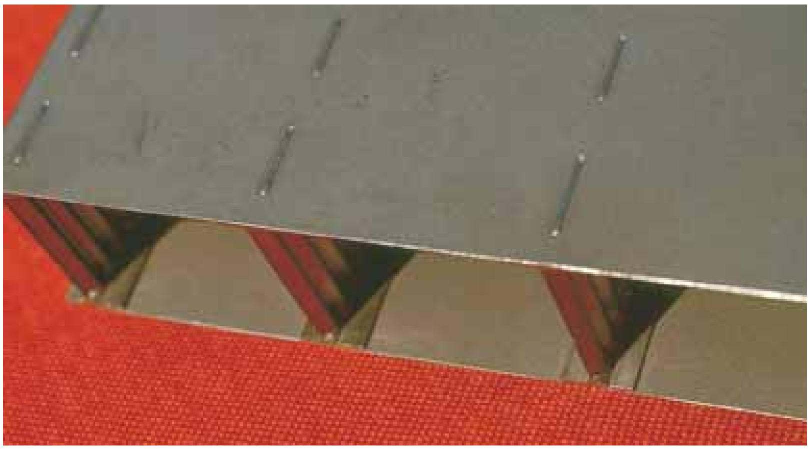


Fig. 142: Study of nacelle door design.

One of the recent applications of EB welding in aircraft industry are armrests for various models of airlines. The hollow arms are a light weight design of pressure diecast aluminium. The requirement to welding is an optically perfect weld bead on the bottom side, as this is visible to the passengers, whereas the opposite side will be covered with an upholstery. It is a high volume production and therefore a multiple rotating tool, which allows to weld all four directions in one evacuation, is being used on a standard load-lock shuttle-machine.

Fig. 143: Armrest from top and bottom side.

Fig. 144: Multiple tool for welding armrests from 4 sides.

A high volume product, designed to reduce weight, are hollow balls in various sizes, which are used for rolling cargo pallets into and inside a plane. The weld requires sound penetration and no undercut at the surface, as the balls are finally polished and must not show any dents.

Fig. 145: Hollow balls for cargo loading.

Fig. 146, 147: Boom with tooling and welded edge contour.

A boom, made from high strength aluminium, is used on helicopters. The casting is closed by a lid, which is EB welded all along the edge contour.

Aircraft Engines

Fig. 148: EB welding machine for aircraft engine components with a 10 m³ vacuum chamber, fully CNC controlled.

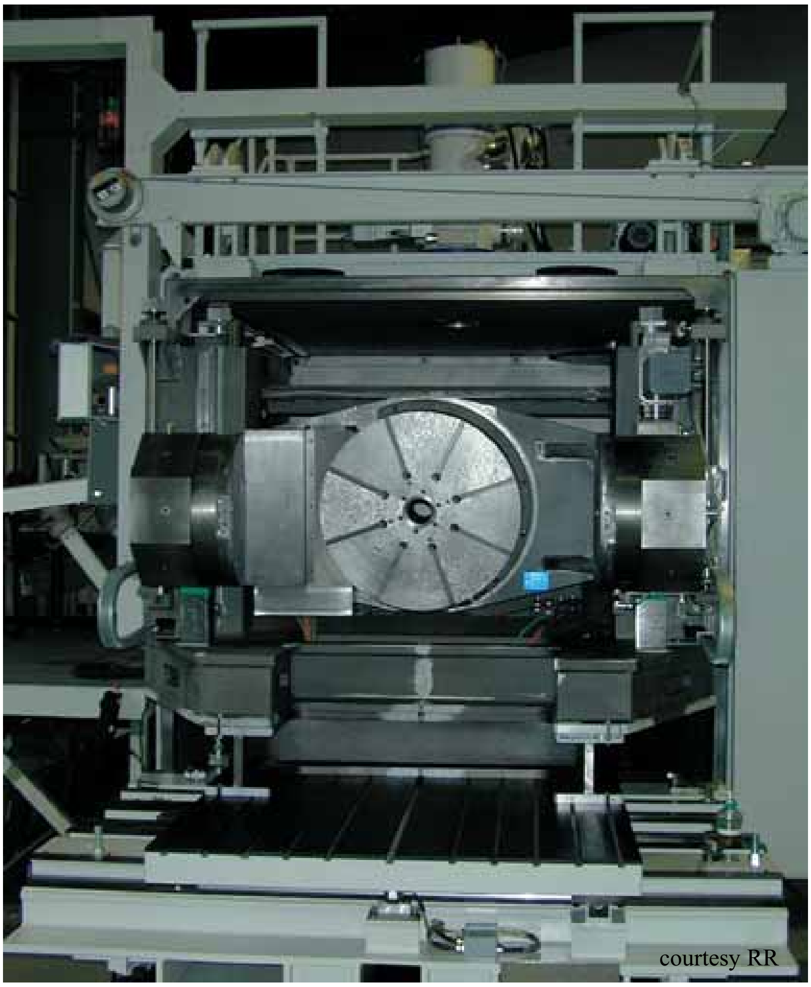


Fig. 149: Typical 4-axes manipulator of above machine: x-y table with rotating and tilting device.

The aircraft engine industry, which is using quite a number of medium sized EB machines with vacuum chambers between 10 and 20 m³ invests already in its 3rd generation of EB equipment. Contrary to automotive industry the aeronautic companies use highly sophisticated machines with all features that help to secure safe production of sometimes extremely valuable components, such as rotors or blisks for aircraft engines. It is also a typical aspect of this industry, that welding parameters, once developed and homologized on a certain machine, are frozen for the entire period of production of these parts. Neither the machine nor the welding procedure specification (WPS) may be changed without a cost effective new evaluation and certification of the WPS. The main reason for this precaution is, that the materials e.g. nickel-base super alloys, as typically used in aircraft gas turbines, must reliably operate at elevated temperatures. As this class of super alloys is susceptible

Fig. 150:
Rotor of an aircraft turbine, assembled from several disks.

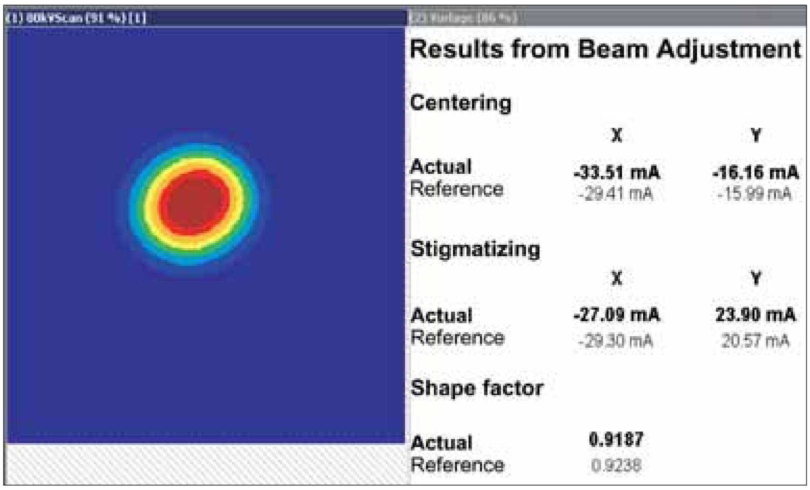
Courtesy RR

Fig. 151, 152:
Blisks (bladed disks) are parts of the highest safety class. They are made of dissimilar Ti-alloys and used in the high pressure compressor. The blades are integral part of the disks. Circumferential welds join the disks to a rotor drum.

Courtesy MTU

Courtesy MTU

to hot cracking, all process parameters including pre- and post-weld heat treatment have to be carefully evaluated and maintained exactly. It is hoped, that the recently introduced online beam analysis, which allows to characterize and compare electron beams of different machines, will eliminate these relicts from earlier machine generations. The basic idea is, that 2 electron beams from different machines or performed at different times on the same machine, produce exactly the same weld under condition that the power and its distribution are the same. Physicists



Results from Beam Adjustment

Centering

	X	Y
Actual	**-33.51 mA**	**-16.16 mA**
Reference	-29.41 mA	-15.99 mA

Stigmatizing

	X	Y
Actual	**-27.09 mA**	**23.90 mA**
Reference	-29.30 mA	20.57 mA

Shape factor

Actual	**0.9187**
Reference	0.9238

Fig. 153:
Automated beam adjustment includes focusing, centering and stigmatizing and analysis of the beam results in a beam shape factor.

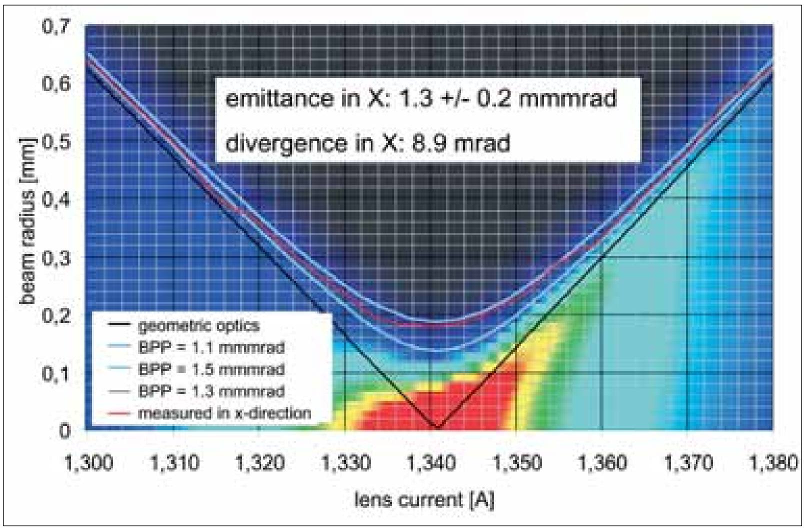


Fig. 154:
The beam parameter product depends on the quality of the optical elements and is a function of beam power.

would say: beams with identical beam parameter products (mm x mrad) and the same power perform identical welds. This kind of quality control is much more precise and time saving, compared to wedge probes or alternative destructive testing methods.
There are numerous gears in aircraft engines, which are EB welded under high quality specifications, mainly weld integrity and mechanical tolerances.

All gears by courtesy of P&W.

Fig. 155, 156, 157, 158, 159, 160: Gears of gasturbines.

Propellant Tanks

Another big improvement is the latest progress in seem tracking. Earlier systems required well defined joint edges to clearly direct the beam automatically into the proper welding position. Now it is possible to detect joints, which are sometimes invisible with the eye, a telescope viewing system or with the camera and still to position the beam with high accuracy.

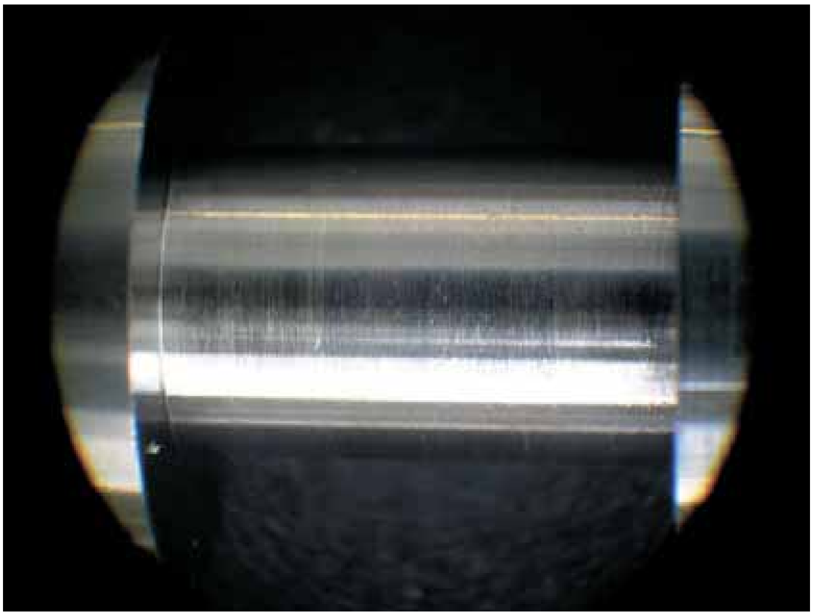


Fig. 161:
Titanium parts were assembled with a press seat and turned on a lathe. The joint is no longer visible.

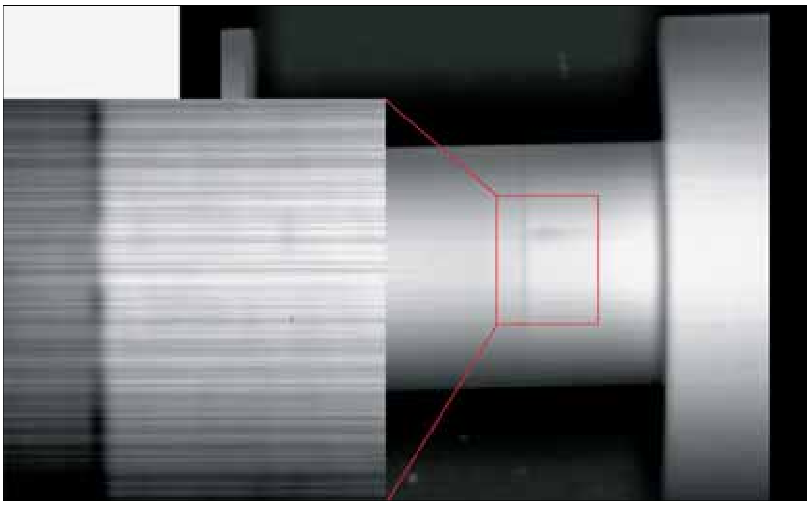


Fig. 162:
Scanning with an electron beam not only detects the joint position, but also reveals that there are different Ti-alloys, not visible by the eye or telescope.

A typical product, which needs this feature are satellite tanks, as the shells are so precisely machined, that it is sometimes difficult to detect the edges of the joint. With the use of back scattered electrons, the information for exact positioning is improved.

All tanks by courtesy of EADS.

Fig. 163, 164, 165, 166:
Titanium propellant tanks in different sizes with girth pole and interior welds.

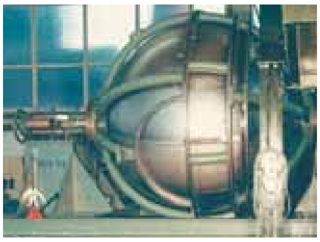
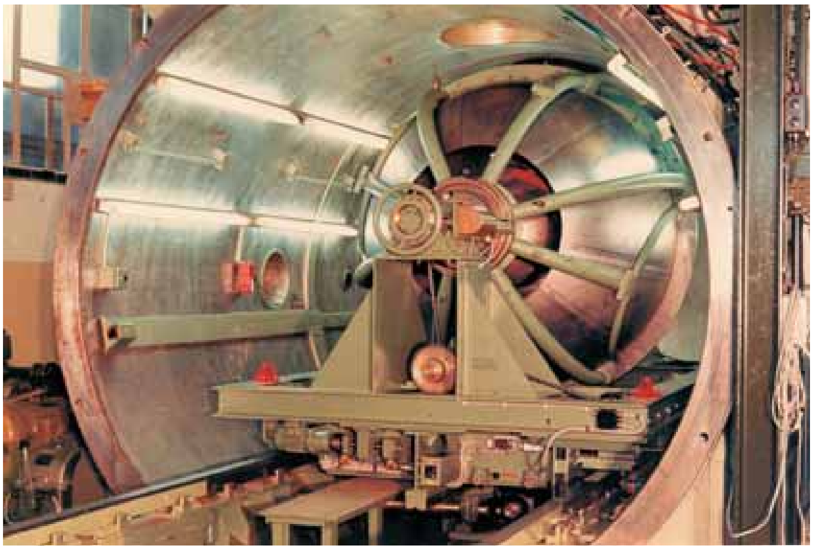


Fig. 167, 168:
Old Ti-tank from 1965 with meridional welds.



Propellant tanks for satellites and rockets are manufactured from titanium in sizes from a few cm^3 to several m^3. Whereas in early years the large tanks were fabricated from pre-shaped sheet metal segments, which were welded in meridional direction, today they are machined from forgings and welded in azimutal direction. In addition to the EB welds at the shell there are quite a number of EB welds at the inner structure for fuel management or at the inlet and outlet valves, which are proprietary to each manufacturer. A difficult weld is to be performed at the tank pole from the inner side at a distance of up to 2 m. Only a very good beam quality is able to penetrate deeply and to hit precisely at such long distances.

As parts of the fuel management system are very sensitive to differential pressures, the last welds to close the tank have to be evacuated and vented with a maximum pressure drop of 4 mbar per minute, which results in a pumping and venting time of up to 10 hours each. Therefore pro-beam built a machine with an auxiliary chamber for pumping and venting. This allows to make use of the welding facility for other welds. When the final pressure is achieved in the auxiliary chmber, the tank is transferred under vacuum into the weld chamber, thus improving economy considerably. This machine has a vertical and a horizontal gun with a vertical travel of 500 mm, allowing to weld on different positions without breaking the hard vacuum, necessary for titanium alloys.

Fig. 169:
Pole piece of a tank welded from outside.

Fig. 170:
Large EB welding equipment, specialised for propellant tank welding with a vacuum chamber size of 45+10m^3.

Surface tension propellant management devices are used to separate free gas from liquids by wetting micro porous membranes. Applications include control of liquids from storage tanks of space vehicles, operating under zero gravity as well as propellants during high-g maneuvers of aircrafts and missiles. The membranes for separation are of woven wire mesh or of EB perforated screens. Both are welded into structures inside the tank.

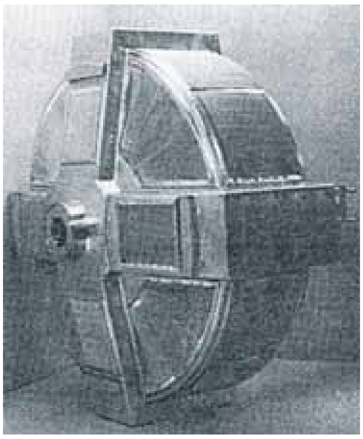


Fig. 171, 172:
Surface tension fuel management systems.

Fig. 173, 174:
Ariane tanks for main (right) – and upper stage (above), forged from welded plates and machined.

Fig. 175, 176:
Weld root and macro section with counter weld required for pressure tanks.

Fig. 177:
The plate with 6m in diameter just fits into the vacuum chamber.

Fig. 178:
A special transport is necessary for shipment.

High pressure tanks, the central stage main tank and the upper stage tank are built up of large domes. As aluminum plates, 70 mm thick, are not produced in the required width, they are EB welded from smaller segments. Then the plates are forged into the desired shape of the dome and machined with necessary ribs for stiffening and weight saving.

Propulsion Units

Thrust nozzles are existing in very small to very large dimensions. The small ones for orbit control of satellites have up to 20 EB welds including the valve assembly. The thrust nozzles of the upper stage as well as of the main stage of the Ariane rocket have 4 EB welds each.

Fig. 179:
Thrust nozzles for orbit control of satellites.

Fig. 180:
Thrust nozzle for Ariane. The LOX-dome is located on top of the nozzle.

The injection system of the central stage, the so called LOX-dome is EB welded with 3 seams with high requirements regarding integrity.

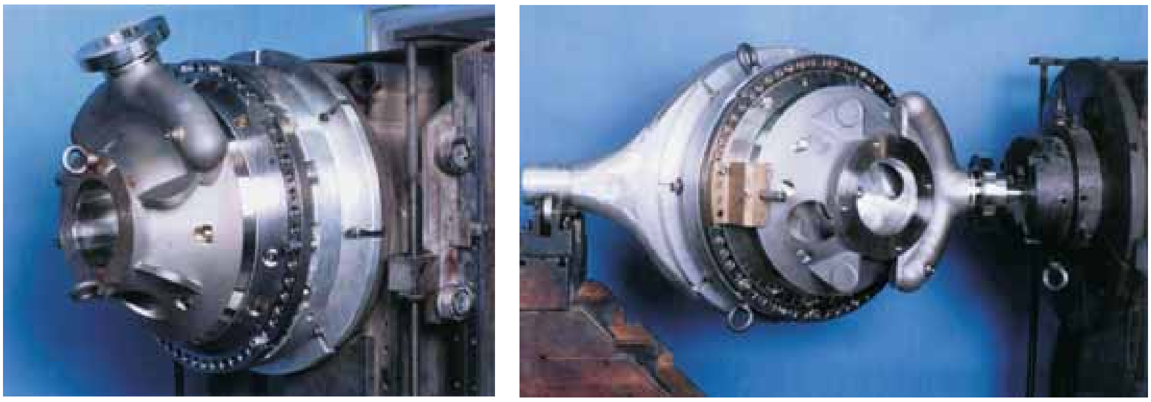


Fig. 181, 182:
Fuel injection system of the main engine of Ariane in 2 weld positions.

Electron beam welding is not only applied to products used in space, but also as a method for use in space. The existing good vacuum environment allows simple hand-held equipment. No pumps are needed, however the acceleration voltage of the electrons has to be reduced in order to protect the operator from hard x-ray radiation. Typically 15 kV is used. EB welding in space with hand-held equipment was developed both, by Americans and Russians. It is used for set up of antennas and for repair welding of the skin of space stations in case of meteorite damage.

Working in aeronautics and space industry is the most challenging field of EB welding, as the kind and variety of materials is pretentious, the parts varying from micro to huge sizes are of extraordinary value and nearly all welds are safety relevant. This results in requirements for exceptional stability, reproducibility, reliability and control of all processes including quality assurance. New electron beam machines are able to fulfill these requirements.

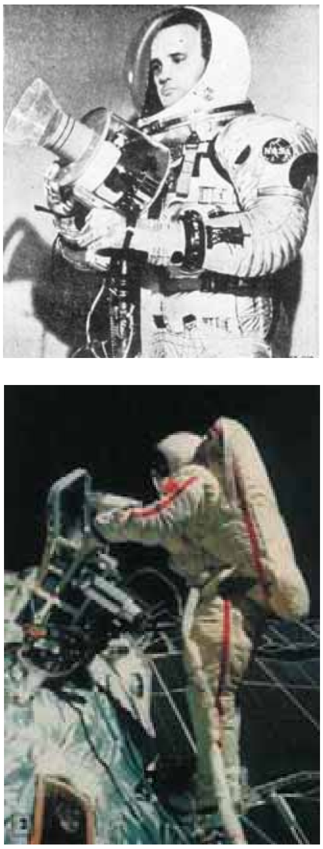


Fig. 183, 184:
American and Russian astronauts with hand-held EB guns.

Railway Industry

Fig. 185:
The high speed train ICE is designed to improve economy and comfort.

The railway industry is said to be conservative with its selection of materials and manufacturing processes. However, this has changed with the high speed trains. Reduction of weight and noise level is as important as in automotive industry in order to save energy and to improve comfort. The use of wear-resistant materials increases the lifetime of wheels and rails. And of course the need for cost reduction brings new manufacturing technologies into production.

Trains

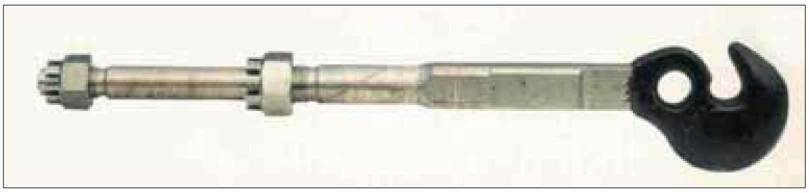
Fig. 186, 187:
Railroad car with EB welded cross beam.

Fig. 188:
Beamprofile with 2 EB welds, 35 resp. 40 mm penetration.

Fig. 189:
Makrosection of the welds.

A cross beam on the railroad car is made of extruded aluminium profiles. As these profiles are too large for extruding in one piece, and as the length of the two sections is different, they are joined by EB welding with two opposite welds. When a train is accelerated the full weight is hanging on this cross beam.

Fig. 190, 191: Couplings between railroad cars.



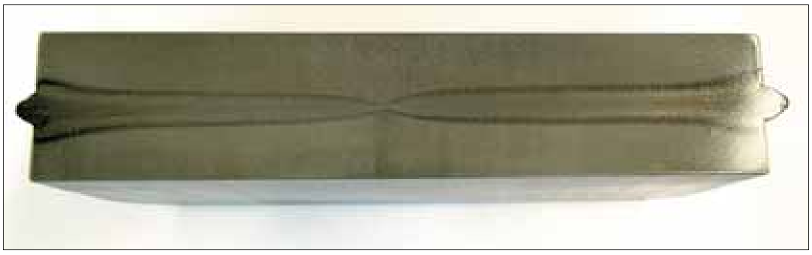


Fig. 192, 193:
Hook of a locomotive (above) and cross section of the opposite welds.

The locomotive hooks up the train, and the cars are connected via couplings. Both the hook and the couplings are EB welded. The idea underlaying this design is cost saving. The hook and the eyes are standard products, forged in larger series. The other sections are individually designed according to each application from the Shanghai underground to the high speed German ICE train.

Fig. 194:
Locomotive waiting for axel exchange.

Fig. 195: Quill bearing boxes welded to the axel casting.

The exchange of quill bearing boxes of locomotives saves the central casting of the axle. High repeatability of the weld shrinkage tolerance is essential as total coaxiality angularity and length tolerances are extremely narrow. Contrary to original manufacturing there is no subsequent machining.

Fig. 196, 197:
Flexible membrane shaft is stiff in torsion.
Detail (right).

Fig. 198: Intermediate shaft with 2 welds.

A coupling which is flexible in axial direction but stiff in rotation is constructed by joining several spring disks with EB welding. It compensates tolerance allowances between the motor and the driving system, whereas the intermediate shaft is stiff in all directions.

Rails

Fig. 199:
Switch tongue with track.

Fig. 200, 201, 202:
The point of the switch is reinforced on it surface by wear resistant maraging steel. Weld penetration 100 mm.

One of the big challenges in electron beam welding are rail switches. The central part is underlying abrasive wear, as the wheels of trains are partly not actively steered, but moved in a new direction by friction. Up to now the surface is reinforced by adding a plate of maraging steel and this block is subsequently machined to form the pointed switch tongue. The idea to splice and weld standard rails is old but up to now, it was not possible to do this as the high carbon content of 0,8% resulted in cracks and blow outs.

Fig. 203, 204, 205: Cracks formed during self quenching of the melt and blow outs are the result of inproper welding the standard rail.

By using today's computer simulation capabilities, it was possible to find a narrow band of process temperature, which resulted in an acceptable hardness, while maintaining the perlitic structure of the rail.

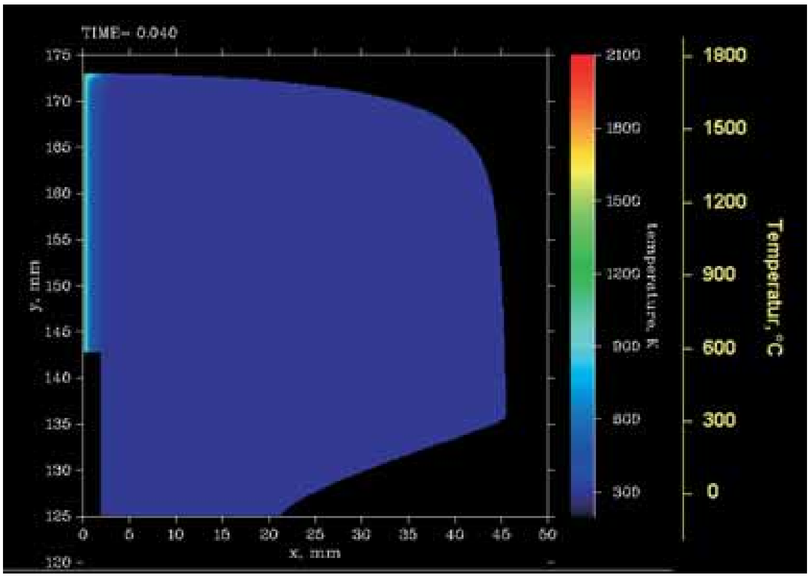


Fig. 206:
Simulated temperature distribution of an EB welding. The heating of the melt is limited to a narrow volume.

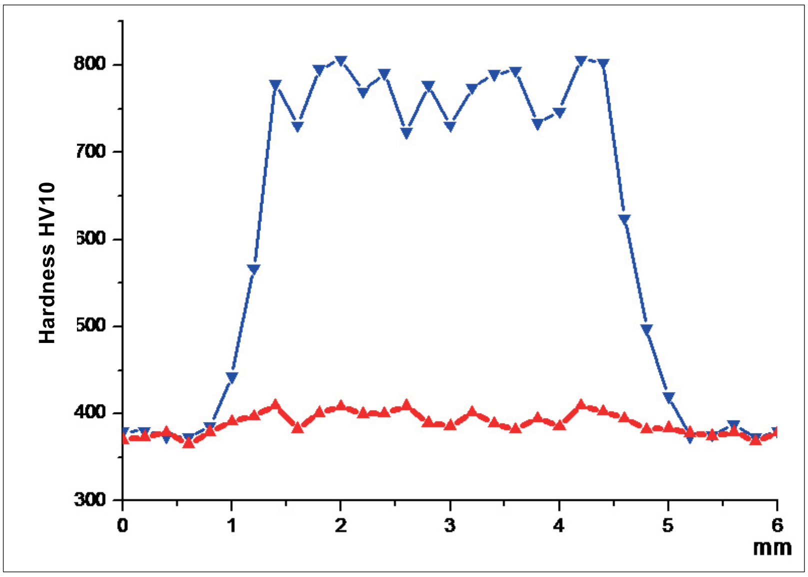


Fig. 207:
Hardness distribution with and without proper heat treatment.

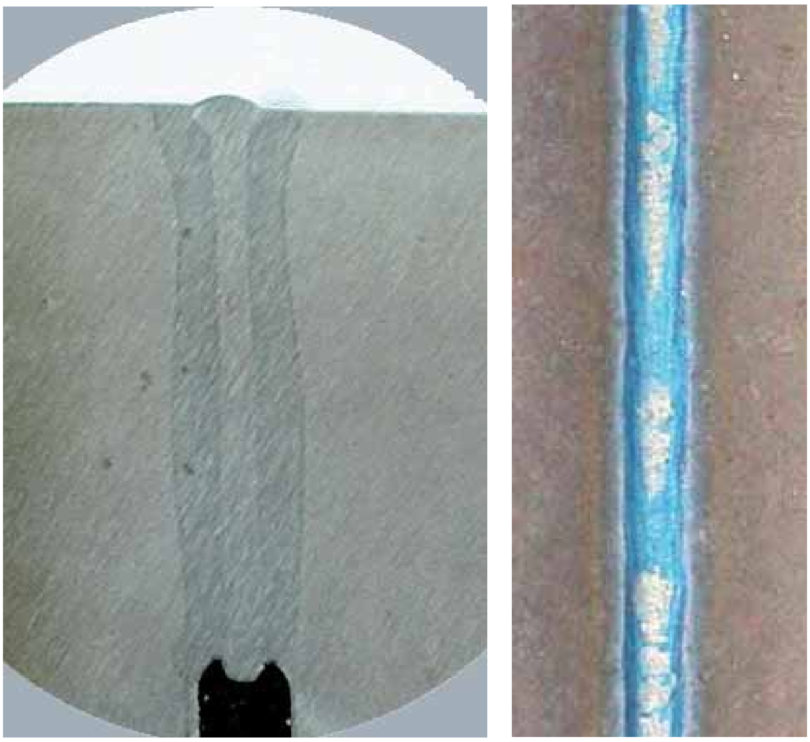


Fig. 208, 209:
Cross section of a properly welded switch point and weld seam.

Fig. 210, 211:
Cross sections at different distances from the point.

Fig. 212: The EB welding machine with clamping yoke.

A key asset to this process is a rapid and uniform heating which must not show any temperature gradient in the rails. This was achieved by using the UMH (Uniform Magnetic Heating) process.

Fig. 213: 4 switch points for testing.

Fig. 214: Uniform magnetic heating device.

Fig. 215: Test for pulsating fatigue strength.

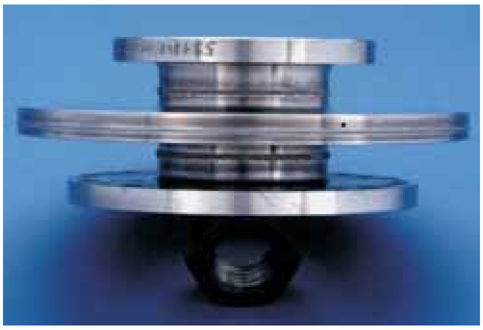
The specified load cycles of 2 million with a load of 320 kN was by far exceeded to 5.5 million cycles with a final load of 570 kN. The positive welding result ended in a fully automated production line, including assembly and clamping tools, preheating, EB welding, post heat treatment, quality control and documenttation.

EB welding of rail switches is one of the examples where a successful combination of experiments and computer simulation resulted in an attractive product.

Shipbuilding Industry

Fig. 216: Submarine bodies are EB welded in large vacuum chambers.

EB welding in shipbuilding has only a few applications. The most prominent is EB welding of the body sections of submarines. There are two large EB welders with a vacuum vessel of 10 respectively 12 m in diameter and capable of welding steel or titanium sheets up to 100 mm wall thickness. Unfortunately there is no public information available on further parts which are welded on these machines. We can think of the rudder fin and axis of rotation with weld penetrations between 50 and 100 mm.



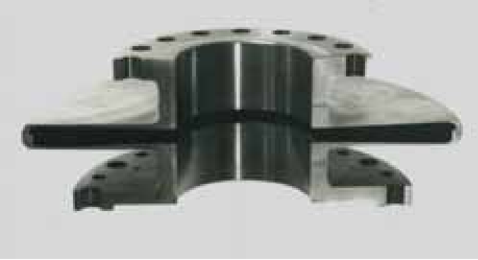


Fig. 217, 218, 219: Clutch hub and membrane couplings.

The engine is coupled to the clutch hub and to the propeller hub by membrane disks. They are designed with 3 EB welds. Their task is to compensate for vibrations of the engine. Marine propulsion shows similar, but larger, welds as with trucks on pistons, injection nozzles or gears. For transportation of large ship engines lifting lugs are being EB welded.

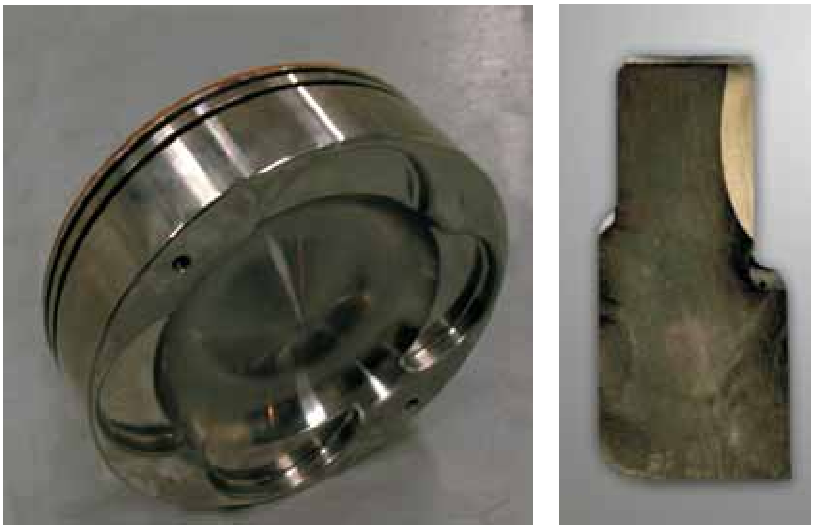


Fig. 220, 221: Pistonhead of a diesel engine for ships and makrosection, showing EB hardened wall of the ring groove.

Fig 222, 223: Lifting lugs for ship engines (left). Diesel injection nozzle of ship engine (right).

Fig. 224: Rocker arm for steering the boat in Fig. 225.

Fig. 225: A high tech propulsion system for tractor ships with variable thrust in power and direction allows to rotate the boat on the spot.

The Publisher of this Book:

pro-beam was founded in 1974 as job-shop for electron beam technologies. The activities started with two people and two second-hand machines, one for welding and one for drilling. 10 years later, the first lasers were incorporated.
Today after 33 years of continuous growth, the pro-beam group has 225 employees in five German and three overseas locations. 32 EB welding machines, 5 EB perforation machines and 5 lasers work up to 7 days a week in 3 shifts for pro-beam customers. The beam power ranges from 1 to 60 kW and the vacuum chamber size is from 0,05 to 630 m^3. The Nd:YAG- and CO_2-lasers range from 150 W to 12 kW. With this capacity pro-beam is not only the largest EB contractor in the world, but also the only one with decades of experience in all the main areas of EB applications: welding, drilling, cutting and surface treatments such as hardening, remelting, and alloying by means of laser and electron beam. pro-beam handles all orders from single parts to high volume production.
Utilising the experience from the large variety of applications, pro-beam has developed its own EB equipment product line. The designs were first tested in pro-beam's own workshops and only following their success they were marketed. Since the year 2000 pro-beam is well positioned as an EB equipment supplier with its own production subsidiary "pro-beam Anlagen GmbH", Chemnitz, Germany.
Today more than 30 pro-beam engineers are working together with a number of research institutes and companies to develop the next generation of machines and processes in order to explore and extend all new areas of electron beam application. It is pro-beam group's aim to improve its prime position in EB welding, drilling, surface treatments and machine manufacturing and at the same time consolidating its position as a market leader.

pro-beam is certified according to DIN EN ISO 9001:2000, ISO/TS 16949:2002 Automotive, DIN EN 9100 Aircraft and space, DIN 6700-2 Railway, WTD 61 Defence, HP0 Pressuretanks, DIN EN 729-3 QS and pro beam's machines according to DIN EN ISO 14744:2006, as well as its staff according to DIN EN 473 and the operators to DIN EN 1418 for EB machines and lasers.

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It would not have been possible to write such a book without having pictures of a large variety of applications. Therefore my sincere thanks go to pro-beam customers, who have been bringing their products to be welded to our workshops over a long period of time.
I hope that in return they get stimulations and encouragement to take advantage of what they have seen in this book.
Furthermore my special thanks go to my colleagues who handled many of the shown products: Mr. Franz Rappold, who headed the production for 25 years and Mr. Manfred Mülller, who was responsible for design and sales over 20 years. Both are now in their meritorious retirement.

Dietrich von Dobeneck

From left: Manfred Müller, Franz Rappold, Dietrich von Dobeneck.