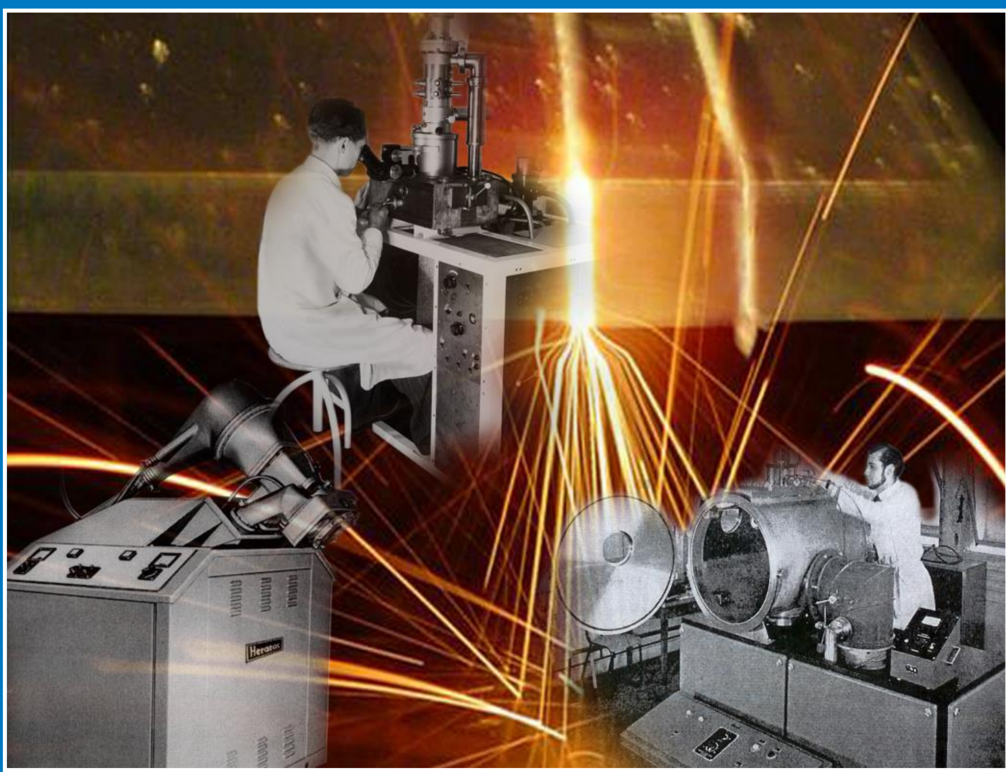
AN INTERNATIONAL HISTORY OF ELECTRON BEAM WELDING

Dietrich v. Dobeneck, Editor



pro beam

An International History of Electron Beam Welding

by

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pro beam

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Titel page:
Top: Steigerwald's first EB machine at Süddt. Lab. (AEG-Zeiss) 1949
Left: Lorenz's first EB Non Vac machine at Heraeus 1953-58
Right: Stohr's first EB machine at CEA 1954-1958

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Left: The most powerful EB welder at Osaka University
Right: Zeiss EB welder built in 1952, shipped to USA in 1958

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Introduction by D. v. Dobeneck

Over and over again, people have asked me to write down all the details, stories, anecdotes and facts related to the history of electron beam welding, which I have collected or which I was part of. I was reluctant to do this, as I thought there were more knowledgeable witnesses more intimately involved in this process than I was. However, most of the pioneers have now died, and the next generation who played a role in the first half-century or so of electron beam (EB) history has already retired. So, if our generation does not document the beginning and the development of this now world-famous technology, nobody will be able to.

The basis of my research was a cupboard full of personal documents and pictures belonging to Dr Karl Heinz Steigerwald, which I inherited after his death in 2001. This material proved to be not enough for a comprehensive history. I therefore invited colleagues from six different nations to contribute to this book, and I am very glad that they all were happy to participate in the project.

When their contributions arrived, I was pleased to see that each of the authors had dealt with different aspects of the history of electron beam welding. There is the very personal account of Dr Steigerwald's experiences as an inventor and entrepreneur with what today would be called "venture capital from a business angel"; the evaluation of technical improvements described by Dr Sayegh; the competition between all the EB companies in the U.S.A., compared to the planned economy in the Soviet Union, where six industrial complexes are each responsible for a certain aspect of the whole; then the straightforward evaluation, starting with license agreements from Hamilton Standard to Nippon Electric Company (NEC) or Hawker Siddley, each with outstanding R&D institutions to promote the technology, at Osaka University in Japan and The Welding Institute (TWI) in Great Britain; Dr Dietrich deals with the generation line from Zeiss via Hamilton Standard to Leybold/Heraeus and PTR. It has been my task to collect information on the activities at many universities and companies all over the world, in an attempt to make this book as complete as possible.

This history also discloses two contrasting kinds of inventions: Dr Steigerwald was experimenting with electron microscopes and discovered their potential for drilling and welding. He had a solution and was looking for applications. Dr Jacques-André Stohr, on the other hand, had a problem to solve, the welding of reactive material, which required a vacuum process, and found his solution in EB welding.

The History of Electron Beam Technology

An address given by Dr Karl Heinz Steigerwald at the Institute of Industrial Electronics, Technical University of Vienna, Austria on 9 December 1975 [translation of tape-record and shortened by the editor]

Fig. 1: Dr K. H. Steigerwald (c.1968)

If one follows a certain field of work resulting from an invention back to its roots, it hardly ever follows a straightforward or clear path; one discovers a web of trails, which can be seen by each participant through his own particular spectacles. This is not surprising – for various reasons: firstly, each invention is based on the preparatory work of others. Most innovations are in the air and then one, or, very often, several people give birth to them independently. Then there are those who were "also thinking along virtually the same lines" and who subsequently want some of the laurels. Finally, those climb on board who intend to make something technically or economically useful out of the invention, either as engineer or broker or entrepreneur; each with his own potential and interests, be they fair or impure. Very often the inventors are left out in the cold. And everyone will tell you a different story. Here is mine as I recall it, and, believe me, I am seriously lacking in objectivity.
[This preface was actually written by Dr Edgar Meyer, a physicist colleague of Dr Steigerwald from the early days at Zeiss. Steigerwald made a hand-written note stating that not a word of it should be deleted or changed. *Ed.*]

First indications that mobile electric particles exist – what today we call electrons – date from 1871/72; they were discovered by Wilhelm Hittorff in Göttingen and William Crookes [1]* in Great Britain. Shortly afterwards, Edison discovered the glow emission of electrons. By 1900 the first applications already existed: the x-ray tube and Braun's oscilloscope tube. The electron beam did not only generate x-rays, there was also the danger that the intense EB would melt the anticathode hit by the beam. This technical problem inspired the idea to use an electron beam as a heat source. In 1904 Marcello v. Pirani [2] published a proposal to build a furnace for melting, sintering and joining of tantalum grains to a tantalum block. In 1906 he filed a patent for Siemens and Halske with the title: Production of Homogenous Pieces of Tantalum by Means of an Electron Beam. This patent depicted a simple gas-discharge tube. Until the first quarter of the 20th century, nearly all EB applications were limited to evacuated and fused glass tubes [3].

*Numbers in brackets [1] refer to publications listed in the bibliography (p. 90ff.).

In the 1930s, geometric electron optics was developed. Hans Busch [4] was the first to state, while mathematically analyzing magnetic fields, that these were subject to the same laws of optics as light and, based on these findings, he called this field of study electron optics/particle optics. Busch was professor at the Technical University of Darmstadt at the time. In 1934 Ernst Brüche and Otto Scherzer gave the first systematic treatment of electron optics in their book “Geometrische Elektronenoptik”.
Several researchers under Prof. Kerle worked on the problems of electron optics. The first electron microscopes were developed by Brüche, Mahl and Bolschka at AEG and by Bodo v. Bories and Ernst Ruska [5], [6] with Siemens and further by Manfred v. Ardenne [7]. Everything was concentrated in Berlin: The electrostatic development at AEG, the electromagnetic development at Siemens. Small apertures were needed for these electron microscopes. Von Ardenne had the idea of drilling these with ion beams. He mentioned that he had also tried it with electron beams, but nothing was published in detail.

The Beginnings

After the war Brüche [8] formed a splinter group within the AEG research institute in Mosbach, to which I was recommended by Scherzer. At the end of the war, I worked with him on the development of radar and electron optics. In Mosbach I was responsible for developing high-power electron sources and also for spherical beam trajectory correction by means of high frequency lenses, originated by Scherzer. These are high-frequency resonators, which, like the klystron, act as an electrodynamic lens, making use of the pulse timing effect. After the war, work on high-frequency systems in the range of megahertz was forbidden. Nevertheless, I built a 9 cm klystron and introduced the first far-focused bunching as a pure electrostatic focusing from the cathode itself, since at that time there was no copper available for a magnet coil [9].

Fig. 2: Dr Steigerwald (standing) with his team at Süddeutsche Laboratorien, Mosbach, during a staff outing with bicycles in 1952.

I ran out of money on this, so I had to concentrate on something useful for the electron microscope. I transferred the described beam source to the electrostatic version of an electron microscope, which, in turn, required a very long condenser lens. With my new far-focused beam source the condenser lens could be eliminated, as its function was directly integrated into the source. In later years, this item was called the “Steigerwald gun”. Now I had a source with a long and slender electron beam. The new source was integrated in 1947/48 in high power oscilloscopes, producing a tiny spot on the object plane of the electron microscope. This spot of 5 micrometer diameter could be deflected by a signal via deflecting plates. Thus an oscilloscope with several hundred megahertz was achieved.

Fig. 3: First EB drilling of an unintended hole of Ø 7µm in a platinum aperture, 1949.

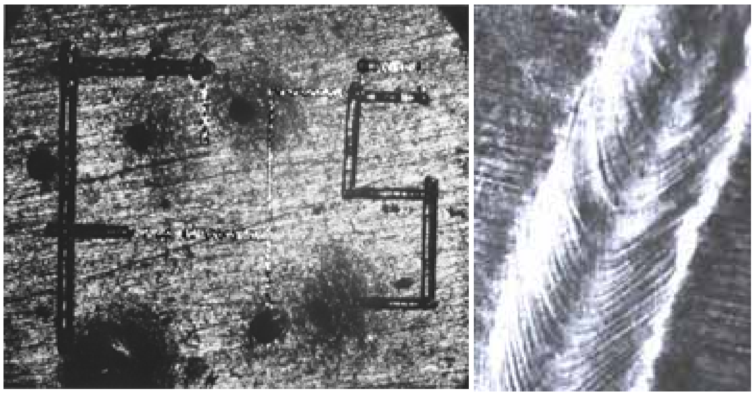


Fig. 4: First EB weld in 1949 (with detail right). Dr Steigerwald called this engraving, but actually it was a bead on plate weld run.

First Material Treatments and Irving Rossi

Making use of this precisely focused beam with the oscilloscope in 1949 I was able to make fine holes and other metal treatments at an energy level of 100 to 200 W (fig. 3) for the first time. [The first hole was, in fact, drilled through a misaligned aperture diaphragm of the microscope, as Steigerwald commented to the editor.]

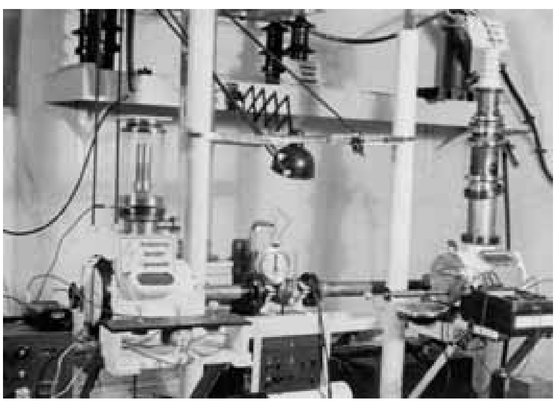


Fig. 5: Test installation, 1949.

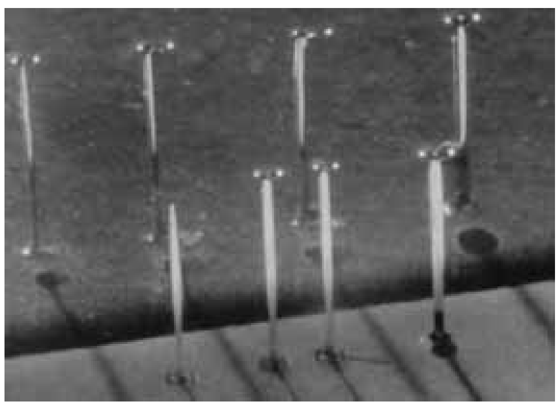


Fig. 6: Drilled holes in a quartz plate, 1950

From now on, things became strange, as AEG deemed this technique uninteresting. But just then an American came along, Mr Irving Rossi, who had been exploring European patents for a long time: for instance, shortly before the war he had bought the explosive-riveting patent from Heinkel and sold it to Dupont. It was then used to build all the American bombers in the Second World War. Rossi was not only a broker, he was also a pioneer in developing the continuous casting process together with Siegfried Junghans, a member of the clock-making dynasty. This Mr Rossi bought my "electronic hole-drilling process" from AEG for peanuts, and AEG was relieved to at least recoup the expenses for the experiments of this crazy Mr Steigerwald.

Fig. 7: Lab prototype, 1951.

Fig. 8: Lab prototype, 1952.

Construction of the Rossi Machines

Rossi ordered two machines from the "Süddeutsche Laboratorien", jointly owned by AEG and Zeiss. After the order had been placed, the management asked: Who is going to design the machines for Mr Rossi? (I had left the company to look for another way to continue my work in the field of material treatment by electron beams.) In the end, I signed a consultancy agreement with AEG on the condition that I could select a few good designers from Zeiss. In this historically significant agreement of 1951, which I still have, it says: "machines for welding, joining processes, drilling, material-removing processes, engraving, material modification and refining". The spectrum of possibilities was thus recognized quite clearly even then, and it was also quite clear that a machine was meant, which uses the electron beam as a tool.

The two machines were built with the means available at that time. I could choose the insulator at the AEG transformer plant. On principle, and from the very beginning, I emphasized dry (oil-free) high-voltage feed-throughs and a trend to high voltage. The very first machine worked with 125 kV, like the electron microscopes of the time. 3 kW could be got out of my machine, but at the beginning there was a terrible thunderclap. The high-voltage power supply had two exits, a well-sieved one for 1 kW and a badly sieved one for 3 kW. For the auxiliary voltage supply I used new techniques. Due to my good connections to the people on the shop floor at AEG in Bad Cannstatt, I could cast transformers for the first time. From the very beginning, the bias voltage supply was at high-voltage level. Today I can say with pride that we succeeded in increasing the power of the electron microscope from 10-20 W to 1000-3000 W in one go. It was a difficult process, until we had this upgrade under control. But now we could make good holes, welds and engravings. Rossi's first machine was finished in 1952 [10 + 11]. It was installed in Mr Junghans' former stables in Schramberg. There we were engaged in micromachining, e.g., the drilling of watch stones.

Fig. 9: EB machine, ordered in 1951 by I. Rossi and finished in 1952.

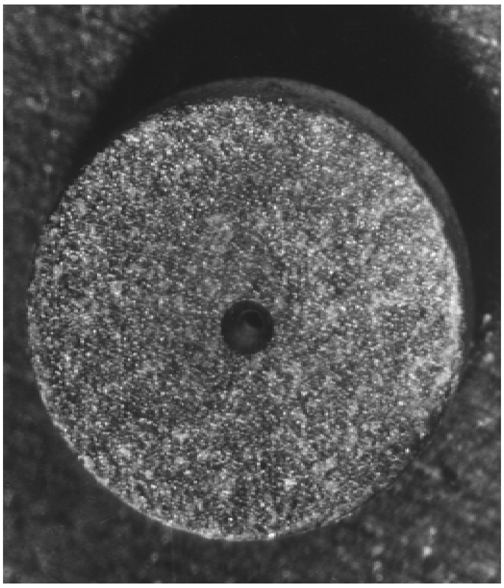


Fig. 10: EB drilled hole Ø 80 µm in a ruby bearing for a watch.

At that time Rossi and I entered into negotiations with Zeiss and, in 1954, Zeiss decided to take EB technology into their programme. I was thus able to set up the second machine at Zeiss and build up a second task force, while the first remained in Schramberg. Things improved fast at Zeiss. A large research and development group of 40 people was put together, which had strong support from the company's management. Dr Wilhelm Scheffels, a specialist in the field of electron optics, joined the group in 1955. The decision-makers at Zeiss were Dr Heinrich Küppenbender and the R&D director Prof. Gerhard Hansen. Moreover there was the old managing director Prof. Walther Bauersfeld from Jena, who, despite his age, was the actual initiator of this activity. At the end of my presentation on EB technology he got up and remarked: "And I tell you, you shall continue working on this properly."

The following reasons were then mentioned in favour of the use of electron beams for material processing:

- Electron beams are chemically neutral; it might be said they disappear in the materials treated.
- There is the possibility of increasing the power density by an increase in the accelerating voltage. Furthermore, one can influence the electron trajectories by matter-free, flexible magnetic lenses.
- Electron beams can be controlled very rapidly.

With hindsight I should like to add that the wavelength is very short compared to lasers, the penetration into the matter depends on the velocity of the electrons and the density of the material (they propagate less in tungsten than in aluminium). These properties of the electron beam are well defined, as against lasers, which reflect light, so their results are virtually irreproducible.
For the first time, we were now systematically looking for applications in industry – a real problem for a completely new process. We talked to many people, but for most of them the combination of physical possibilities, technical realization and economic introduction into a production process was too difficult. What we had to learn was how to prove the economic advantages to industry. To achieve this, we started a lot of applications, such as the drilling of spinnerets or drawing dies, the drilling of tungsten carbides, welding processes and so on [12].

Rossi, the World Patent Rights and the World Market

Rossi intended to lend his two EB machines to industrial companies, to have them installed and further developed there and, in return, he secured the rights to all innovations made with them. He was a very far-sighted man and also a smart businessman. If Rossi had not been involved, things would have ground to a halt about now. But Rossi worked systematically to exploit new ideas and to make a business out of them. He recognized that energy in the form of electron beams would have a great future in industry. He was the only one who saw it that way and who supported us. Again and again he used his contacts in industry to bring electron beam technology to the world of engineers. He founded two sales organizations, one in the U.S.A., "Electrona Inc." in New York with the rights for the U.S.A. and Canada, and the other in Zurich, "Electrona AG" with the rights for the rest of the world except Germany. Zeiss, with the actual working group, was in Germany.

Westinghouse and the Polaris Submarines

Our first sale to the U.S.A. was to Westinghouse through the good offices of my old teacher Prof. Wolfgang Finkelnburg from Siemens. One day he came to see my electron beam machines and said: "I know somebody who has welding problems."

Fig. 11: EB welding of thin to thick was remarkable in the late 1950s.

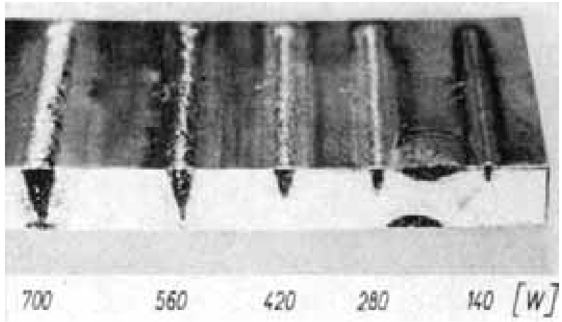
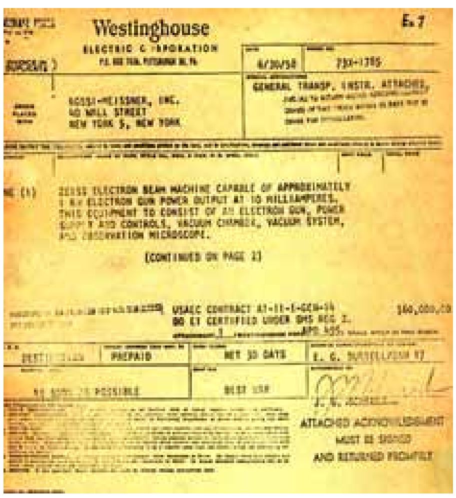


Fig. 12: The first welds in a zircaloy plate, showing the deep penetration effect (1958).

That was Westinghouse, who wanted to know whether it was possible to make a narrow weld in a 5 mm thick plate with my machine. Up to that time we had concentrated almost exclusively on drilling, and we hoped that this inquiry would be the first of many regarding welding. We had welded before, but only on the surface, so we tried to combine welding with workpiece movement. I turned the machine up to full, running the risk of damaging it, but the first deep weld worked – a bead-on-plate weld. Then we tack-welded two plates and fused along the joint. Behind this simple-looking task there was a serious problem – the nuclear reactors for Polaris submarines. The plates are part of the heat exchangers. We succeeded in performing the most slender weld seam we had ever seen. Westinghouse was responsible for fuel-element production and decided in 1958 to buy an electron beam machine. We refurbished one of the old Rossi machines and shipped it by air in July 1958. For series production the machine was equipped with a large vacuum chamber and a second electron beam gun.

Fig. 13: The first EB machine supplied by Zeiss to Westinghouse in 1958.



Westinghouse
6/30/58
GENERAL TRANSP., INSTR. ATTACHED
60 WALL STREET
NEW YORK 5, NEW YORK

ZEISS ELECTRON BEAM MACHINE CAPABLE OF APPROXIMATELY
ELECTRON GUN POWER OUTPUT AT 10 MILLIAMPERES.
THIS EQUIPMENT TO CONSIST OF AN ELECTRON GUN, POWER
SUPPLY AND CONTROLS, VACUUM CHAMBER, VACUUM SYSTEM,
AND OBSERVATION MICROSCOPE.

(CONTINUED ON PAGE 2)

USAEC CONTRACT
PREPAID
NET 30 DAYS
POSSIBLE
BEST WAY
ATTACHED ACKNOWLEDGMENT
MUST BE SIGNED
AND RETURNED PROMPTLY

Fig. 14: The purchase order of June 1958.

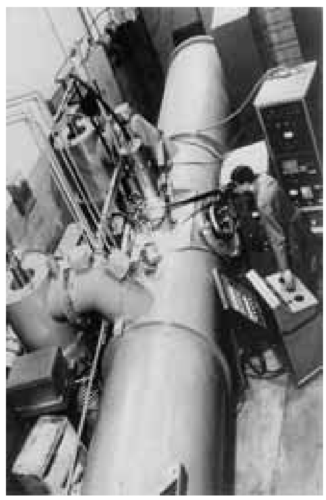


Fig. 15: The second Westinghouse EB machine for production.

Further Interest in Electron Beam Technology

This is the time to point out that, shortly after I started, other people also started working on electron beam technology. For instance, in 1952 Mr B.W. Schumacher [13] from Stuttgart visited me, because he was having trouble with a pressure stage to release the electron beam from vacuum to atmosphere in order to measure the fluorescence of an electron beam in gases – something he needed for his doctoral thesis. Since he had no EB gun with a sufficiently slender beam, I gave him one. He smuggled this electrode system out of the laboratory in his pocket. But then he went to Heraeus with the results of his successful experiments. In 1951 one of the Heraeus brothers had already been in my laboratory and seen my research work. Reinhardt Heraeus was the second industrialist who soon realized how interesting EB technology could be in the long term. So he decided to put together a group and contracted Schumacher. From then on, the Heraeus group conducted electron beam research.

Dr Stohr was also a competitor. He started in France in 1954, based on the technique of x-ray tubes, as he was familiar with their production. Later, he was involved in welding fuel rods of zircaloy for nuclear reactors, where he faced great problems with shielding gas [14+15]. So he tried to weld with x-ray tube systems. The related patent [16] shows that he had a diode system in mind, similar to the one Pirani used for his fusion sinter processes. In fact, Stohr succeeded in making welds, but, due to the low power density, they were only surface meltings. In 1957 he started with an electrode system in hard vacuum, with the accelerating space between cathode and workpiece. This work, carried out by the *Commissariat à l'Energie Atomique* (CEA) was immediately published by Stohr and thus the Americans became aware of the EB technique for the first time in 1957. Stohr's ideas were taken over by Sciaky, a company that pioneered resistance welding. In fact, in 1960 the first machine was built in France to Stohr's specifications and already sold in 1961.

Our Reception in the USA

After our first sale in the U.S.A. there was a strong reaction. Other companies wanted to have machines from us, too [17]. 42 of the 97 machines built by Zeiss went to the USA, and the rest were for Europe. So, very soon it was clear to Mr Rossi and me that we had to co-operate closely with U.S. industry. There were many opportunities – from a Texan oil millionaire to the large concern of Dupont. Finally, a very reasonable co-operation ensued with Hamilton Standard, a division of United Aircraft Corp.. They bought the majority of Electrona.

In the beginning we supplied the EB guns and Hamilton built the equipment according to our plans. Then Hamilton adopted our gun design, since they were not electron optics specialists. In 1963 Zeiss finally sold all world rights to Hamilton Standard. So there I was with my collaborators in Europe, and we were not allowed to work in our own field any more.

Fig. 16, 17: Presentation of Zeiss EB machine at Waldorf Astoria Hotel, New York, 1959. *(See remark in editor's postscript, page 19)*

Self-employment is the answer

In this situation, the only choice left was to found my own company. First I tried to negotiate with Hamilton, explaining that the machines based on electron microscopes are able to weld and drill, but were not really conceived as machine tools. I started again with the experience of the first hundred machines behind me. I tried to explain that they would be making a big mistake if they broke with the team with the know-how necessary for further development. But the opinion prevailed that I was a mere inventor who understood nothing about industrial application. They also ignored the fact that there was an old tradition of electron and light optics in Europe. In the 1950s electron optics had been developed as a theoretical science (e.g., by Prof. Walter Glaser [18] from Vienna) subsequent to the work of those who paved the way for electron optics in the 1930s. What we did was a first harvest in the fields of science. I also tried to convince Zeiss that they should concentrate on new sources of energy beams, not only on light as an image-producing system. I could not convince them, however. I defined my new field of activity as follows: fundamental research on material treatment with electron beams. Everything is of interest where the electron beam can be used as a geometrically defined thermal tool. The beam has to be focused and should not act like a shower. It begins with welding, via material re-moving processes, to tiny engraving in electronics, one could say in operations with high power density in order to penetrate into the material. I tried to explain that the goal was to develop an electron gun with reproducible properties, operated by a small knob with no need for a physicist standing next to it for continuous re-adjustment. This is a precondition for an electron beam machine working in industry and for adapting it to computer control. Using an expensive computer only makes sense when there is an absolutely reproducible beam [19].

In the end, I was assured by the Ministry for Economics of Württemberg and by the Federal Ministries for Research and Defence that I would get orders both for research and development. On this basis I decided to take the risks of going self-employed. I was able to take a few people from my old staff at Zeiss and the contents of my laboratory at reasonable conditions

The Situation with Patents

This was a difficult problem, as there were a number of basic patents, opposing my intentions to redesign and improve the EB guns. It was, of course, a help that I knew which details of the patents were lasting. For a transition period I was able to get guns from Zeiss who continued to build them from remaining stock until 1965. Finally Scheffels and I were successful, and in 1963 I opened an engineering company at Heidenheim. The design office was my garage, complete with two drawing boards; the children's room was the office. [Initially Hamilton Standard refused to allow Steigerwald to use his deep penetration welding patent [20], but Steigerwald threatened them, saying that he had enough material to bring a nullity action, and suggesting that it would be better for them to keep the patent against other competition, but to allow him to proceed. Hamilton Standard did not interfere. *Ed.*]

The Rocket Program

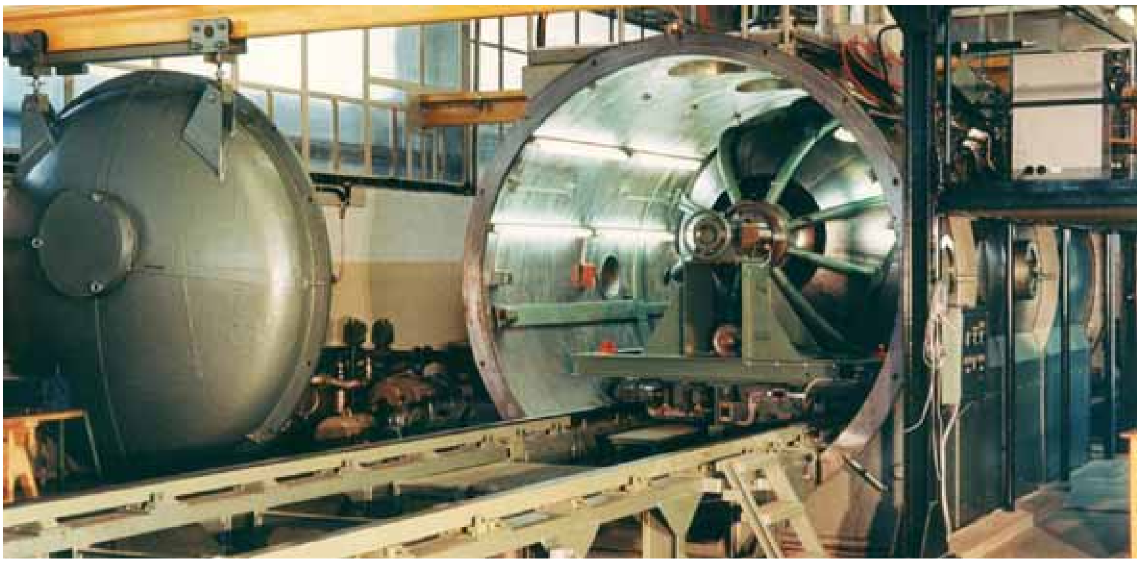


Fig. 18: The VFW machine for welding fuel tanks for the ELDO rocket (1965).

In June 1963 the "Vereinigte Flugtechnische Werke" (VFW) at Bremen was looking for a large EB-machine for the European rocket program. Offers came from Hamilton Standard, Sciaky and myself. The others had large companies behind them, I had only the garage and two employees. The task was to weld tanks of titanium with a diameter of 1.4 m. When we discussed the machine, VFW soon realized that my group was the only one who knew how to make the welds. The others could only propose a box with a gun. I won the order for DM 1.7 Mio. I had no financial resources whatsoever to carry out the order. And I had to learn bit by bit what an employer needs to know in order to deal with such an order. When the drawings for the machine were finished, I moved to Wasseralfingen into an empty manufacturing shop of the Schwäbische Hüttenwerke. From there, my first machine with a beam power of 3 kW was supplied in 1965. [21] [And it was still working in 2007. *Ed.*] We supplied a few more machines with Zeiss guns, but all my efforts were directed towards an EB gun of my own. I started with a 7.5 kW gun that I thought might ultimately manage 20 kW, but now we have realized 60 kW with this design.

Fig. 19: Zeiss EB machine ES 1013 (1960).

Fig. 20: Steigerwald EB machines, for micro-welding and drilling (1970) with CNC control for mechanical axes and beam parameters.

<u>New Start of my Company in Munich</u>

At Wasseralfingen I had only a small core team. So I had to move to a larger city to recruit the necessary staff for a growing company. Dr Meyer proposed moving to Munich. A lot of people were interested in our advertisement (young team wanted for modern technology) and so I hired two rooms in a hotel and, together with Meyer, interviewed 60 people in two days. With a new team of 15 people we first started at Steiner Strasse and then found space at Großhadern in 1965. By then the stock of Zeiss guns had run out and the new company Steigerwald Strahltechnik GmbH had to stand on its own feet. It was essential for us to find partners. After some experiments with venture capital EED and industrial partners, Steigerwald Krauss Maffei GmbH (SKM), I managed to convince the "Industrie Verwaltungsgesellschaft" (IVG), which invested a lot of development money into the company

<u>Today's Working Range</u>

Today we concentrate mainly on EB welding. The design of the guns has been developed in such a way that one can combine computer numerical control (CNC) of beam deflection and mechanical motion of the work-pieces. This simultaneous control brings an important reduction of processing time. The superiority of my machines is based on this dynamic operation. It allows the workpiece to be moved fast and without precision as the beam follows the joint with high precision. Thus the machine makes use of electronic possibilities in two ways: the high operational speed and the immediate error compensation by comparison of nominal and actual data. Further areas of operations are:

- Drilling of small and tiny holes

For the chemical industry the production of filters by means of an electron beam is of considerable interest, because it is possible to make different hole shapes and thus improve the productivity of chemical plants.

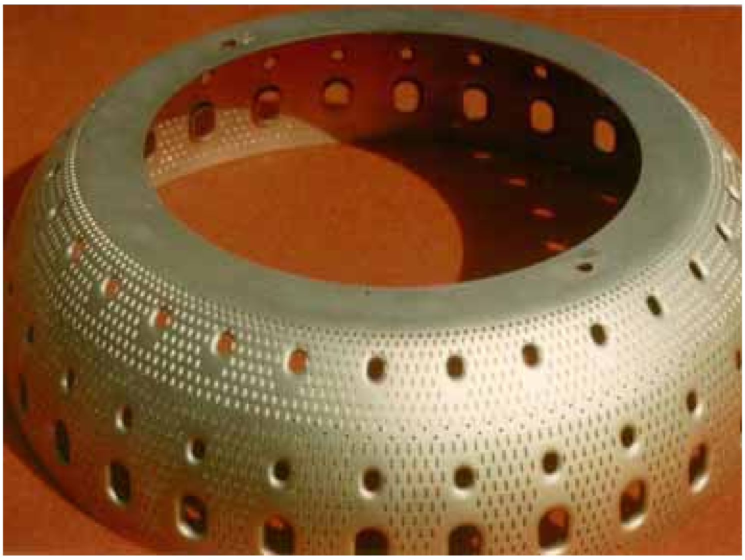


Fig. 21: EB drilling of film cooling holes in combustion chambers from various angles.

Fig. 22: EB drilled fiberizer for glass wool production.

- Melting

Von Ardenne did a lot of preparatory work, but the main activities are at Temmeskal/U.S.A.–Melting is also widespread in the Soviet Union and nowadays Heraeus, Hanau is also strongly involved. There are furnaces that reach the megawatt region.

- Coating

Strip steel is vaporized with aluminium at Cockerill, Liège, Belgium. The diffused electron beam is bent in a bow to heat the target material.

- Material Removing

By this drilling, cutting, milling and engraving are meant. We started developing a system for the engraving of rotor gravure cylinders, which the company Hell continued. Producing small grooves with variable depths and diameters into copper at high precision and speed is a difficult task. [In 2007 the equipment is used to structure the surface of rolls with small bumps for car body sheet metal production at 200 kHz. *Ed.*]

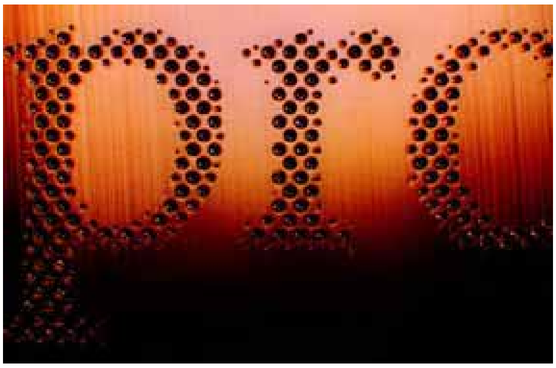


Fig. 23: EB rotogravure at Hell (1996).

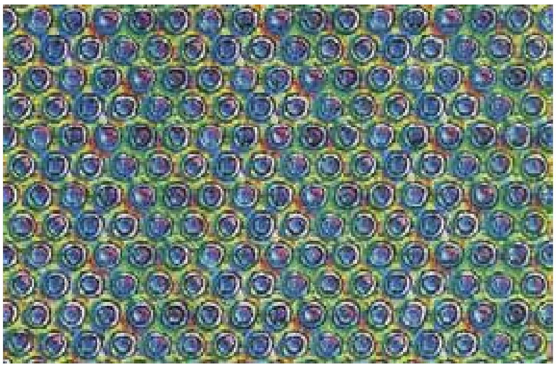


Fig. 24: EB texturing of steel rolls at Sidmar (2000).

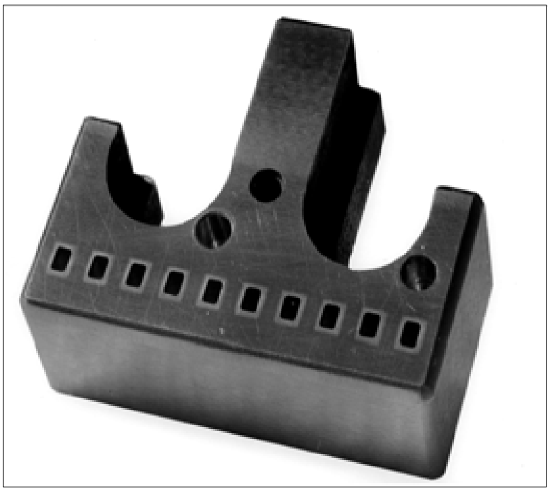


Fig. 25: Bottom die of a film cutting matrix EB transformation hardened.

- Surface Treatment

This includes surface hardening, local hardening or spot hardening for a grid, both in steel and in aluminium. Another line of material refining is by local melting. For example, grey cast iron can be locally fused and self-quenched. Carbon goes into solution and hard white structures are achieved. Another process under evaluation is to alloy surface layers, for example aluminium with iron or nickel.

Additional Remarks

In order to complete this review, I would like to comment on the development in the East. What has been established at the von Ardenne Institute in Dresden is quite an independent development. I know their interesting welding machines and equipment for trimming of thin film resistors.

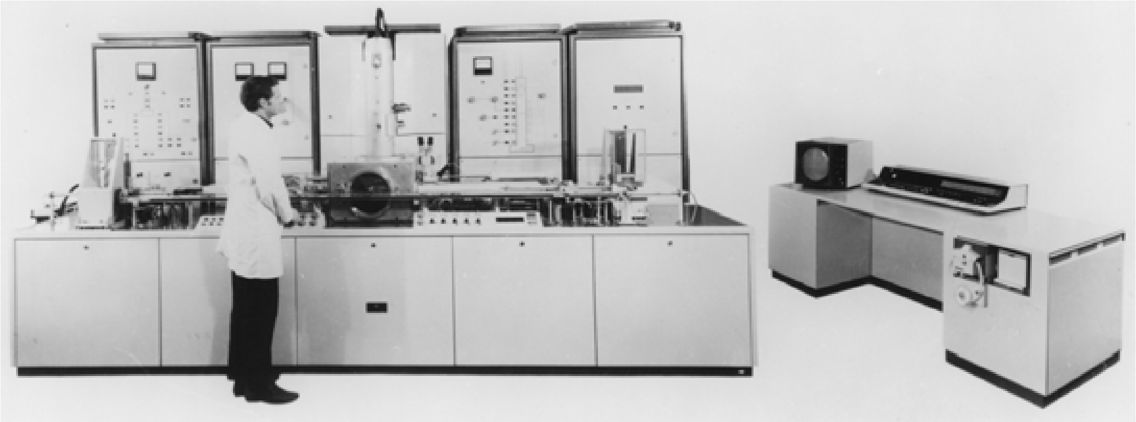


Fig. 26: Elmigraph 60, EB production plant for trimming thin film resistors.

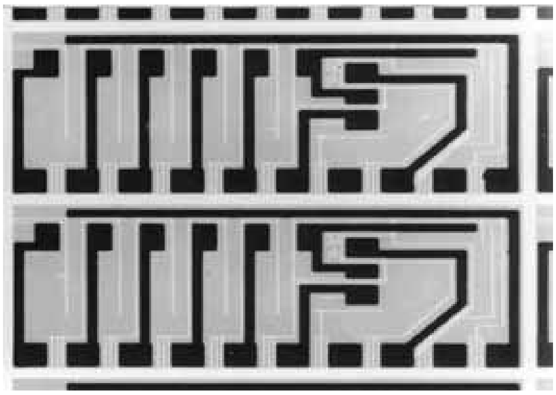


Fig. 27: Segment of a network for resistors.

Fig. 28: Manfred von Ardenne with universal EB microscope of 1940.

At the Paton Institute in Kiev there were only five people working with EB in 1965, but now (1975) there are 160. They follow every direction from micromachining up to 100 kW EB welding guns. They used non-vacuum systems up to 175 kV.

The EB welding on atmosphere, developed by Heraeus, has only been practically used up to now in the U.S.A. for applications without deep welding. Deep welding means that heat transfer is not by heat conductivity, but by a vapour capillary. I observed this phenomenon in 1958, but I did not publish it until much later, in order not to make other people aware of it.
These days I am working on how to achieve a vacuum locally between the workpiece and the gun. That is to say a mobile vacuum. I expect this technique to result in a wide spectrum of applications.

Postscript by the Editor

In the late 1970s Steigerwald was intensely involved in welding thick sections in combination with a mobile vacuum. However, these trials, partly financed by Japanese steel companies, bore fruit in Japan, but never got a foothold in Europe. In 1980 Messer Griesheim bought the company and Steigerwald, the initiator of ideas and the motor of the company, left. In 1995 the Austrian company IGM bought a share of the company and, in 2002, took it over completely. In 2005 it became part of All Welding Technologies AG with a staff of 34 people after a maximum of 225 in 1969 (incl. SKM).

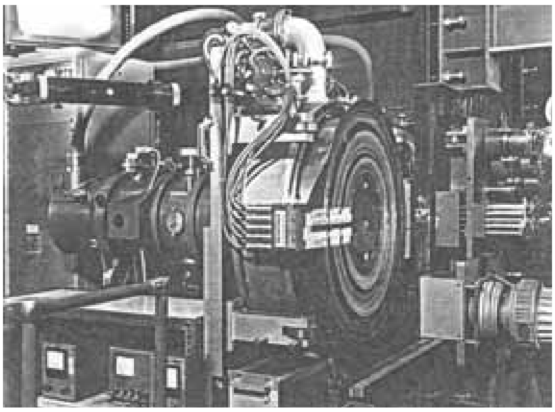


Fig. 29: Horizontal EB gun with sliding seal for mobile EB welding under partial vacuum (1980).

[Note on the presentation at the Waldorf Astoria Hotel (page 13): Steigerwald explained to the audience that EB welding has so little heat input that parts come out cold. When he finished welding, he opened the chamber and took out the part. People sitting in the front rows saw smoke coming out from between Steigerwald's fingers, but he showed no reaction. The operator had forgotten to switch on the cooling water.]

Karl Heinz Steigerwald

Born in 1920, studied electrical engineering and physics in Berlin and Darmstadt under Prof. Scherzer. During the war he developed radar techniques and took his diploma in 1945 at the Süddeutsche Laboratorien under Brüche, Scherzer and Möllenstedt. He developed the electrostatic far-focus system [9] later called Steigerwald gun. 1950/51 construction of the first equipment for thermal treatment of materials with electron beams, 60 kV, 10 mA.

1951-1954	Co-operation with Irving Rossi
1954	Scientific co-operation with Zeiss, built up a research group for electron beam microscopy and material treatment
1963-1980	Manager of Steigerwald Strahltechnik GmbH under various owners.
1981	Consultant for Messer Griesheim and Beijing University
1970	Dr rer. nat. h. c. in natural science from the University of Tübingen.
1977	Diesel medal in gold from the Institute for Innovations.
2001	died

History and Evolution of Electron Beam Welding in France

Georges Sayegh

Introduction

Electron beams, used in welding, apply the principles of electro-optics, which have been well defined and explored since the beginning of the 20th century. Electron beams were first employed mainly for radio and electronic tubes; by the 1930s they were also used in electron microscopy and as heat sources for melting refractory metals such as Tantalum and Zirconium.

The use of electron beams in welding was discovered accidentally during manipulation on X-ray tubes in France by Dr Jacques André Stohr [15] at the research laboratory of the Atomic Energy Commission (CEA) in 1954. At almost the same time, Dr Steigerwald in Germany obtained welds by manipulating beams in electron microscopes.

Fig. 30: J. A. Stohr, c.1960.

Rapidly two parallel techniques were developed:

- One, resulting from electron microscopy, used an accelerating voltage of 125-150 kV with a fixed gun on the vacuum chamber.
- The other, seeking to miniaturize the electron gun, in order to render it mobile inside of a vacuum chamber, used an accelerating voltage of 15-60 kV.

1956 may be regarded as the date of birth of Electron Beam Welding (EBW). Industry soon recognized the significant advantages of the process and their research centres were involved in developing the new joining techniques. In less than 10 years production machines were offered by equipment manufacturers for mass production in the automobile and aircraft industries, followed by many other industrial fields.

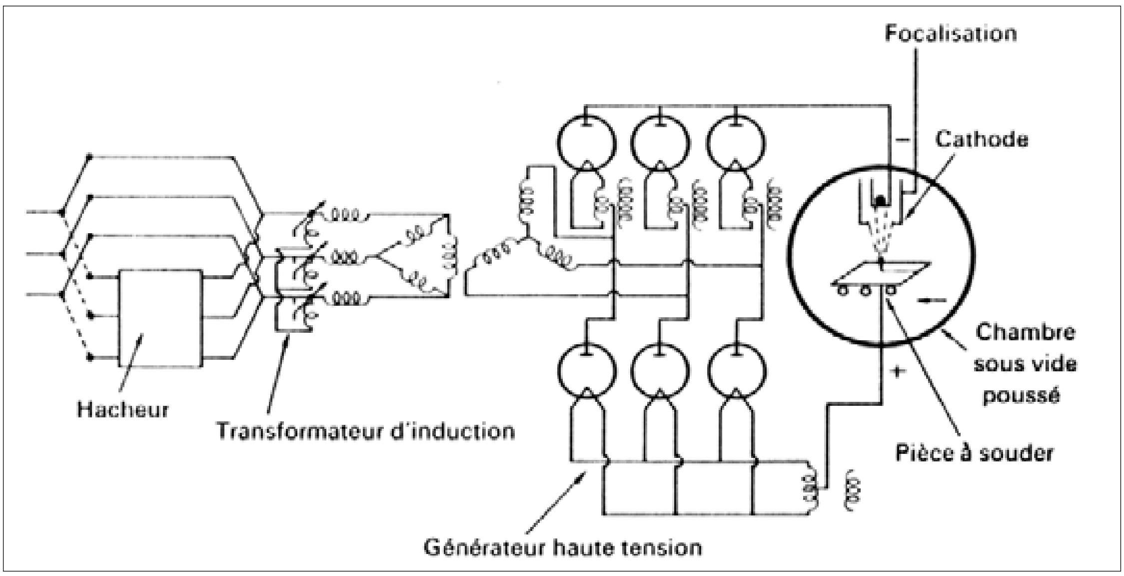
In the 1980s, EBW technology reached its golden age. It took advantage of all the progress achieved in the various scientific and technical fields involved in its technology, such as solid-state electronics, high automation, vacuum and a new generation of pumps, to improve its performance and its reliability in production.

EBW generated considerable interest among scientists and researchers active in many branches of physics, such as: electron optics, electronics and electrotechnology, computer science, and last but not least, metallurgy, where whole new horizons have been opened. It is not surprising, therefore, to see that in the 1980s EBW literature occupied a prime place in the R&D of welding processes. It was also during this period that laser beam welding

was seen as the major competitor of EB welding. Indeed many applications of EBW were successfully replaced by laser beam welding.
Here I would like to render homage to Mario Sciaky († 2006), President of Sciaky S.A. Company [22], a real visionary in the field of this technology, who saw its advantages for industry very early on. It was largely due to him that EBW became an industrial production tool in France.

First steps of EB welding in France

In 1954 Dr J.A. Stohr from the Commissariat à l'Energie Atomique (CEA) was manipulating an X-ray tube when he obtained a fusion zone on the anticathode producing a deep penetration in the solid metal. In 1956 he had the idea of using the electron beam to realize joints in Zirconium alloys, which need a vacuum to avoid oxidation. This is how the first machine was built in 1956. Fig. 31 shows the principle of the first mock-up, where the parts to be joined constituted the anode and were bombarded directly by the current issuing from the cathode, which was a simple filament. Fig. 32 shows the first machine built on this principle at CEA and used to produce circular or linear welds in Zirconium alloys, Uranium and Beryllium.



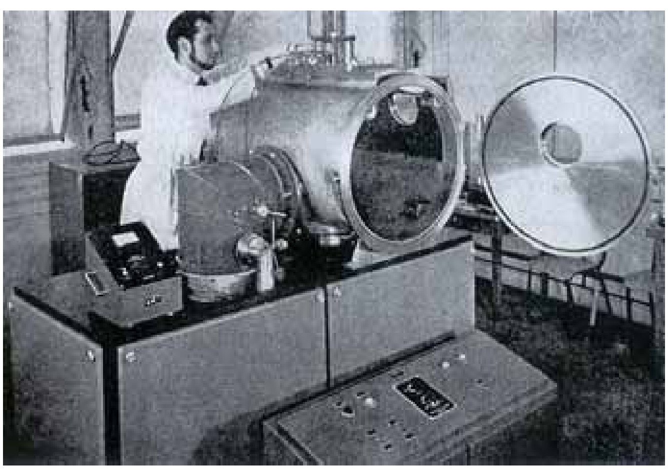


Fig. 31: Above: Diagram of power supply of the first EBW equipment in France [22].

Fig. 32: Left: First EB welding equipment in France 1956.

Mario Sciaky, President of Sciaky Company in France and a classmate of Stohr in the 1930s, rapidly recognized the potential of this new joining process, and a licence agreement was signed between CEA and Sciaky S.A. which was later extended to Sciaky Bros. in the U.S.A.
Close collaboration ensued between the two partners to industrialize the concept and manufacture production equipment, initially for the nuclear industry. This rapidly extended to other industrial fields.

Short Background on Electron-Optics.

The first production of electrons between two electrodes in a tube with rare gas submitted to a high voltage of several thousand volts was obtained by W. Crookes at the end of the 19th century; In 1897 J.J. Thomson identified them as negatively charged particles in motion. In 1906 Lee De Forest worked on a tube with three electrodes called a Triode. But we can say that the real birth of electronics dates from the 1940s, even though electron beams were used in electron microscopy and in refining refractory metals in vacuum furnaces in the 1930s.
In 1946, Zworkin published his book *Electron Optics and Electron Microscopy* which defined the equations and the physics for the production and manipulation of electron beams. In 1954, J.R. Pierce published his book *Theory and Design of Electron Beams* [23]. These books may be regarded as the fundamental tools for the design and the optimization of electron guns used in the first generation of welding equipment.
Electrons are produced by an emissive surface (cathode) connected to a negative potential (several thousands of volts) and heated appropriately to a temperature of 1200-2700° C, according to the nature of the cathode. The electrons acquire kinetic energy when crossing the electric field created between the cathode and the earthed anode (electrostatic part). An additional electrode called “Wehnelt” surrounding the cathode plays the role of a “Grid” in an electronic valve by controlling the electron emission. In addition it favourably affects the formation of the beam and particularly its electrostatic concentration in the crossover. The image of this crossover, through one or more electromagnetic lenses, is placed on the work piece to be joined and constitutes the heat source used for welding. Beams which can have a diameter of 10 to 50 mm are concentrated by appropriate means to small spots of 0.1 to 0.5 mm, thus producing heat sources with very high energy densities, up to the order of 100 million W/cm^2.

Because of high-voltage breakdown, risks of oxidation of the cathode, which is at a very high temperature, and dispersion of the beam by air molecules, it is vital that all the electrostatic part is held in a vacuum of less than 0.01 Pascal pressure, which is obtained by appropriate pumping systems. In the electromagnetic part of the gun, the electron beam needs a vacuum of less than 1 Pascal for its propagation and to avoid dispersion and loss of energy density. Some companies, however, have manufactured welding machines in which the beam propagates a short distance in helium atmospheric pressure before reaching the joint.

Design of Electron Guns for Welding (for Details see Ref. [24])

The design and optimization of EB guns requires the solution of complicated equations which define the physical phenomena in the gun relative to:

- extraction of electrons from the emitting surface,
- formation of the beam and its acceleration in the electrostatic part of the gun and
- focusing on the joint to be welded by appropriate electromagnetic fields.

When the cathode is heated to a given temperature, it emits a "cloud of electrons", which remains close to it, in the absence of extractive forces such as an electric field. The difference of potential between the cathode and the anode creates the electric field which extracts the electrons from the "cloud".

Three types of emission can be distinguished:

- Temperature-saturated emission, when all the electrons in the cloud are extracted (generally used in melting and refining).
- Space-charge limited emission, when only some of the electrons in the cloud are extracted (generally used in welding).
- Schottky, or field-effect emission, when in addition to the electrons in the cloud, other electrons are extracted from the solid cathode by the electric field (generally used in electron microscopes).

The equations defining beam characteristics (trajectories, divergence, and power distribution) are of the Laplace and Poisson type associated with 2nd differential equations which can be resolved analytically only for electrodes with simple geometrical shapes (e.g., sphere or cylinder). Pierce developed this solution further, in order to define a certain type of electron gun. When such configurations were employed in the first EB guns, used in vacuum furnaces, it soon became clear that for welding one needs much more complicated shapes, which cannot be resolved analytically.

At the beginning of the 1970s, many computer programmes were available in France to resolve precisely the complicated equations which define all the characteristics of the beam in an electron gun, without exaggerated simplification of the equations. For example, the computer programmes took into account the relativistic effect of the electrons which travel at 100000 to 200000 km/sec and the effect of partial neutralization of the electronic space charge.

Thus manufacturers of equipment were able to precisely define, by successive approximations, the elements of an electron gun capable of producing the required beam characteristics.

Needs for an Automatic Control of the Process (for Details see Ref. [25])

The consequence of the very high power density on the joint is that the beam instantaneously vaporizes the metal at the impact point and creates a deep capillary, which is filled with plasma-type metal vapours. The calorific energy of the beam is therefore transmitted to the workpiece through its entire thickness, unlike other welding processes, which transmit heat by conduction from the top surface of the workpiece. As a result EBW joints are characterized by narrow and deep welds with minimal distortion of the welded parts. On the other hand, it soon became clear that this joining process could not be performed manually, but had to be executed automatically by controlling the numerous welding parameters affecting the quality of the beam.

The history of EB welding is closely related to the evolution of its automatic control, which will be presented hereafter, considering the different operating parameters of the process:

Vacuum Control

As seen earlier, electron beams can be generated only in high vacuum (< 0.01 P), whereas the welded part can be in a vacuum of 1 P. Pumps, piping, baffle and gauges comprise the vacuum system, where a well defined automatic operating cycle should be used to achieve the desired vacuum.

Pumping is achieved in two stages: first primary (mechanical) pumps get the pressure down to 1 P, and then a diffusion (later turbo-molecular) pump brings the vacuum to 0.01 P.

The pumping cycle (the starting and stopping of pumps, the opening and closing of valves, the measurement of the pressure) operates automatically according to a well defined sequence by the simple pressing of a button. In the first generation of EBW equipment, the automatic sequence was achieved by relays and switches. More recently, microprocessors and computer controls have been used.

Control of Movement and Alignment of the Beam on the Joint

In order to obtain a high-quality weld, it is necessary to use a carefully controlled welding speed between the impact point and the parts to be welded. The variation in the speed ought to remain within 1 to 2%, even when the fluctuation of the voltage supply is 10%.

In the first generation of welders, electric motors with separate excitation were used on the primary circuit of the high-voltage transformer and servo-mechanisms, allowing three-dimensional movement with adjustable and constant speeds throughout the welding cycle – all of which was integrated into the control.

Later, CNC systems, already used in the machine-tools industry, were integrated into EB equipment, producing a high degree of precision, flexibility of application and excellent reliability.

The control of the alignment of the beam on the joint in the first-generation machines was achieved by an ordinary telescope which made the impact of a low power beam on the joint visible and which manually adjusts the beam-impact position to make them coincide. Later, a camera and monitor were used to ensure this alignment.

It is interesting to point out that very early in 1968, the principle of “back-scattered electrons” was used, based on the interaction of a low power beam with the solid edge of the joint, to identify the exact position of the impact point on the joint. The same principle was used later on, when computers were available, to automatically seam track any configuration of joint during the welding cycle.

Control of Beam Parameters:
The Cathode and its Heating

Cathodes used in EBW guns can be either a ribbon or a filament of a refractory metal such as Tantalum or Tungsten, formed into a circular emitting surface. These cathodes, usually used when the beam current does not exceed 500 mA, are heated directly by Joule effect to a temperature of 2000-2700 °C.

When a higher beam current is needed (1 A or more), massive cathodes are used. They are heated indirectly by an auxiliary electron beam which bombards the rear part of the cathode, or by an induction system located round the cathode.

In each case the temperature of the cathode needs to be controlled and maintained with precision, as it has a considerable affect on the beam current and power distribution. The first generation of EB equipment achieved this by classical electronic and closed loop circuits. Later, the heating system was integrated in the computer control of the whole process.

High Voltage and Beam Power

The stability of these parameters during welding is essential to produce quality welds reliably. I should now like to explain how these parameters were controlled on the first generation of EBW equipment in 1966.

The voltage was controlled by driving a variable autotransformer by a low-inertia motor coupled through a reducer. The latter is controlled by a position servo-mechanism which achieves equilibrium between a measured and preset voltage. Thus it is possible to adjust and programme a stable voltage precisely, give or take 1-2%.

To control the power in the beam, an electronic device was introduced, which multiplies the measured voltage by the current in the beam and compares the result to a pre-set value. An amplifier transmits the detected error to the control circuit of the bias voltage to automatically adjust the beam power to the desired value.

Another way to control the beam power is to act on the difference of potential between the cathode and the Wehnelt. The consequence is to

modify the electric field in front of the cathode and thus the electrons which are extracted from the electronic cloud there.
Thus, since 1965 it has been possible to provide a stable source of energy, capable of producing the high-integrity joints so valued by industry. Later, all these systems were integrated into a single computer controlling the entire process.

Focus of the Impact Point

The beam is focused with an appropriate magnetic field of a lens coil. The stability of this focusing current is essential to keep the focus position and the diameter of the focus point and thus the energy density constant – this is essential to produce a weld of constant quality.
This is particularly important in cases of inclination and of varying thickness of the parts to be welded. When computer control of the process was integrated into the equipment, simple methods using appropriate software with adequate interfaces were employed to control, adjust and program the above-mentioned parameters.

Accelerating Voltage and Mobility of the Electron Gun

EBW equipment developed in France in the sixties used 30-60 kV accelerating voltage, which was derived from the sources employed in electron beam furnaces for refining refractory metals. The choice of this accelerating voltage was guided by the following criteria:

- A choice was made to move the gun inside the vacuum chamber, which implies a miniaturized mobile gun. The 150 kV system, used, for example, in Germany, requires large isolation distances at this voltage. This renders the gun cumbersome and difficult to move inside a vacuum chamber.
- Protection from soft X-rays produced by 60 kV accelerating voltage is much easier to achieve than protection from the hard X-rays produced by 150 kV beams.

Furthermore, as computer programmes to optimize the gun became available, it was possible to design guns operating at 30-60 kV which produced 30 kW beams which could be concentrated on very small spots with a very high power density, producing deep welds sufficient for industrial requirements.
When higher beam powers (50-100 kW) were needed for heavy industries, other designs using 100 kV and 150 kV were used, but the gun was generally fixed, except for very special applications.

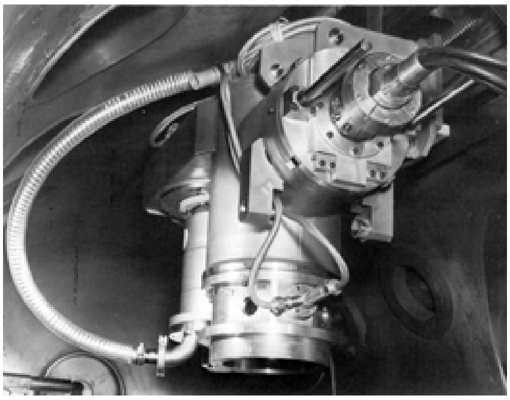


Fig. 33: 100 kW EB gun designed by CEA.

Here are the main characteristics of EBW guns manufactured in France:

Voltage (kV)	Power (kW)	Mobility	Fields of application
30	3	fixed and mobile	small mechanics
60	15-30	fixed and mobile	Auto, aircraft …
100	50-100	fixed	heavy industry
150	30	fixed	prototype

In the first mobile gun concept, the gun was housed inside the vacuum chamber (fig. 34) on a carriage moving on one axis, and the part to be welded was mounted on another carriage, which could move on a perpendicular axis or rotate around it, enabling welds on a level surface. An example of a large chamber to weld cumbersome components for the aeronautical industry is shown in fig. 35.

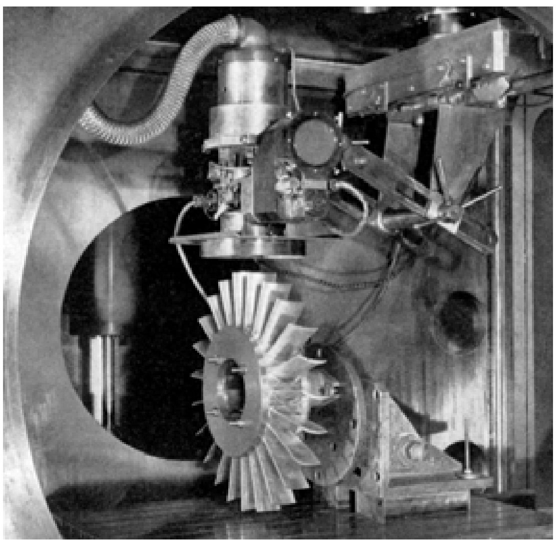


Fig. 34: Mobile electron gun in the vacuum chamber for welding a compressor rotor.

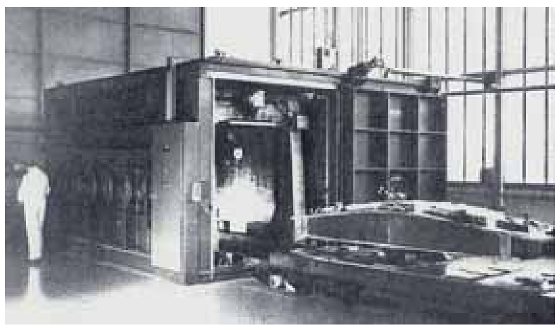


Fig. 35: Large vacuum chamber for welding central components of variable wing geometry aircraft. The mobile gun can be seen inside the chamber.

In more sophisticated systems, the gun was mounted on an articulated arm with several degrees of freedom. The movement of the gun may be compared to the movement of a robot with up to five degrees of freedom which permits curvilinear welds in 3D.

<u>Vacuum Chamber and Production Rate</u>

EBW equipment covers a range of power from 2 to 200 kW, using vacuum chambers ranging from a few litres to several hundred cubic meters and ensuring a production rate of one part per day (aircraft structures, heavy industry, and the petrochemical industry) to more than a thousand parts per hour (automobile).

For the design of the large chambers, special attention needs to be paid to the deformation of the walls and door, which can result in a distorting effect on

the different moving axes of the gun. It is easy to imagine the distortion of a box submitted to a pressure of 10000 kg/m^2. Fortunately computer programmes were soon available to evaluate and choose the appropriate dimensions of the chamber structure.
Finally, when designing the chamber, attention needs to be paid to protecting the operators from X-rays. Today, it is clear that this protection was, unfortunately, not much of an issue in the first generation of French EBW machines. Indeed, many operators, especially in research laboratories, had health problems related to the high level of X-rays to which they were submitted.
The time required to pump the chamber generally takes up a disproportionately large amount of the total welding cycle. From the first generation of EBW equipment onwards, the manufacturers developed tools and manipulators specially adapted to increase production. The most interesting development was the indexed rotating-table concept with multistations, which was largely used in the automobile industry, where production could be from a few units per hour up to 1200 parts per hour. This is the concept, used not only in France, but also in many other countries for mass production of gears for the automobile industry:

- An indexed rotating table, with several local stations equipped with appropriate tooling.
- The part to be welded is loaded onto the tooling in one of the local stations, and, by swivelling the table, is moved under the fixed gun, which is mounted on a small local chamber open at its lower part.
- A lifting device is used to raise the tooling, holding the part to be welded up to the bottom of the local chamber.
- Seals fitted at the top of the vacuum chamber and on the top of the tooling ensure vacuum sealing of a limited volume which contains the parts to be welded.
- The sealed local vacuum chamber is pumped to the desired vacuum.
- The weld is realized by a drive mechanism or by deflection of the beam.
- After welding, the bottom is lowered and the table swivels back to the station, where it is unloaded.

Hundreds of EBW units based on this principle were manufactured for the auto industry for the mass production of gears, clutches, cams etc. Fig. 36 shows an example of such a system with six stations, equipped with two EB guns to increase productivity.
Some 150 kV units operate in atmosphere (Non-Vacuum Electron Beam Welding), and can perform the same type of application. The beam comes out into atmosphere where the workpiece is located close to the orifice, through successive vacuum chambers and nozzles. A number of prototypes based on this principle were manufactured in France.

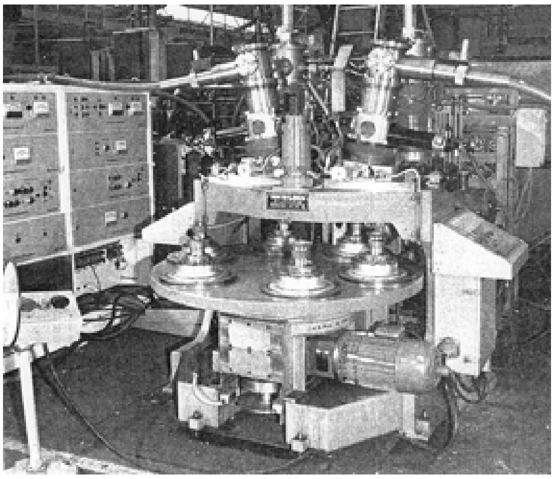


Fig. 36: EBW machine with a 6 position rotating index table, equiped with 2 guns to increase productivity for the automobile industry (1974).

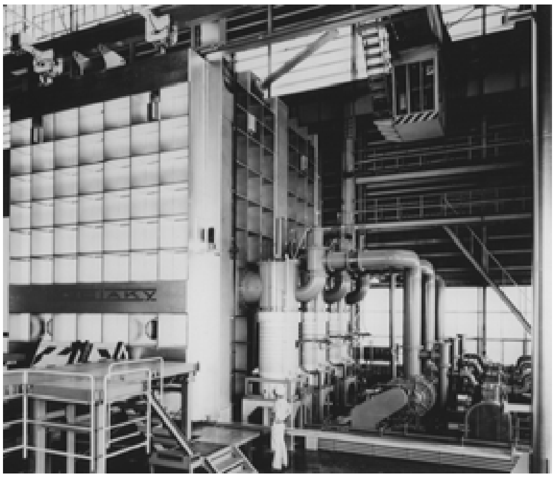


Fig. 37: Giant EB machine of 264 m^3 for welding nuclear components (1980).

Special Machines

Fig. 38: EB gun for welding tubes into heat exchanger plates using local vacuum.

Many prototypes of special machines for heavy industry were manufactured in the years 1970s and 1980s. They were tested, and some prototypes of heat exchangers, plate welding for shipbuilding etc. were produced. But the demands of heavy industry (e.g., gap tolerance, quality control and industrial reliability of the equipment) seemed insurmountable in production at that time. I believe that more R&D work was necessary in the field of active electronic components to improve the performance of these units, so that they could be accepted by industry.
Fig. 37 shows a very big machine of 264 m^3 for welding internal core-barrels in the 1980s for the nuclear industry with an internal gun of 45 kW. Later, even bigger chambers of 800 m3 were realized by Techméta in France for welding submarine components.
The system depicted in fig. 39 is even more spectacular, developed by TOTAL and SAF in the late 70s to butt-weld pipelines to be laid on the sea bed. It shows a different concept called “Local Vacuum EBW”. This technique creates the vacuum in a limited volume round the seam to be welded, and leaves the rest of the workpiece at atmospheric pressure. Based on this concept, various types of equipment were manufactured.

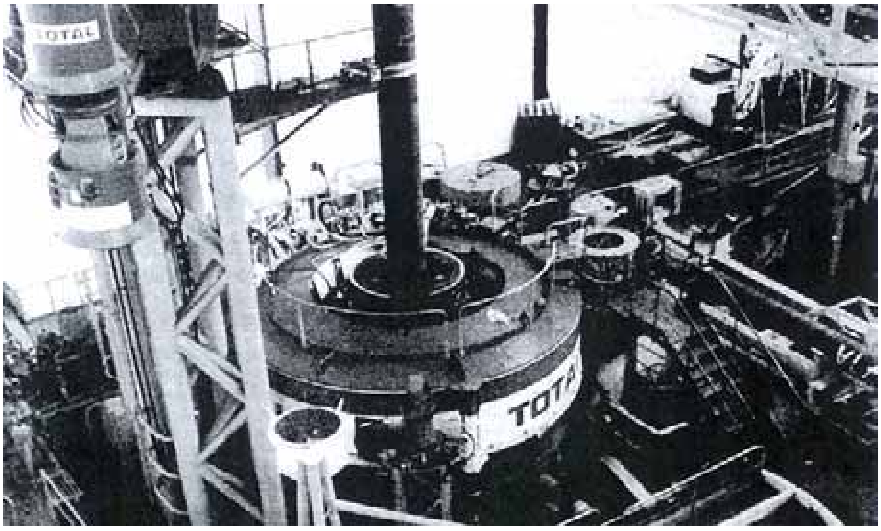


Fig. 39: Local vacuum machine for welding pipelines in the J position (1978).

At Sciaky, a stationary local vacuum is formed only along the whole length of a linear seam, and the gun, mounted on a carriage, slides on the plate to achieve the weld.

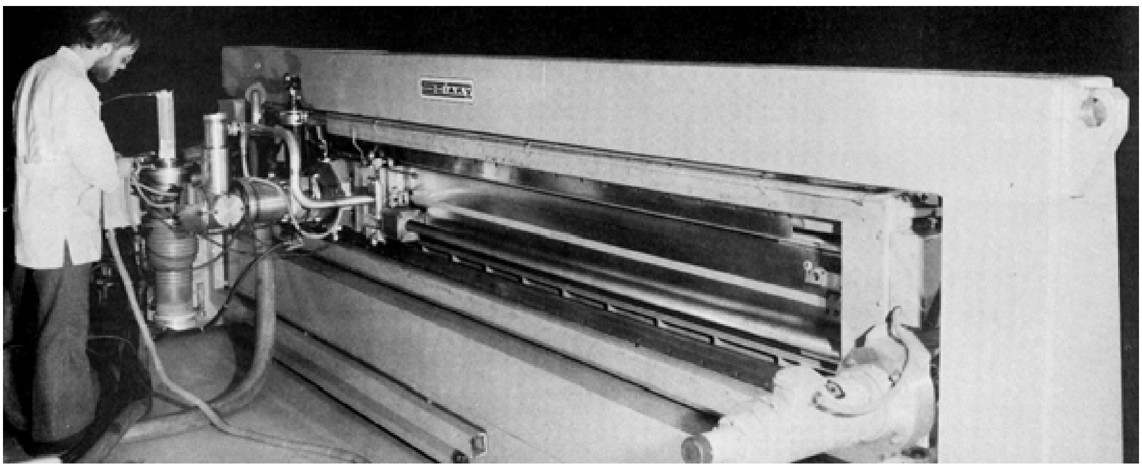


Fig. 40: Linear guide system for mobile EB gun to weld under local vacuum.

EB Welding Equipment Works in France

- From 1956 to 1960 CEA designed and manufactured several EB welder prototypes for their own use. They did not sell any machine to external customers.
- Clover, a small company with only a handful of employees, founded by an ex-employee of CEA, manufactured a few prototypes in 1973, mainly for CEA and, it appears, one machine for Japan. Clover was taken over by Sciaky in 1974.
- Alcatel, who manufactured EB melting furnaces in the 1960s, started manufacturing welding guns and machines in 1966. About 15 people, including myself and M. Sommeria, were involved in this activity. Alcatel sold the activity to Air Liquide/SAF in 1972. SAF produces a range of EB equipment from small, standard machines to large tailor-made machines and had a sales co-operation with Steigerwald for some years (fig. 41).

Fig. 41: Small standard chamber machine manufactured by SAF 1978.

Fig. 42: Production machine for 500,000 parts per year manufactured by Techméta. The workpiece carriers are transferred around the chamber.

- M. Sommeria, who was an active engineer who believed in the technology, founded Techméta in 1972. He employed up to 60 people in his company, where a lot of semi-industrial components were subcontracted for EB welding (fig. 42). After his death in 1990, his wife, brothers and sons tried to carry on his work. In 2007 the company was sold to "bodycote".
- Sciaky entered EBW in 1956. The activity of Sciaky France was essentially turned to electric resistance welding for aircraft and automobile industries. The company employed up to 2000 people, among which 60 to 80 people were concerned directly to EBW. Sciaky stopped EB activities in 1992.

Relations between Sciaky France and Sciaky U.S.A.

David Sciaky, the eldest of four brothers, one of whom was Mario Sciaky, founded his first companies for resistance electric welders in 1930 in Austria and in France. During the war, the family went to the U.S.A. where they founded Sciaky Bros. in Chicago, specializing in welding structures for the aircraft and automobile industries and the automatization of welding processes. Sciaky Bros. became a player in the EBW stakes just after the licence agreement of Sciaky France with CEA in 1960. The shares of both companies were in the possession of the families. In the 1980s Sciaky Bros., who employed up to 700 people, was bought by an American fund and subsequently transferred to several other owners.

Sciaky France experienced financial difficulties in 1989 and was taken over by a financial trust who, in 1995, sold it to Comau.

The Situation of EBW and its Future

The specific advantages of EBW, compared to other welding processes, can no doubt be found in other chapters of this book. I shall present here only some generalizations about its areas of application and its position vis-à-vis laser beam welding which became its main competitor in the 1980s.

EBW applications serve a whole range of industries such as: the aeronautical, automobile, energy, nuclear, and electric appliances industry. The EBW units were used:

- to join very expensive components (jet engines) as well as in very cheap ones (gears, cams)
- in mass production (automobile, electrical appliances) as well as in unit production (internal core of nuclear reactors)
- in welding small parts (pressure transducers) as well as very large components (bodies and wings of airplanes)
- in welding thin components (saw blades, pacemakers) as well as very heavy sections (pressure vessels)
- in welding ordinary metals (structural steels) as well as exotic metals (titanium, gold, silver...)

It would take too long to cover here even a few of these applications. We may just say however, that EBW technology has been systematically adapted to better satisfy the specific needs of its users [26].

It is difficult to evaluate the total number of EBW units manufactured in France. One estimate comes close to 850, of which 250 were exported and 360 are still operational in France.

Conclusion:

When I was asked to participate in this venture, it was with great pleasure that I agreed to prepare this contribution. Indeed, it is very important for future generation to know about this technology that was born in Europe – France and Germany – and has spread all over the world in the last 50 years.

A wide range of industries have taken advantage of the specific characteristics of this technique to improve the performance and the quality of their products.

Georges Sayegh:

Georges Sayegh D. Sc - D. Eng

Involved in the design of EB guns in 1967 in the Scientific Department of Alcatel Company in France. From 1972 to 1992 he worked for the Sciaky company, manufacturer of welding equipment, where he acted successively as research engineer in the Electron Beam division, scientific director and director of R&D. This paper presents the fruits of his active experience of EB welding technology in France during this period.

Electron Beam Welding in the U.S.A.

Robert Bakish & Donald E. Powers

Introduction

Experimentation on using electron beams to join nuclear fuel elements began in the U.S.A. in the late 1950s, [27] and the first formal employment of the electron beam welding (EBW) process as a production tool for this task was established in July 1958 when the Bettis plant of Westinghouse acquired a Zeiss electron beam welding unit. These developments, together with Stohr's 1958 announcement [14] about the applicability of electron beam welding to the nuclear field, triggered a high degree of interest in this new process in the U.S.A.

Throughout the 1960s and into the early 1970s a variety of suppliers (Alloyd Corporation, National Research Corporation, Air Reduction Company, Electro Glass, Sciaky, Brad Thompson, Nuclide, High Vacuum Corp., Hamilton Standard, Union Carbide, Westinghouse, Veeco, ACRO, Steigerwald Strahltechnik etc.) were all active in selling electron beam welding equipment to the U.S. market. This was the golden era of EBW machine sales in the U.S.A., with annual sales totalling between 50 and 100 units per year in the 60s – before tapering off to between 20 and 40 units per year in the 70s. During this period, Veeco/BT/Nuclide/Acrotron (put out by ACRO)/Union Carbide (aka ERI & Linde) and Sciaky were noted for providing low-voltage (25 to 60 kV) style equipment, while Westinghouse/Steigerwald (first distributed in the U.S.A. by Farrel – and then by Messer Griesheim after they acquired them)/Hamilton Standard-Zeiss, Leybold-Heraeus and Leybold were noted for providing high-voltage (150 to 200 kV) style equipment.

With the advent of the late 1970s and early 1980s, many of these EBW equipment suppliers fell by the wayside – and by the mid-1980s the two primary parties left supplying the U.S. market, as well as providing EBW equipment to overseas users, were Sciaky and Leybold. A synopsis of the first 25 years of EBW growth in the U.S.A has already been provided by R. Bakish, in 1983 [28, 29]. Since then, a variety of other U.S. suppliers (EBTEC/CVE-Wentgate/AVR-AVT/Techmeta/K&S-KSET/EBW etc.) have come into existence – many of whom continue today, along with Sciaky and PTR (formerly Hamilton Standard/Leybold-Heraeus), to provide EBW equipment to the U.S. market.

Milestones and Special Features

Starting out initially as a laboratory-style vacuum technique that required it process items at ambient pressures of 10^{-4} Torr and below, electron beam welding has since matured into a production tool of much broader versatility and greater applicability. As its acceptance grew, and its users began to have a better understanding of the process, two important modifications ensued: the development of the so-called soft or partial-vacuum mode of EBW (introduced to the U.S. market in about 1966 [30,31]) and the non-vacuum or atmospheric mode (originally developed in Germany during the 1950s [13]; this process was initially introduced to the U.S. market in around 1963 [32]). Sciaky and Hamilton introduced the soft or partial-vacuum mode to the U.S. market almost simultaneously in the mid 1960s; then Hamilton and Leybold went on to become the major party involved with supplying non-vacuum EBW systems to the U.S. market from the late 1960s to the early 1980s; today, PTR (along with its AWT Group associates in Germany) continues to be the primary supplier of non-vacuum EBW units worldwide.

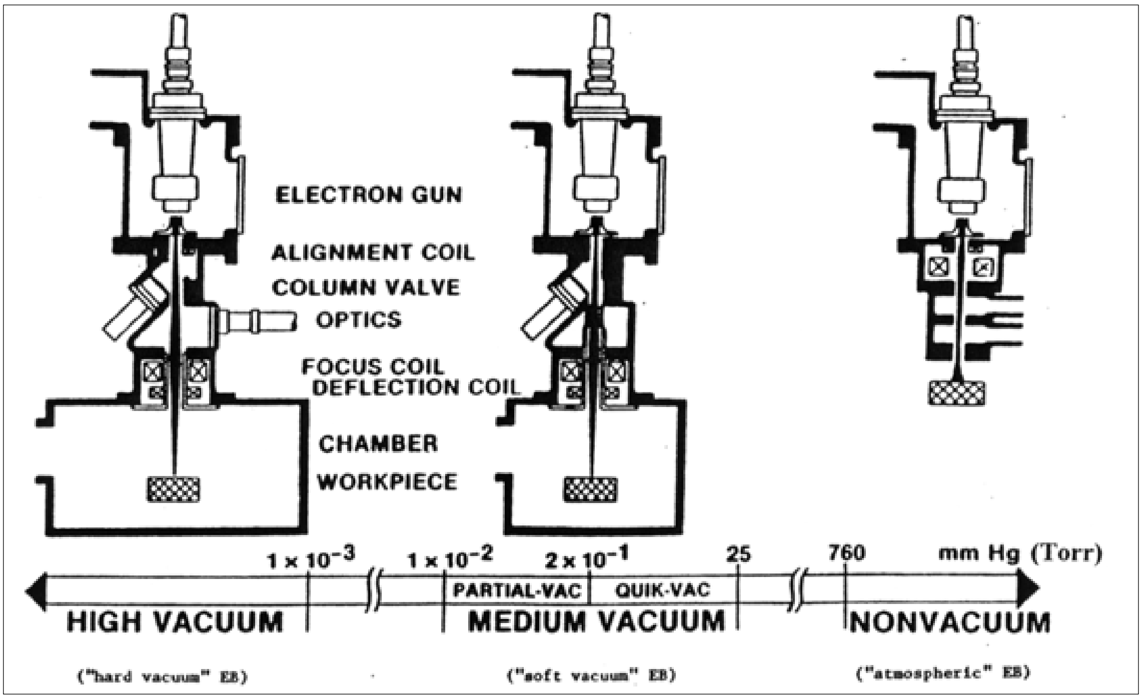


Fig. 43: Three basic modes of EBW processing.

To sum up, then, when we speak today (2007) of electron beam welding, we mean three separate ambient-pressure-dependent modes of operation:

- the original hard-vacuum mode, carried out at pressures below 10^{-4} Torr,
- the soft or partial-vacuum mode, carried out in the 10^{-1} to 10^{-2} Torr pressure region and
- the non-vacuum or atmospheric pressure mode, carried out at pressures greater than 100 Torr.

Each of these different modes of operation has carved a specific place in the U.S. welding industry in general and in the electron beam welding business in particular. The operational (i.e., the EB gun accelerating) voltage used was another key factor in the development of the electron beam welding process, and has resulted in units with operational voltages of 20 kV, 30 kV, 60 kV, 150 kV and 200 kV having been sold in the U.S. market during the past 50 years. Of these, those operating at 60 kV and below are normally referred to as low-voltage EBW systems, while those operating at above 60 kV are generally referred to as high-voltage EBW systems; both high and low-voltage systems are utilized for the hard and soft-vacuum modes of EBW, but only high voltage is employed for the non-vacuum mode of EBW.

The hard-vacuum EB welders are generally available with either stationary (fixed, high or low-voltage gun, externally mounted) or movable (low-voltage gun, internally mounted on a device allowing various degrees of gun motion) beam generation systems, with the internally mounted and movable form of gun concept being a distinguishing feature of Sciaky's equipment – in addition to that of certain other overseas-based EBW equipment suppliers. One of the first users of EBW, the French Atomic Energy Commission, while seeking to precisely accommodate components of specific configuration, developed the use of sliding vacuum seals and localized weld chambers.
These developments were then introduced into the U.S.A. by Sciaky at about the same time that HSD/L-H was also advancing the idea of using localized weld chambers to help reduce processing cycle times; whereas these two adaptive-vacuum approaches helped contribute solutions for better accomplishing specific joining tasks, they did not make a major impact on the state of the technology itself.

The increasing acceptance of electron beam welding also necessitated that EBW machines already in use, which for the most part were initially limited to providing a maximum beam-power output no greater than 3 kW, be either retrofitted to (or replaced by) a unit having a higher beam-power output capacity. The range of today's newer electron beam welders is generally 5-45 kW; several suppliers can also provide units between 60 and 100 kW of beam-power output.

Electron beam welding's ability to produce finished joints at very high weld speeds necessitated the automation of the process to help eliminate any restrictive dead times from the processing cycle – this was notably enhanced by the development of computer technology. In 1982 Sciaky advised one of the authors [33] that of the approximately 360 machines it had delivered until then (the total worldwide), only roughly 120 had

computer-style controls. Subsequently, according to a more current estimate by PTR, of the approximately 500 machines it (i.e. PTR/LH/HSD) has delivered to the U.S. market since entering the business, roughly 150 now have computer-style controls.
In 1983, based on conversations with suppliers and users of the EBW process, the author mentioned above estimated that, while 30-40% of the electron beam welders being produced at that time had computer-style controls, only about 5-10% of these units had additionally incorporated automated operational features.

Whereas electron beam welding was initially used only in the nuclear and aerospace industries, known for their highly specialized demands, it has long since spilled over into numerous industrial areas [34]. Thus the technology has also made major contributions to the manufacturing segments of both the automotive and metalworking industries, to name just a couple. While it is difficult to be precise, one of the authors (D. Powers) has estimated that there are in the order of 1000 electron beam welding machines in service in U.S. industry today – many of which have origins dating back to the 1960s or 70s, and yet are still being utilized on a daily basis (if not by the original purchaser, then by the 2nd or 3rd owner of the unit).
Of these, about 30% are in the aerospace industry, 15% in the automotive industry, 20% in the nuclear industry and the remaining 35% are spread out over various other industrial areas (i.e. consumer product and/or medical/job shop/electronic/etc. industries).

Limitation

The introduction of a new technology almost invariably leads to exaggerated claims about its capabilities from over-zealous promoters of its virtues. Thus, at the time of its introduction to the U.S. market, electron beam welding was generally touted as being a technology that would be able to solve all welding problems, and eventually entirely replace the use of conventional arc welding – two claims which the process was never able to substantiate. Yet the multi-functional electron beam welding process that has evolved over the past 50 years has definitely proved to be an extremely powerful welding tool when applied within the confines set by normal physical metallurgy and metallurgical thermodynamic limitations. Although electron beam welds are not immune to the same type of defects (e.g., porosity, spatter, shrinkage, cold shuts, cracking, etc.) that also tend to plague most other welding processes, the extremely precise and virtually instantaneous energy input control available with the EBW process allows users to better minimize the occurrence of such weld defects [35].

The cost of an EB welder has been, and can still be a significant factor in determining whether or not EB welding is selected as the joining process of choice by the end user. In the early days, especially in situations where EBW was the only viable solution to a particular joining problem, the cost of the equipment required was secondary. The availability of funds in the nuclear and aerospace industries in the early 60s was of essential significance to what, at the time, was a technology in the early stages of its development. The nature of such funding assured its survival and growth. But in the recession economy of the early 1980s, EBW equipment manufacturers had to fight hard for sales, and EBW equipment had to compete against other joining processes on the basis of economic viability.

By the mid 80s the cost of purchasing an EB welder had grown significantly since the introduction of the process 25 years earlier; this was due in part to the advancements that had been made to the technology, with greater use of solid-state and computer-style control devices providing a much higher degree of beam application flexibility [36] and to the fact that significantly increased beam-power output capacities had been developed. Consequently, whereas in the early 60s a fully manual style EB welder with a fairly small chamber (less than 3 kW) might have been purchased for between $ 50,000 and $ 150,000, by the mid 80s the cost of purchasing a partially to fully automatic style EB welder with a moderate sized chamber (15 to 45 kW) had risen to between $ 500,000 and $ 1,000,000 – with larger units complete with a range of optional accessories included, costing between $ 1,000,000 and $ 2,000,000 (or more). However, the present cost of an EB welder hasn't really increased significantly from the prices of the mid 80s, since small chamber/low-voltage/6 kW/PLC-style units today sell for in the order of $ 500,000 and large chamber/high-voltage/25 kW/fully CNC-style units sell for somewhere in the region of $ 1,000,000 to $ 2,000,000 (or more). As with all highly sophisticated machine-tool purchases today, the acquisition of an EB welder must be justified on the basis of economic viability. Thus, while in many cases a partial utilization for second-shift work might help justify the acquisition of an EB welder, a multi-shift operation requirement could assure enhanced productivity that would certainly reinforce this justification, and, in many instances, might be a necessary prerequisite for procuring an EBW unit.

Achievements

The achievements of a technology are realized by the capabilities of its tools. In electron beam welding the term "tools" refers to the modes of ambient processing environment that the technology employs. These include not only the three basic methods of processing previously defined, i.e. the high vacuum (HVEBW), partial vacuum (PVEBW) and non-vacuum (NVEBW)

Fig. 44: Air-to-air style EBW system made by Hamilton Standard.

ambient vacuum modes illustrated in fig. 43, but also "air-to-air" (A-AEBW) processing, which involves a technique mainly utilized in producing the EB welded bi- and tri-metal strip used for manufacturing electronic and saw blade components (fig. 44). This method provides the means to uninterruptedly EB weld (employing either a high or low-voltage beam generation device) both bi- and tri-metal strip continuously being fed from atmosphere – through vacuum – back to atmosphere again totally "on the fly", thereby allowing an HVEBW form of weld to be performed on this strip material in a continually uninterrupted fashion. The attached pictorial review (figs. 44 to 60) on the types of EBW equipment employed to accomplish a variety of different joining tasks over the 50 years between 1957 and 2007 will help illustrate the progress that has been made in state of the art of EBW equipment during the last half-century.

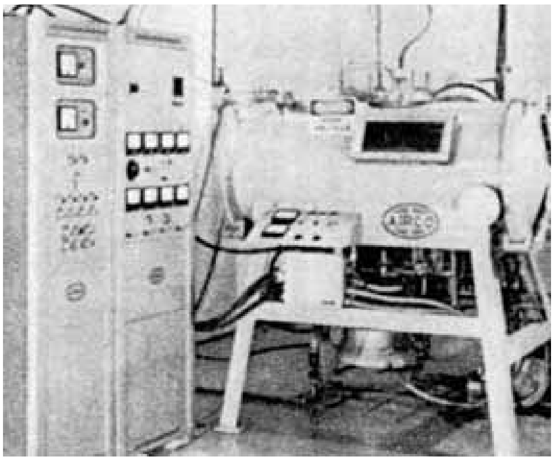


Fig. 45: 1950s-style Air Reduction Company EB welder.

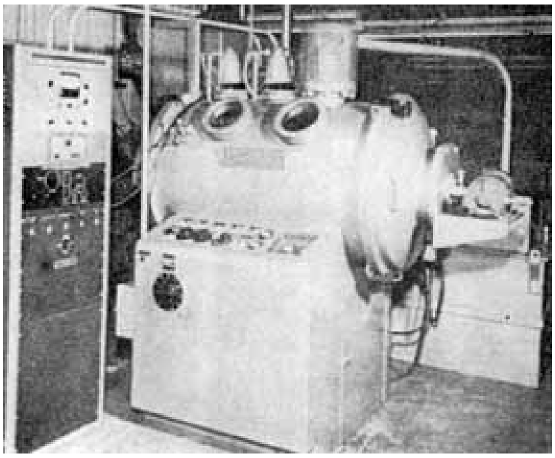


Fig. 46: 1950s-style High Vacuum Corp. EB welder.

Figs. 45 and 46 show a late 1950s-style Air Reduction Co. and High Vacuum Corp. EB welder (respectively), both low-voltage units, while fig. 47 shows an early 1960s-style Sciaky Brothers unit, also a low-voltage machine.

Figs. 48 and 49, on the other hand, show early 1960s-style Zeiss and Hamilton-Zeiss EB welders, respectively, both of which are high-voltage units. All five are HVEBW units, fitting the mould of a vacuum chamber with a fixed-location beam generation system mounted externally. Then, with the introduction of the PVEBW method, a new concept was introduced: EBW machines designed specifically (both vacuum-chamber size and part tooling/fixturing wise) for welding a particular workpiece, or family of workpieces in the shortest time possible.

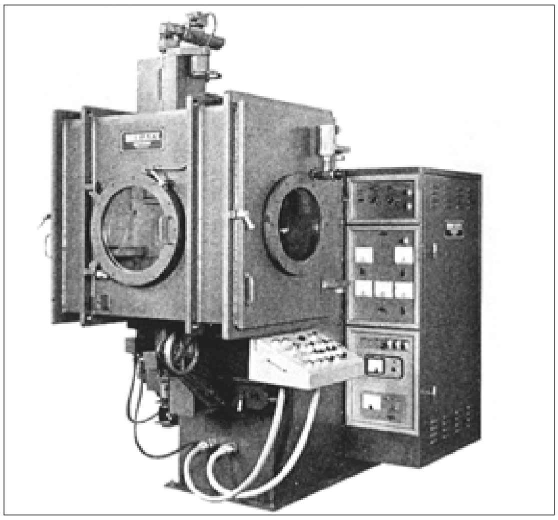


Fig. 47: 1960s-style Sciaky Brothers EB welder.

Fig. 48: 1960s-style Zeiss EB welder ES1002.

Fig. 49: 1960s-style Hamilton-Zeiss EB welder.

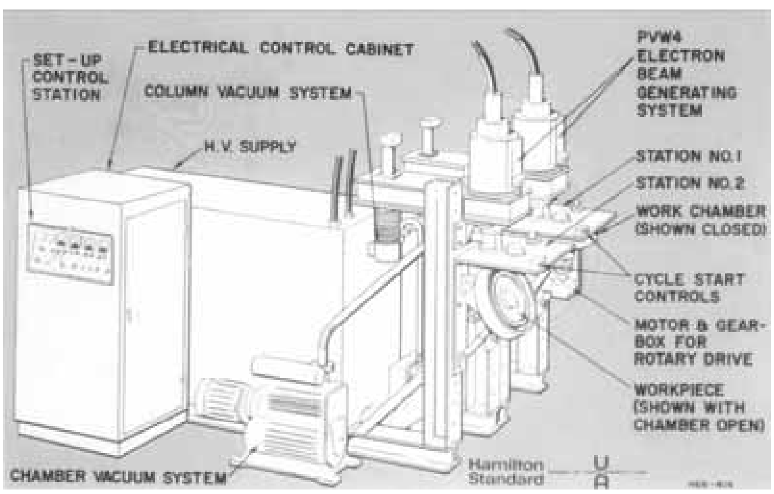


Fig. 50: 1960s-style Hamilton Standard high voltage PVEBW unit with twin gun and chamber.

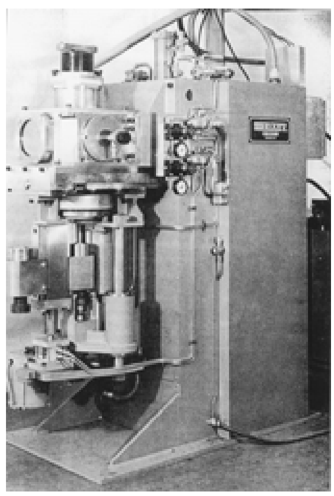


Fig. 51: 70s-style Sciaky low voltage PVEBW unit.

This style of EBW machine led to the substantial growth of EB welding in the automotive industry [37]; Fig. 50 depicts a late 1960s Hamilton Standard high-voltage PVEBW unit for the automotive industry, while fig. 51 shows an early 1970s Sciaky low-voltage PVEBW machine for the same industry. These are but two examples of the large variety of EBW machines delivered to the automotive industry from the late 60s to the early 80s. The large variety of machines included systems using both static and dynamic vacuum seal schemes, for cyclically transferring parts through the weld zone, as well as ones utilizing some form of digital-style (PLC/CNC) controls – and almost all required a beam power output capability of less than 10 kW to accomplish the joining task required. Fig. 52 provides a view of a present-day version, production style, low-voltage/nominally 6 kW/PLC-fully automatic/production style, PVEBW variety unit.

Fig. 52: Modern version of PVEBW style PTR unit.

Fig. 53: Modern day version of NVEBW style PTR unit.

Fig. 54: 1960s version NVEBW unit made by Hamilton Standard.

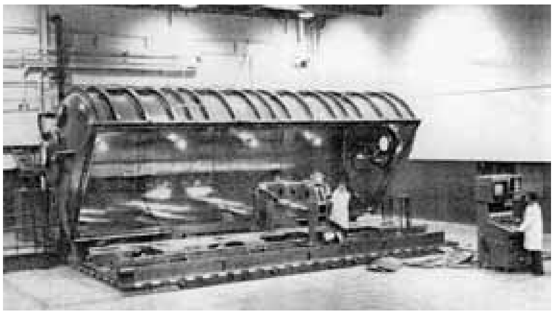


Fig. 55: 1970s version specialized EBW unit made by Sciaky called "clamshell".

In order to better meet the automotive industry's increasing desire to be able to EB join the greatest number of parts possible in the shortest period of time feasible, the NVEBW mode of EB welding was introduced to the industry during the late 1960s; Fig. 54 shows one of the earliest (a 12 kW max. beam power output) NVEBW-style units used at an automotive facility then. Three such units, all individually coupled to carousel-variety tooling packages, were installed at GM'S Saginaw Steering Gear Div. at the end of the 60s – providing them with the capacity to produce over 600 non-vacuum EB welded steering column jackets per hour. Fig. 53 shows a modern version NVEBW (with a 30 kW MAX. beam power output capability); this unit, installed at a U.S. Daimler Chrysler plant in early 2000, is now in use for non-vacuum EB welding lockup rings onto torque converter impeller bowls.

The aircraft and aerospace industries were the leaders in the development of highly specialized EBW machines, many of which were prompted by the size and complexity of the parts requiring processing. Fig. 55 shows Sciaky clam-shell style, low-voltage/internally mounted/movable variety gun system that was specifically built during the 70s for use in EB joining the wing box and pivot assembly employed on the F14 & F15 aircraft. Fig. 56 shows a (HSD/L-H) large chamber, high-voltage/externally mounted/fixed gun (all weld motion, X/Y/ROT provided via part movement alone) style system similar to those commonly utilized for aircraft engine O&R tasks during the 70s and 80s while fig. 57 shows a Sciaky large chamber, low-voltage/internally mounted/movable gun style system used for the same task during the same period. However, not all EB welders built in the 60s, 70s and 80s were for use on earth, and fig. 58 shows a hand-held EBW unit developed for use in space, for use by astronauts needing to do either weld fabrication or perform repairs in outer space [38].

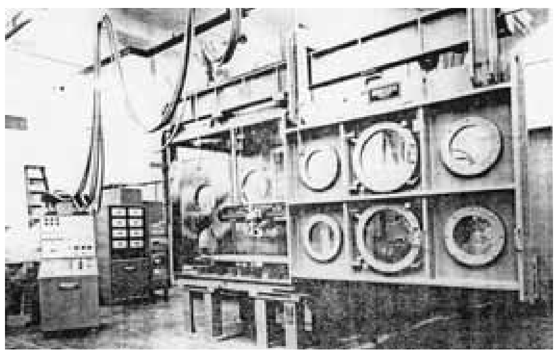


Fig. 56: Above left: Large chamber/high voltage/fixed-gun style (HSD) EBW unit.

Fig. 57: Above right: Large chamber/low voltage/moving-gun style (Sciaky) EBW unit.

Fig. 58: Left: Hand held EBW unit developed for NASA by HSD.

The transition from fairly small-chamber/very low-power/relatively limited work-handling capacity EB systems of yesterday to the moderately large-chamber, highly complex work-handling and beam-generation (both totally computer controlled) EB systems of today has been impressive. Today's EB systems are remarkably versatile and capable of meeting the vast range of welding requirements of virtually all industries using joining technology. The accomplishments of EBW technology and its capabilities as we complete the fifth decade since its introduction, would have been considered a flight of fancy, had they been expressed in the early days of the technology.

Present and Future

Electron beam welding in 2007 continues as a multi-pronged process, HVEBW/PVEBW/NVEBW/A-AEBW, with numerous EB systems operating in these various modes being used on a daily basis by a broad spectrum of companies covering a wide variety of industrial areas and end-uses. EB welding requirements outside this vast customer base are met by the large number of contract welding ("job shop") facilities located in the U.S.A., a network consisting of some 50 such facilities currently in operation, fairly evenly spread out across the country (approx. 20 on the East Coast, 18 on the West Coast and 12 in between) and catering for a wide range of requirements.

The needs for new (and/or refurbished/retrofitted) equipment are still primarily served by Sciaky, a member of the PSI Group, and PTR, a member of the AWT Group – both these manufacturers based in the U.S.A., both able to provide a full range of customer support capabilities (e.g., spare parts and accessories/equipment servicing & trouble shooting/contract welding/etc.), and both having been in this field of endeavour since its original inception. In addition, since the late 80s, several other viable manufacturers have entered the field: CVE/Wentgate (based in the UK, with a sales and service office in the U.S.A., a member of the Aquasium Group), KSET (distributes Russia's Paton EB Technology-style equipment through a sales and service organization it has in the U.S.A.), and AVT (an individual-owned company, based in the U.S.A., offering customers both new and used equipment – and service).

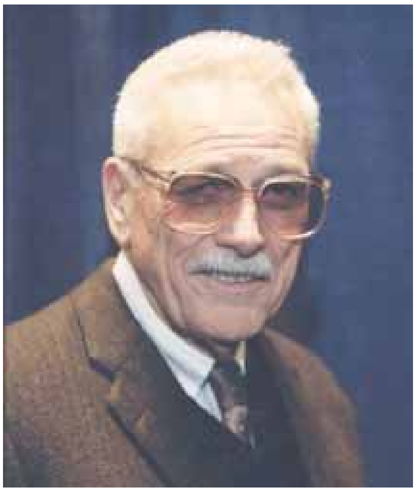
Fig. 59 shows a modern day, large-chamber/fully CNC-controlled – 5 axes of workpiece motion: X/YZ/ROT/TILT and numerous beam parameters: I/V/Focus/Deflection/etc. – all under CNC command, high-voltage (30 to 60 kW) capability system, while fig. 60 depicts a modern-day, small-chamber/PLC-controlled (work-motion and beam parameters), low-voltage (3-6 kW) capability system. As these figures show, today's EBW machines are highly sophisticated units, equipped with a much greater degree of control capability than was ever previously available. Switch-mode high-voltage power supplies, variable frequency/programmable pattern-type deflection generators, on-line beam diagnostic devices and PLC/CNC forms of overall system control are just a few of the many highly advanced process-control techniques readily available on most of the machines currently being supplied to today's users of the EBW technology. As a result of the continuing enhancement of the process' functional capabilities, today's EBW machines utilize a much smaller footprint than previously required (the unit depicted in fig. 60 requires an installed floor space, for welder/vacuum system components/power supply/control cabinet/etc. – the entire functional unit – of less than 70 square feet/a maximum area of 7 foot by 10 foot), and are much more capable of providing users of the process with a complete range of operating modes (manual/semi-automatic/fully-automatic) and have the capacity for achieving conventional part-size production throughputs in the range of 300 to 600 pph when operating under fully-automatic-mode conditions.

Fig. 59: Modern day, large chamber/fully CNC controlled version EBW unit made by PTR.

Fig. 60: Modern day, small chamber/PLC controlled version EBW unit made by PTR.

In short, the authors believe that the prevailing multi-faceted vacuum mode of EBW operation will continue to remain an integral part of the U.S. welding community's future – and that EBW, having achieved a 50-year track record as a proven performer, will continue to grow both in technical capability and process applicability [39, 40] far into the foreseeable future. In addition, since literally hundreds of the many hundreds of EBW units put into service during the 60s and 70s (prior to the existence of today's newer control capability technology) are still in use today – a fact that clearly illustrates the durability of these older units – "upgrading" (i.e. refurbishing/retrofitting and/or modernizing) these older units, has become a growing market in recent years – a trend that should also continue well into the future.

Donald E. Powers



Don Powers received his MS degree in physics from the University of Connecticut in 1959, and joined the Plasma Physics Group at the United Technologies (then called United Aircraft) Corporation's Research Lab as a Research Scientist the same year. Shortly thereafter Mr Powers transferred over to United's Hamilton Sundstrand (then called Hamilton Standard) Division, joining the newly formed Electron Beam Welding Department – the product line of which was eventually acquired by Leybold-Heraeus in 1976, and then by PTR in 1989, thus providing Mr Powers with upwards of 45 years' experience in the field of EB processing.

During his career Mr Powers has participated in presenting and publishing numerous papers on EB welding, particularly the nonvacuum mode of EBW, has twice served (between 1985 and 2000) a four-year term as Chairman of the American Welding Society's C7-High Energy Beam Welding & Cutting Committee – a committee he played a major role in helping to establish, received the American Welding Society's Honorary Member Award in 1988 and was selected as a Counselor of the American Welding Society in 2002.

Recently retired, Mr Powers currently serves as a Technical Consultant to PTR.

Robert Bakish

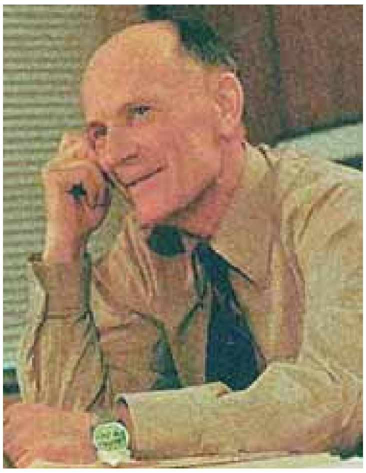
Robert Bakish, B.S. Columbia, D. Eng. Yale, both in Metallurgy. He has numerous publications in Physical Metallurgy, Corrosion, Desalination, Vacuum Processing, including books on EB Technology, EB Welding; he has lectured at UCLA and Fairleigh Dickinson University. In 1983 he started the Electron Beam Melting and Refining Conference, held annually until 2000, editing their proceedings. He is president of Bakish Materials Corp. of Englewood, NJ.

Historical Note on Electron Beam Welding in the Ukraine and Russia

O.K. Nazarenko

Introduction

The study of the potential of EBW and the principles of the construction of equipment for EBW began in the USSR in 1958 – almost simultaneously in the Moscow Energy Institute [41] under the guidance of Professor N.A. Olshanskiy and in the E.O. Paton Electric Welding Institute of the National Academy of Sciences of the Ukraine (PEWI) under the guidance of Academician B.E. Paton [42]. This was when the first laboratory-scale machines were designed and various small workpieces were welded. Within the year, the EBW method was in great demand –



B.E. Paton

- in the nuclear power industry,
- in the production of electronic vacuum devices,
- in the production of liquid-fuel rocket engines.

Thanks to effective co-ordination at governmental level, in 1961-1962 the first commercial EBW machines were put into operation at a number of branch enterprises. Within the next few years, the application of EBW expanded in the above-mentioned fields of industry. But at the same time EBW was adopted by the aircraft industry and the power engineering industry, as well as the transport power engineering industry. Development of vacuum chambers was thus frequently required, but their transport to the operation site was complicated, due to their size. At the same time, buyers had the opportunity to produce a high-quality vacuum chamber themselves – within a short period of time. All that then had to be done was to equip the manufactured chamber with the welding gun, the high-voltage power supply source, and the control system. As a result, in the 1960s, PEWI organized the full-scale production of power supply sets in the Ukraine, developed by PEWI for the EBW of metals predominantly of medium and large thickness on the basis of the specialized enterprise “Sumy Factory of Electron Microscopes and Electric Automation” (SELMI).

Creative teams in the areas of research and technical development were formed in various fields of industry, whose main efforts were the designing and improving of EBW equipment and the development of EBW techniques and procedures.

In particular:

- Since 1959, the Research and Development Institute of Production and Industrial Engineering (NIAT, Moscow), the major technological institute of the aircraft industry, has developed more than 30 kinds of electron beam machines, many of which are still fully operational. V.A. Kostyuk has led this facility for many years [43]. Full-scale and pilot production of the machines was and still is carried out by the "Electromechanics" factory (in Ržev), also largely for the aircraft industry. This factory has produced in total more than 450 multi-purpose EBW machines to date;
- The development and production of equipment, thorough investigations of EBW techniques and procedures for the production of vacuum-electronics devices, including those operating in the range of super-high frequencies, has been performed by the team of employees at the Research and Development Institute "Istok" [44] in the town of Fryazino not far from Moscow. V.V. Gorbanskiy and A.F. Khudishev have been in charge of this team for many years. The institute's operating departments and its factory, located in the town of Kaliningrad, has produced some 200 machines of type A.306.13, 100 machines of type A.306.05 and 120 machines of type LEV.80-1 – in total 420 machines with comparatively small vacuum chambers, power supplies with 5 kW and an accelerating voltage of 25 kV;
- Since the mid-60s, NIKIMT, the parent organization for welding in the nuclear power engineering and nuclear industries, has been engaged in the development, production and industrial use of machines for electron beam hermetic sealing of fuel elements, the welding of process channels and other elements of nuclear reactor cores [45];
- The team of employees under the guidance of I. Yu. Zybko at the Central Research and Development Institute of Heavy Engineering (CNIITMACH, Moscow), has been engaged in the development of EBW techniques and procedures, including its use in the field of heavy power engineering;
- Extensive application of EBW in the production of gas turbine engines for ships, transmission shafts, reduction gears, heat-exchange equipment, etc. was unquestionably a major achievement of the teams of employees at shipbuilding enterprises – first and foremost Mashproject Association Southern Turbine Factory in Nikolayev (the Ukraine) and Kaluga Turbine Factory (Kaluga, Russia);
- Working from the original technical documents of PEWI, the association SELMI, under the guidance of P.P. Barzilovich and M.I. Tregubov developed this production documentation and produced, over a period of time, 72 complete units of the power-supply machines of type SP-30 (25 kV, 500 mA), 330 complete units of type U-250A (30 kV, 450 mA), 320 complete units of type ELA-60 (60 kV, 250, 500 and 1000 mA) and ELA-120 (120 kV, 1000 mA). The same association, under the guidance of Professor A.N. Kabanov, produced 32 complete units of the machines ELURO PT (150 kV, 1.5 kW) for electron beam drilling and machining.

Electron Beam Welding of Workpieces in Nuclear Power Engineering

The peculiarities of the machines for EBW of workpieces in the nuclear industry are as follows [45]:

- The overwhelming majority of the machines are equipped with loaders and unloaders for workpieces for integration into automated lines;
- Oil-free pumping system of the vacuum chamber and of the gun is used;
- In order to increase efficiency, only the welded-joint area is hermetically sealed; the lock is placed inside the welding chamber and the workpiece is subject to rough evacuation;
- Multi-positional boxes are used for the welding of workpieces of small diameter;
- For the welding of thin-wall workpieces, guns with a gas-discharge cathode are frequently used. Ion guns are used for pre-cleaning of the workpieces' surface in the weld zone, as well as for the implantation of inert gases into the coating surface. Both kinds of guns were designed by Tomsk National University of Control Systems and Radio Electronics.

NIKIMT developed and put into operation several types of machines for the production of circumferential welds located at hermetic seals of fuel elements, for the welding of process channels and other elements of reactor cores.

Machines CA330, CA340 and CA413 allow welding of workpieces with a diameter of up to 140 mm and a length of up to 4000 mm with end pieces (stoppers, tails, adapters). Up to 120 workpieces can be welded in machine CA330 within one evacuation cycle, in machines CA340 and CA413 only the weld zone is evacuated.

The multi-functional machines CA424, CA424M, CA445, CA451 are meant for the welding of circumferential, edge and longitudinal welds of work-pieces with a thickness of up to 30 mm, a diameter of up to 500 mm, a length of longitudinal welds of up to 700 mm and a length of circumferential welds of up to 400 mm.

In order to increase efficiency, the specialized machines CA252, CA508, CA558, CA613, CA472 are equipped with locking devices for loading and unloading, positioners, feeders, storage and other devices.

Machine CA252, meant for the hermetic sealing of chemically active materials in aluminium shells, is equipped with an aisle and a glove box.

Machine CA508, meant for welding tubes into tube plates, has a double beam deflection system, thus permitting welding in out-of-the-way places.

The machines are equipped with power-generating sets with accelerating voltages of 30-75 kV and power of up to 12 kW. The guns with gas-discharge cathodes are energized by power-generating sets with accelerating voltage of 3-25 kV and power of up to 2.5 kW.

Electron Beam Welding of Space Facilities

EBW has consolidated its position of strength in the production of space facilities, since it has been responsible for an increase in the functional reliability of workpieces and a reduction in their weight and production time. The fact that more than 116 machines are used at branch enterprises, not to mention the organization of autonomous EBW shops [46], clearly demonstrates the successful application of EBW in the production of space facilities. Specialized use of EBW has taken place in close co-operation between the teams of employees at PEWI, the branch Research and Production Association "Technomash", and the plants themselves. Table 1 represents the data on EBW production methods adopted and extent of their application.

Name of assemblies	**Welded metals**	**Kind of welded joints**	**Number and type of used machines**
Liquid-propellant rocket engines	Copper-based alloys, stainless steels, nickel-based alloys, titanium alloys	Bodies of combustion chambers, valve assemblies, sprayer heads, high pressure gas guides, rotors and bodies of turbo-driven pumping machines	32 chamber machines
Fuel tanks	Aluminum alloys of systems: Al-Cu, Al-Mg-Mn, Al-Mg-Li	Longitudinal welds at shells	Ten chamber machines and two machines with local evacuation of weld zone
		Circumferential welds	23 chamber machines and two machines with local evacuation of weld zone
		Set-in flanges	Three chamber machines and three machines with local evacuation of weld zone
Bodies of different devices	Aluminum alloys, titanium, stainless steels	Welding of flanged edges	51 chamber machines

Table 1: Mastered production methods and extent of their application in space industry.

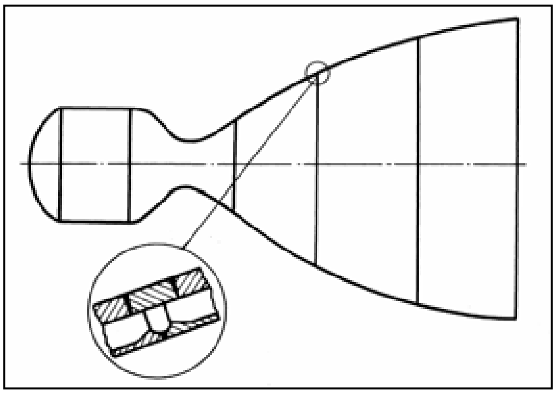


Fig. 61: Location of circumferential electron-beam welds of combustion chamber in liquid-propellant rocket engine. Dissimilar materials like copper-based alloys, steels and nickel alloys are welded. The collector weld is 20 mm deep and 3mm wide compared to 6 mm wide with argon-arc welding, which is weaker.

The decision to use EBW here (see fig. 61) instead of argon-arc welding was first taken in the early 1960s by a team of employees under the guidance of the famous rocket-engine designer V.P. Glushko [47].
Later, all the factories producing liquid-propellant rocket engines were equipped with more than 32 chamber machines for EBW. In most cases, the vacuum chambers were, in fact, produced by the customers' factories. The factories preferred to produce the vacuum chambers with some "allowance" in dimensions, in order to use them for the welding of new workpieces in the future.

During the EBW of fuel tanks (fig. 62, 63 and 64) made of high-strength aluminium alloys of systems Al-Cu, Al-Mg-Mn, Al-Mg-Li, welding of flanges into cylindrical shells, the thickness of welded edges can be up to 42 mm. In this case, EBW provides a welded-joint strength not worse than 0.8 of the base metal strength, minimum welding deformations and high weld impermeability, i.e. lowers the structure's weight and increases its geometrical accuracy. The major characteristic of the machines designed for tank welding is the integration of tools for the machining of the edges subject to welding – directly in the welding position. Only then is it possible to provide the required small gap in the butt joint of welded edges – usually less than 0.1-0.15 mm – in a short time.

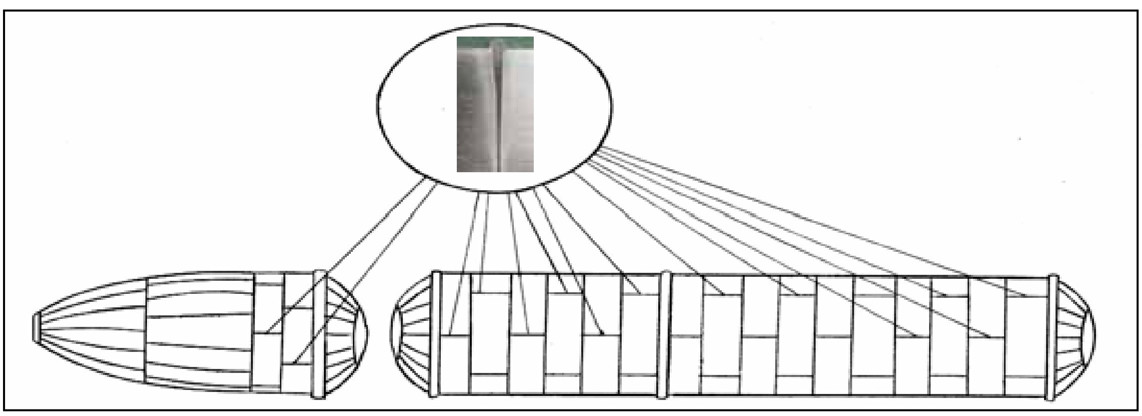


Fig. 62: Location of longitudinal welds on fuel tanks of the carrier "Energy" with an outer diameter of 7.8 m.

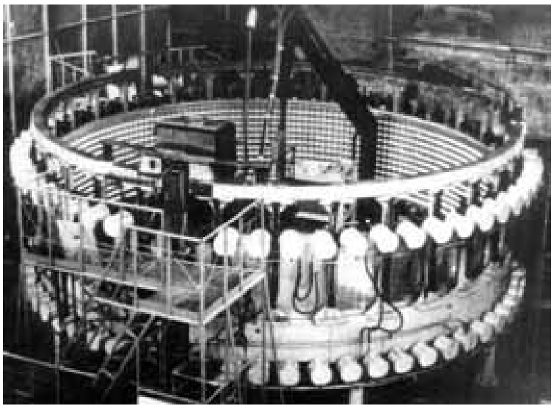


Fig. 63: General view (left) of the machine for EBW in local vacuum and on-site quality control of welded joints.

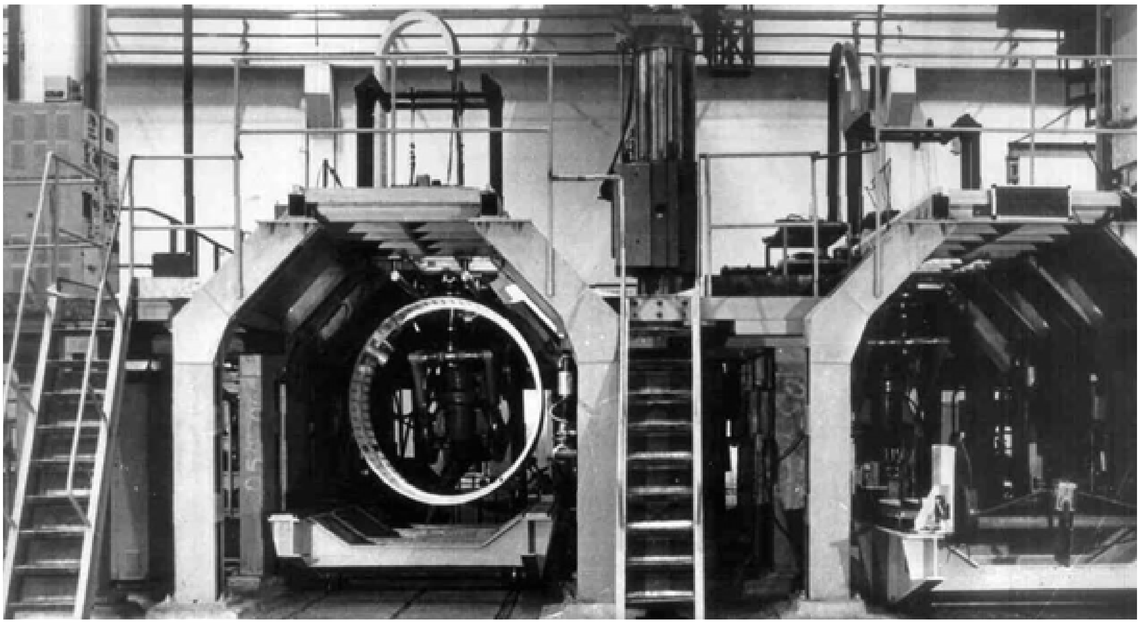


Fig. 64: The machine for EBW of flanges into cylindrical shells with local evacuation of weld zone, containing two workplaces for disposal of shells and with common device for hole machining.

Bulky Industrial Machines for Electron Beam Welding

It was in the USSR that machines with bulky vacuum chambers were specially designed and successfully used. In 1985, the machine type ELU-24 x 16, developed by NIAT jointly with PEWI and produced by several aircraft factories [48], was put into operation at Kazan Aircraft Production Association named after Gorbunov. The vacuum chamber of this machine consists of the main tower (fig. 65) with inside dimensions of 4 m (length) x 10 m (width) x 12 m (height), and the tunnel parts adjacent to it from both opposite ends, each tunnel part being 17 m (length) x 4 m (width) x 4 m (height). Thus, the total length of the chamber is 38 m and the total volume of the vacuum chamber is 1160 m^3. The machine is equipped with the loading table containing the rotator with the disposed vertical axis of rotation. The intra-chamber welding gun is placed on the manipulator in the main tower and moves along its height (travel 3.3 m) and in cross direction (travel 4 m). The power-generating unit was designed by PEWI and contains the automatic seam-tracking system; maximum beam power is 120 kW at an accelerating voltage of 120 kV.

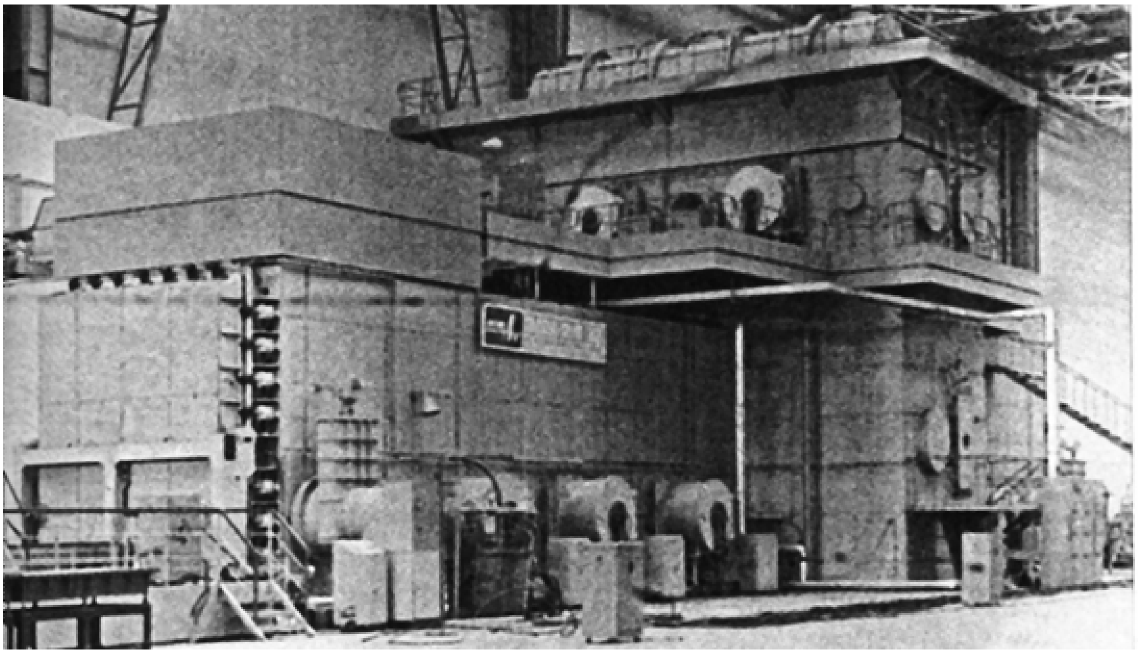


Fig. 65: General view of EBW machine type ELU-24 x 16.

For single-pass welding of longitudinal and circumferential welds for bulky marine structures made of titanium alloys with diameters of up to 8 m and wall thickness of 100 mm and more, the machine UL-214 (Fig. 66) was put into operation at Production Association “Sevmashpredpriyatie” (“North Machine-Building Enterprise”), at the town of Severodvinsk near Arkhangelsk in the 1980s and is still in use there today [49].

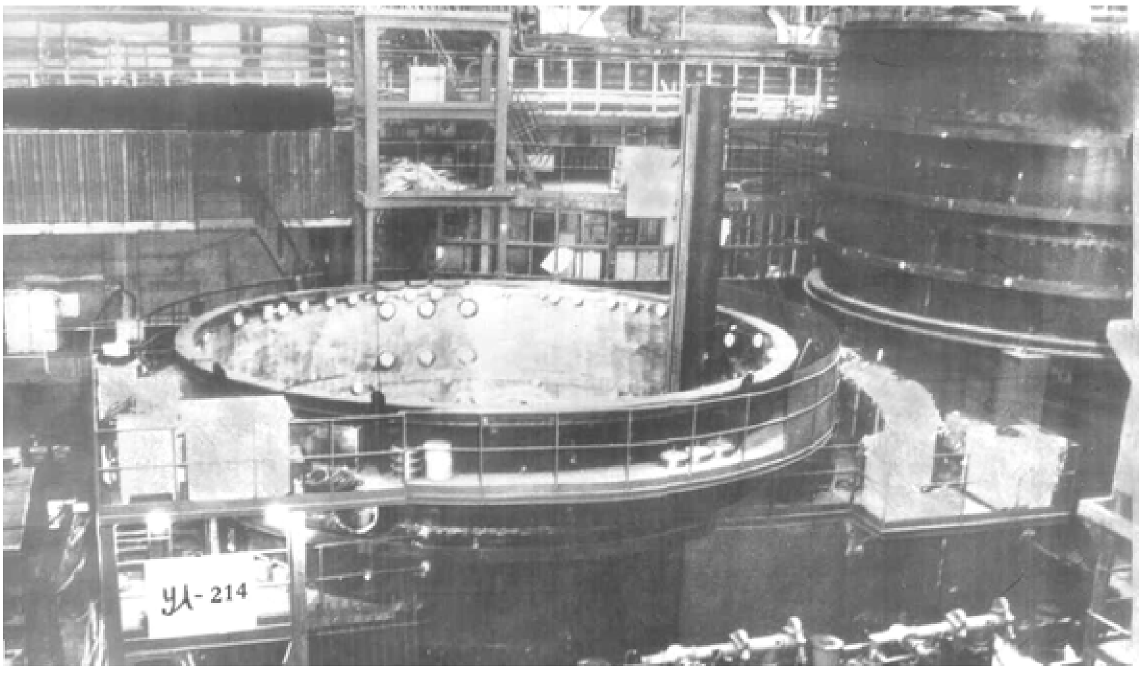


Fig. 66: General view of machine type UL-214 for EBW of bulky marine structures made of titanium alloys.

The project was developed by PEWI, and the Institute's pilot factory produced all the electrical parts and the vacuum system of the machine. The production of the vacuum chamber itself and the mounting of the whole complex were also carried out by Production Association "Sevmashpred-priyatie". The Central Research Institute of Structural Materials "Prometey" actively participated in the development of welding techniques and procedures.

The power of the power-generating unit is 60 kW at an accelerating voltage of 60 kV. Experience of operating the machine type UL-214 has demonstrated the possibility of the successful welding of titanium alloy PT-3B with a thickness of 100-200 mm and gaps in the butt joint of up to 1.0-1.5 mm, edge displacement of up to 15 mm, and edges opening from face and back of the weld up to 1.5-1.7 mm.

Electron Welding Guns and Power Supply Sources

A breakdown in the gun can have dramatic consequences in cases of high cost workpieces, and it is impossible to repair the weld after the breakdown of its formation. Efficient development of the electron-optical system and the electron welding-gun structure has permitted an increase in the dielectric strength of vacuum insulation of the acceleration gap. In the early 1960s, PEWI began intensive development of a new approach to solving the problem of breakdowns – initial breakdown suppression by means of the selection of optimized circuits and parameters of the high-voltage power supply sources [50]. For the first time, the powerful electron tube was used as the linear transit element in electron beam power supply sources, and this decision has been adhered to till now.

Right at the beginning of an arcing, at an increase in specified beam current of 5-10%, the electron tube interrupts the accelerating voltage for the time τ = (0.1-0.15) d_e/V_w, i.e. the time, corresponding to the displacement of the beam axis by 10-15% of its diameter (d_e) at welding speed (V_w). In a few milliseconds, when the dielectric strength of the emissive system has been fully restored, the accelerating voltage in the gun is also restored, and the welding process proceeds without any affect on the quality of the weld formation.

It is impossible to control the discharge of the distributed capacitances of the cable and the high-voltage circuits; this process takes place within sub-microseconds. But discharge of the ripple filter Cf is effectively broken off by the control tube and this is why the energy emitted during the discharge does not exceed the energy emitted during the discharge in cases of the applied high-frequency power supply sources. Besides, high-frequency power supply sources, as demonstrated by experiments [51], have considerably more drooping-load characteristics (fig. 67).

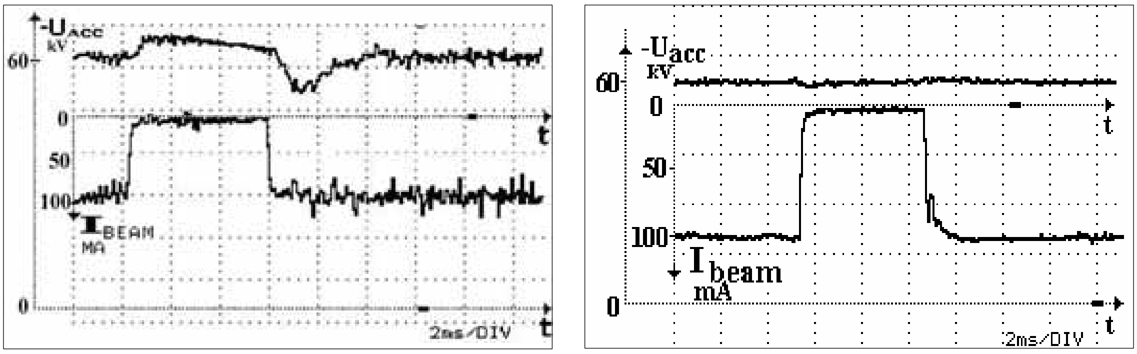


Fig. 67: Change in accelerating voltage rate at pulse change in beam current in high-frequency resonance power supply source (left) and in power supply source with control tube (right).

High stability of accelerating voltage maintenance and the suppression of electric breakdowns allows for defect-free, “spiking”-free weld formation during its fade-out on thick wall constructions of steel (Fig. 68).

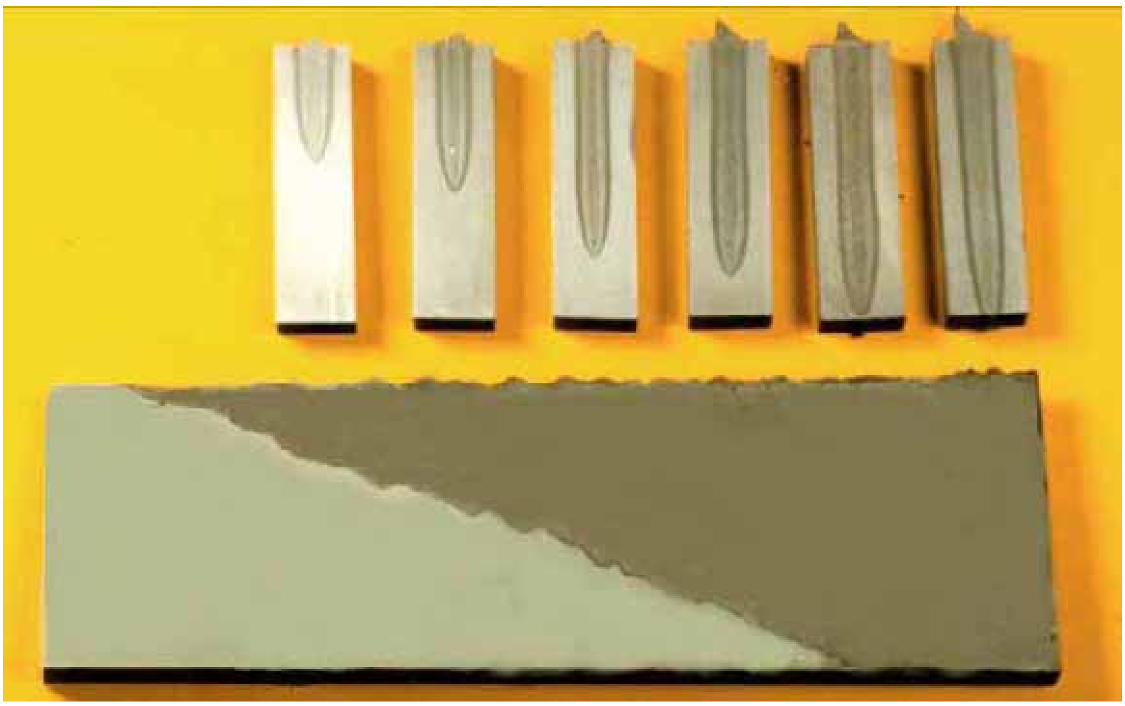


Fig. 68: Macrosections of cross (above) and longitudinal (below) sections of cast area in the time when the weld is faded out on heat-resistant steel 130 mm thick [52].

Peculiarities of Vacuum Chambers Structure

The distinctive feature of the machines designed by PEWI for EBW of bulky workpieces is an application of intra-chamber electron guns, moving within the limits of 12 metres.

This allows the factor of the application of the vacuum chamber content to be increased to the maximum. However, if there is substantial deformation of the vacuum chamber walls during the process of evacuation, it is difficult to avoid deformation of the guides along which the welding gun moves. This is why the chambers are constructed with two vacuum-tight walls (each 8-

12 mm thick) shells, connected to each other by stiffening ribs – the frames [53]. The chamber doors are constructed in a similar way. The use of such box-shaped construction for walls and doors, instead of the conventional T-shaped construction, makes it possible to obtain double the moment of inertia and, as a result, lower wall-deflection during the chamber evacuation.

Fig. 69: General view of the typical vacuum chamber with box-shaped walls.

Computer Control of EBW with Multi-Co-ordinate Movement System, realizing Visual Programming Method

By the end of the 1990s, computer systems, including the devices type CNC and PLC connected to each other by interface buses, but functioning independently, were already in general use to control electron beam machines.

The CNC performs the welding programmes containing the nominal co-ordinates, the method and parameters of interpolation, speed, beam current and focusing, sweep and deflection currents. Additional tasks such as axis synchronization or speed stability maintenance are also given in the CNC program. Where the simultaneous handling of several co-ordinates is required, the resulting trajectory represents a complex space curve.

The traditional procedure envisages the drawing of the workpiece with a CAD (Computer-Aided Design)/CAM (Computer-Aided Manufacturing) system with a special post-processor to convert the trajectory to CNC programme code. This procedure is very time-consuming, depending, as it does, on complexity of the trajectory. Furthermore, it requires the adaptation of the programme computed by the CAD/CAM system to the real workpiece with all its inaccuracies.

In the late 1990s, PEWI, jointly with the “Institute of Problems of Mathematical Machines and Systems” of the National Academy of Sciences of the Ukraine, developed software tools that allow an operator to use the so-called visual method of designing EBW programs for complex constructions [54]. The hardware architecture of the whole computer control system is represented in Fig. 70.

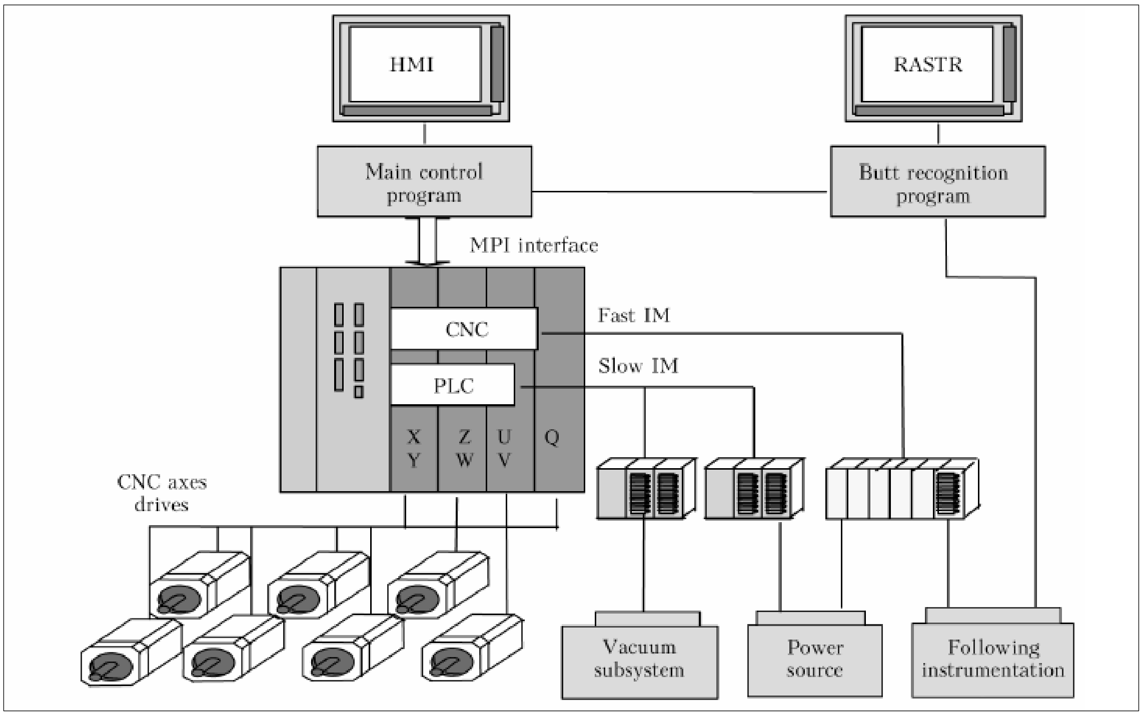


Fig. 70: Hardware architecture of the computer control system.

The traditionally applied computer system containing CNC and PLC is additionally extended with:

- A higher level of HMI (Human machine interface) – an operator’s interface for the visual designing of CNC programs and for controlling the welding process.
- An independent computer provides the butt joint identification by receiving an image of the workpiece surface from the tracking equipment RASTR, as well as automatic “teaching”, correction and tracking the butt joint together with the HMI computer.

RASTR [55] is based on the detection of secondary electrons, performed by scanning the workpiece surface every 300 ms with a sharply focused low-power beam. The interruption of the welding process lasts up to 5 ms.

The image of the workpiece surface received from the secondary electrons is memorized by the computer and reproduced on the monitor RASTR after special software processing. Interface modules (IM) provide exchange between control signals and the machine equipment. In particular, the control of currents and the synchronization of interaction with RASTR are carried out via the fast interface modules.

This does away with the need for traditional CNC programmes and achieves software control of the EBW process by means of consecutive performance of the following stages:

- Development of a three-dimensional, virtual representation of the arrangement inside the vacuum chamber (Fig. 71)
- “Teaching” of the motion system for moving along the butt joint.
- Online tracking of the butt joint during welding in order to compensate for any occurring welding deformations.

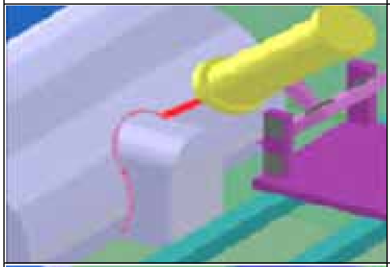
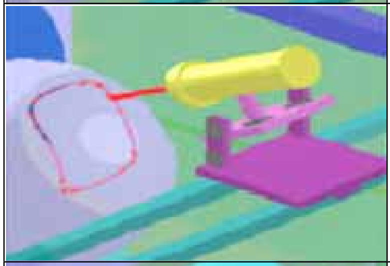
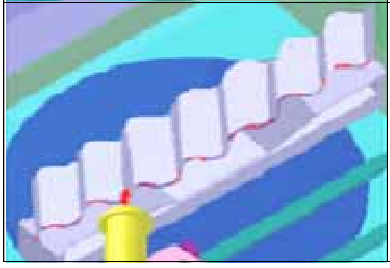
Kinds of products	Description of the Butt	Required Welding Displacements
	Oval shaped branch-pipe is welded into an extended thick-walled cylinder	Rotation of the products, gun displacement along two linear axes and its inclination
	Welding-in of a rectangular segment with rounded-off corners into a spherical surface	Gun tilting or rotation, gun displacement along three linear axes
	Welding a corrugated sheet to a trapezoidal base	Gun rotation and displacement along three linear axes

Fig. 71: Examples of arrangements inside a vacuum chamber together with requirements for welding movements.

To create the welding programme of a spacious complex weld, automatic “teaching” procedures based on images of secondary electrons are used.
A dark line against the background of the lighter workpiece surface represents the butt joint in such an image.
An operator, manually moving the gun or the workpiece, matches the starting position of the weld with the electron beam and starts the automatic “teaching”. While moving in the direction initially specified by the operator, the programme detects the butt joint in each new image and defines the vector of displacement to the new trajectory point. For operation, the visually designed welding programme is automatically converted – without operator participation – to CNC programme code.

To compensate for possible workpiece deformation during welding, the online tracking of the butt joint according to the written programme is used. The image of the workpiece surface shows the butt joint as well as the real and the rated position of the electron beam. The area of butt-joint detection lies before the current welding position. The detected drift of the trajectory from the butt joint is compensated by beam deflection and stored by the programme. It can be reproduced several times, for instance for cosmetic travels along the butt joint.

Biographical Data:

Oleg Kuzmich Nazarenko, born in 1936 in region of Donetsk oblast, in the Ukraine. In 1958 graduated from the radiophysics department of Kyiv National University. A Radiophysicist by training. Candidate of technical sciences (1963), doctor of technical sciences (1976), professor. Diploma of the Presidium of the Ukrainian Supreme Council, 1984. Honoured representative of science and technology of the Ukraine, 2004. State Prize of the Ukraine in the field of science and technology, 2006. Associate member of the Ukrainian National Academy of Sciences, 1992. Head of the department "Investigation of physical processes, technology and equipment for electron-beam and laser welding" (1997). His main areas of scientific research – the phenomena observed at interaction between solid metal and highly concentrated electron beam, the issues of powerful electron beam formation, physical and technical feasibility of possible defect avoidance in welded joints at breakdowns in electron gun by means of short-term de-energization of accelerating voltage. This is what the advanced power sources were based on. The principles of automatic electron beam direction along welded joints and the proper systems that use secondary-electron emission from the welding area as the source of information were developed.

The historical Process of Electron Beam Welding at W.C. Heraeus GmbH and their Follow-up Companies Leybold-Heraeus GmbH and Leybold AG at Hanau

Walter A. Dietrich

Preface

In this contribution I will only discuss electron beam welding out of the wide range of EB activities at W.C. Heraeus.

When I joined the high-vacuum department of Heraeus in 1961, with responsibility for e-beam technologies, this field was in its infancy. However, it developed rapidly into a business area where large-scale metallurgical vacuum process equipment for melting and casting – soon with beam power in the megawatt range – played a dominant role. Thanks to my early activities with electron microscopy at the Süddeutsche Laboratorien at Mosbach/Baden, with Carl Zeiss at Oberkochen and at the Institute for Applied Physics at the University of Tübingen, I had the requirements for this position. My close personal contact to Karl Heinz Steigerwald, which survived times of intense competition, dates from these early years together.

Fig. 72: K.-H. Steigerwald with Dr W. Dietrich and Prof. Dr G. Möllenstedt, University of Tübingen, on an internal EB conference in Mosbach/Baden in 1965.

My report is, of course, written from my point of view and reflects my recollections, but I shall strive to be objective, beginning with my almost 30 years at Heraeus, when I was responsible for EB technology there. Thanks to a supportive management and passionate colleagues, I was able to devote much effort to this central aspect of my larger business unit. Development results could often be directly transferred to other EB equipment. Until my retirement in 1990 we supplied 140 EB machines from Hanau. After that, a new period began for the EB welding group, now operating from Germany and the U.S.A. It was sold to PTR and my team continued to work successfully under the new flag.

The Electron Beam as an Energy Source for Applications

In the 1950s an EB was used as an energy source both in West Germany and in the U.S.A. Steigerwald demonstrated at the Electron Microscope Conference at Innsbruck in the spring of 1954 that small holes could be drilled with this technology. In France J. A. Stohr, working at the *Commis-*

sariat à l'Energie Atomique (CEA), together with P. Thomé, and R. G. Routier used an electron beam for welding reactive materials for nuclear applications for the first time in 1955 [14].
As early as 1954, high-temperature and reactive metals were melted in electron beam furnaces in the U.S.A. And let us not overlook a piece of equipment at Robert Bosch GmbH Stuttgart, which, in the early 1940s, during the Second World War, was vaporizing searchlight reflectors. The later chief physicist there, Dr Rühle, equipped the plant with EB guns for vaporizing materials.
The early activities of the countries in the East did not come to my attention.

First developments at W.C. Heraeus

Two separate lines of thought made using electron beams as an energy source at Heraeus worthwhile. One was the drilling of small holes in thin sheet metal. When this potential was recognized, EB became an alternative to the very time-consuming method of producing spinnerets from tantalum. In 1952 the physicist Dr A. Lorenz was assigned to build a suitable EB generator [56, 57]. The second came from the thesis of B.W. Schumacher, who built an EB generator at the Technical University in Stuttgart, which allowed the electron beam, produced in hard vacuum, to pass via pressure stages into atmosphere [13]. Heraeus acquired his patent rights.
A. Lorenz soon realized that the power density of a beam, transferred through such pressure stages, is not suitable for material treatment. Therefore, he developed a system with much-reduced length. In addition, he added a stage for use with inert gas to protect the nozzles. Meanwhile the power was increased to 3 kW, which resulted in the first promising welding tests. A machine sold in 1961 to General Electric Company, Evendale, Ohio, was presented at the vacuum metallurgic conference 1962 with first results in non-vacuum electron beam welding. In the following years, the further development of the EB generator for atmosphere welding was pushed through numerous application trials, but with no corresponding breakthrough in sales [58].

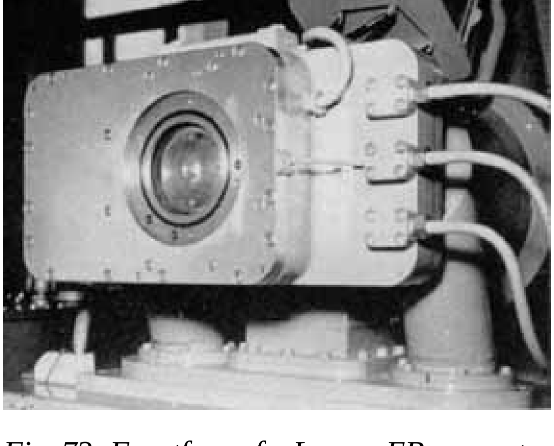


Fig. 73: Frontface of a Lorenz EB generator with horizontal beam exit at W.C. Heraeus.

Fig. 74: EB equipment at W.C. Heraeus to weld on atmosphere, 3 kW, 160 kV.

The Lorenz EB generator with 3 kW and 200 kV was a completely independent development of the beam source and beam guiding system with two lenses, even though there were contacts to Steigerwald at Süddeutsche Laboratorien, to Carl Zeiss and the Quartz-Lampen-Gesellschaft, where Steigerwald worked for a year near Heraeus at Hanau.
At that time, Heraeus was successfully promoting high-power EB technology for melting, with EB welding very much in its shadow [59]. The Steigerwald group with Carl Zeiss, Oberkochen, dominated the German market at least with fully developed machines for welding and drilling.
The friendly links between Heraeus and Zeiss made co-operation logical. I well remember a meeting at Oberkochen in 1962 with general managers from both sides, which resulted in a meagre outcome:

- Heraeus will completely stop activities for machining with electron beams.
- Heraeus will continue EB welding on a limited basis, only bringing existing contracts and existing inquiries to an end.
- A complete stop of EB welding will be under the condition that Zeiss uses Heraeus vacuum components in their equipment.

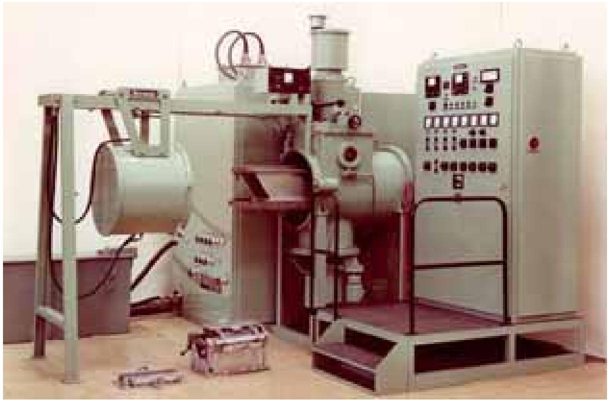


Fig. 75: Standard vacuum EB welder BW 700; 3 kW, 150 kV.

Inquiries for vacuum EB welding machines, mostly from the nuclear industry, were dealt with and a few machines were supplied (fig. 75). These machines were based on the Lorenz generator modified for vacuum operation and on in-house vacuum know-how. Even though they did not have the high standard of Zeiss machines, they did their job over the decades.

The EB Welding Machine for the automatic Series Production of Computer Parts for IBM – a successful Innovation

When Carl Zeiss abandoned electron beam activities except electron microscopes in 1963 and sold them to Hamilton Standard, a division of United Aircraft Corp., the situation changed completely. Heraeus received an inquiry from IBM for an automated production machine. IBM had developed a process on a Zeiss machine to weld springs with small heat-affected zones into the hammer of the printer for a new computer (fig. 76). The High-Vacuum Department of Heraeus saw this as a challenge. Dr Alfred Hauff, chief designer and later CEO of Leybold-Heraeus was closely involved with this project. 40 hammers were mounted on an x-y-table and had to be welded with 4 spots each within an accuracy of 0.01 mm; the process had to be fast and automated. The beam part was redesigned with

automated controls for current, weld time and beam oscillation. The machine was built in 7 months and worked at the first trial with the required stability. However, after a two-week test run, the spot size could not be reproduced. After a month of trouble-shooting the simple reason was found: a pole piece had been assembled the wrong way round.
This delayed IBM with their shipments and they decided to start production at Hanau. Within the next two months, 22,000 hammers with checked quality were produced. Then the machine was transferred to IBM and welded another 2 million parts until the product was discontinued. Due to the following cooperation with Hamilton Standard this machine remained unique.

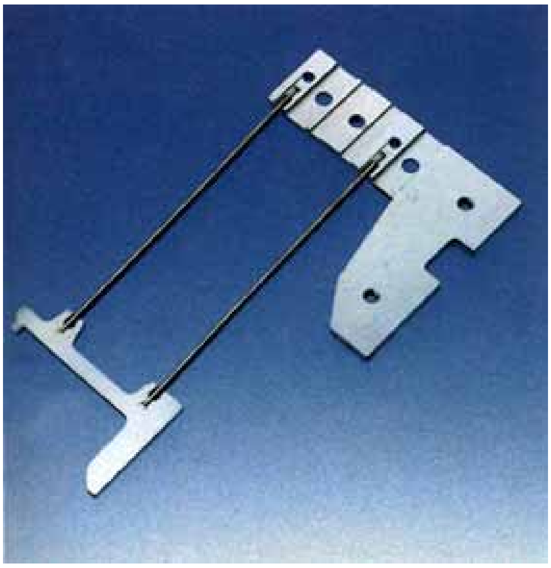


Fig. 76: Oscillating hammer for IBM fast printer.

Fig. 77: Hard vacuum EB welder ESW 1000/3 for automatic production of print-hammers.

License and Co-operation Agreement with Hamilton Standard, Windsor Locks, CT, U.S.A.

After a period of co-operation, in 1963 Hamilton Standard purchased the electron beam activities of Carl Zeiss with all the technical know-how and existing world patents. Then the technology was further developed with considerable effort and investment – a number of new patents date from this time – and Hamilton gained lots of experience in machine building and process engineering, selling more than 400 machines and developing new applications. It was obvious that this innovative technology should be marketed worldwide, limited as it was thus far to the U.S.A. and well protected by patents. Contracts had already been signed for England and Sweden with the British Aircraft Manufacturer Hawker Siddley Dynamics and for Japan with the renowned Nippon Electric Company (NEC).
As of January 1st 1966 the contract between Hamilton Standard and Heraeus Hochvacuum GmbH was finalized, a big step forward for the electron beam

welding group, despite its limitation to central Europe. We had access to rich experience in equipment and processes, could take over key components we approved of directly and could use patents from Zeiss and Hamilton, including the important deep welding patent.
The contract included the obligation to service the Zeiss machines still in operation, which gave us access to former Zeiss customers. Mr Fritz, the Zeiss service engineer, moved to Heraeus. Immediately after the takeover of Zeiss, Hamilton Standard had started an intensive evaluation of the entire technology, especially of the beam generator. Therefore, mature EB guns were available, tried and tested by many users, not only in the nuclear and aircraft industry, but also in the automotive industry and their suppliers. The EB gun, operated in the beginnings with 6 and 7.5 kW, later with much higher power, guaranteed a stable operation with acceleration voltages of 150 kV and above. Using Zeiss technology, we stuck with high voltage. As a beam source we preferred the system of Bricka and Bruck, known from EB microscopy, erroneously called “Rogowski” system.
High beam voltage assures a slender beam, even at high power, and good focus spot projections with variable and long focal distances. The guns were adapted to operate in hard or partial vacuum and a pressure stage had already been developed to work at atmospheric pressure; this, too, had been tried and tested in production in the U.S.A.
The co-operation with Hamilton Standard proved to be a step in the right direction in order to get a foothold in the European market against our often highly subsidized European competitors. The annual licensee meetings at Hamilton Standard helped to improve the contacts between licensor and licensee.

Leybold-Heraeus EB Welders with EB Guns supplied by Hamilton Standard

Once we had agreed on contracts, we supplied standard equipment for R&D to some notable companies, such as Bosch, Porsche and Siemens, but also EB guns to existing vacuum chambers, for instance a generator supplied to CEA, Paris, who was licensor to our French competitor Sciaky. All these guns were of the type 6 kW, 150 kV.
Meanwhile, in 1967, Heraeus Hochvakuum GmbH fused with Leybold at Cologne, becoming Leybold-Heraeus. For EB welding within the new company this meant that the acquisition contract of Leybold with Steigerwald had to be cancelled.

First Series Production Machine for Gear Welding

For series production of gears, partial-vacuum welding had been introduced to the U.S. automotive industry, as well as a few non-vacuum applications. The usually small weld chambers had been adapted to the gear size, and strong rotary pumps reduced the total cycle time.

In order to open a similar EB market for large series in Western Germany, we built an automated cycle machine for Volkswagen in Kassel (fig. 79) in 1961 to weld synchronizing rings to gears of several speeds with low distortion (fig. 78).
After successful testing, the machine was installed at the customer's plant. The workpiece is centred at the drop-bottom of the open chamber, is then rotated and lifted to seal the chamber and, within seconds, pumped to partial vacuum. Pre-programmed weld parameters are applied to the work piece, the chamber vented and the bottom dropped, rotated and unloaded. The cycle time for gears was in the range of 11-13 sec. A programmed column valve kept the gun at hard vacuum. This automated production machine was the prototype for equipment supplied later, also for other applications such as the sealing of pressure tanks. They were usually fully integrated in production lines.

Fig. 78: Above: EB welding of synchronizing ring to gear.

Fig. 79: Right: Partial vacuum EB welder for gear production.

Further examples of the numerous EB welding machines in production to demonstrate their presence on the market [60]:

<u>Machines for the Welding of Aluminium Pistons for Car Engines (1969)</u>
Electron beam welding proved to be especially suitable for the production of water-cooled pistons after extensive weld tests. Ring pieces to close the cooling channel were welded with narrow, deep-penetrating welds with an aspect ratio of 40 to 1. The chamber size was adapted to the piston size and a sliding system allowed the gun to be positioned at various weld diameters, thus avoiding a translatory x-y-motion of the pistons with correspondingly larger chamber volume (fig. 81).

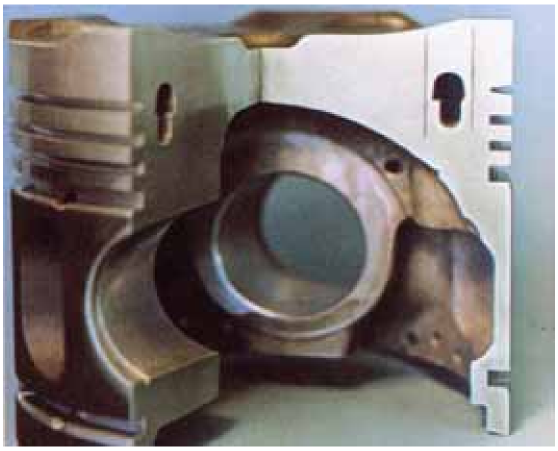


Fig. 80: EB welded piston for Diesel engines. The cooling channel is closed by two axial welds.

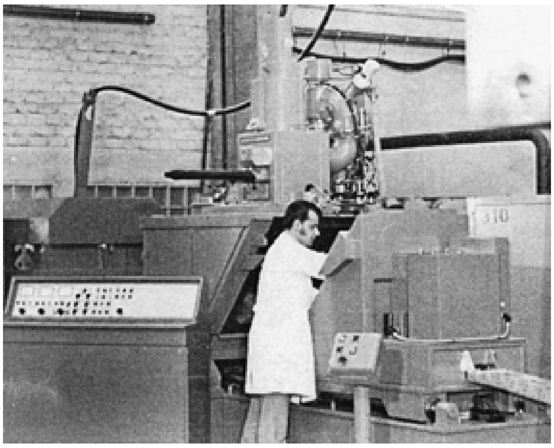


Fig. 81: Partial vacuum welder ESW 12-D with 12 kW power at 150 kV with an inclined opening plane.

The First CNC-Controlled Chamber Welding Machine in Western Germany

Fig. 82: Numerically controlled EB welder for hard and soft vacuum use.

CNC-control of the workpiece motion was introduced to larger machines for the automatic production of various workpieces. It also controlled beam parameters. Such a machine was presented at the Hanover fair in 1970. Samples demonstrated the high positioning precision and showed a variety of pre-programmed patterns for beam deflection. The machine with 12 kW, 150 kV (fig. 82) was intended for a customer to weld high pressure armatures. In the 1980s the majority of machines were equipped with CNC-control.

Two EB Welders, Integrated in the Production Line for Truck Axles (1972 and 1975) [61]

The manufacturer of commercial vehicles, MAN, decided to produce the rear axles from two forged half shells and to join them by EB welding. Thus, the axles could be load-optimized and filler material for welding could be saved (fig. 84). Two horizontal EB guns were mounted in opposite positions and could be adjusted to the joint (fig. 83). The half shells were fixed and clamped in a jig and then brought into the 5 m³ chamber. After 80 sec. pumping time, the necessary vacuum of 10^{-2} mbar was achieved and the weld carried out. The entire process was automated. The net welding time was 3.5 min. The total cycle time was slightly above the calculated value for the production line of 7 min. After 1 year of two-shift production of more than 10.000 axles, the installation of a 2nd machine with power increased to 25 kW reduced the cycle time by nearly half.

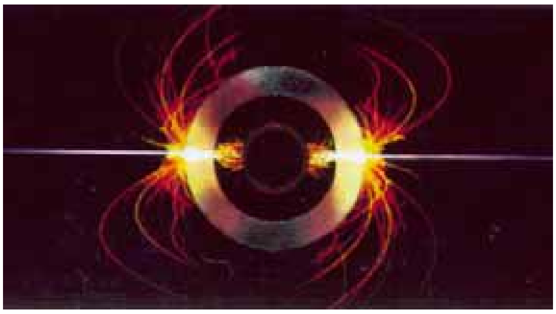


Fig. 83: Welding in partial vacuum with opposing horizontal guns.

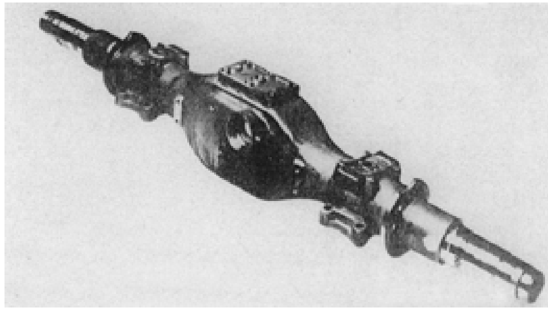


Fig. 84: Welded axle ready for installation.

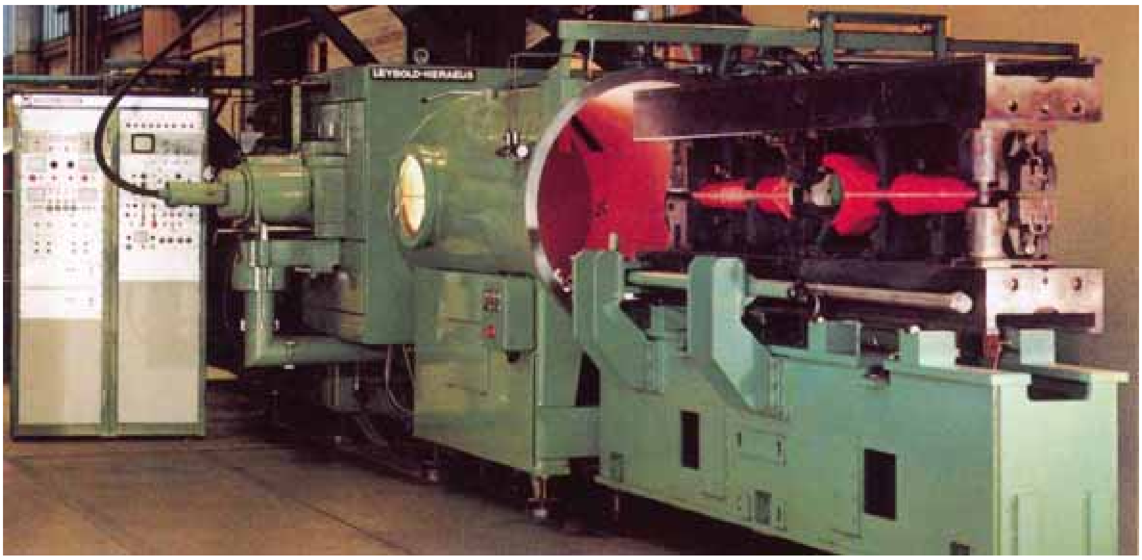


Fig. 85: Clamping tool with axle in the open vacuum chamber.

High and Low Voltage, a Complementary Development at Leybold-Heraeus

For historical reasons, EB technology was split for decades into two blocks of equipment manufacturers, each one praising the advantages of his own version. High-voltage machines (130-200 kV) need less beam current to achieve the necessary beam power. Consequently, smaller cathodes can be used. The more slender beam can be focused at a greater distance and thus bridge larger working distances. Moreover, the beam is less sensitive to scattering at partial vacuum. Low-voltage machines need less technical resources to produce the beam, and their more compact gun size allows them to be more easily manipulated inside larger chambers; this, and the abandoning of lead cladding due to the softer x-radiation are all cost-effective.

For many applications (the sealing of pacemaker covers, the welding of small electro-motors, of pressure cells or gauges etc.) low-voltage machines are just as suitable, especially when low power or short working distance is a given. Therefore, a development started at Hanau in the early 1970s, using a 60 kV gun but with the experience and know-how of 150 kV technology. Soon the first production machines were equipped, first with 3 kW power, later with guns up to 15 kW. These machines were soon in great demand on the market.

Co-operation with Research Institutes

EB welding was warmly welcomed at a number of research institutes in Germany and elsewhere. Its scientific basis had been continuously extended by diplomas and doctoral theses. In this connection, institutes of higher education developed auxiliary instruments, which brought improvements to equipment and the actual processes. Leybold-Heraeus signed a contract with the University of Stuttgart for the University to supply rapid deflection amplifiers and rapid beam current controllers [62]. The Technical University of Aachen received an order for real-time seam trackers [63].

Inventors and Patents

Research in the field of patents has shown that none of the esteemed pioneers, not even Stohr or Steigerwald, can, in the narrowest sense of the term, call himself the inventor of EB welding. A French patent, dated 1925 [64] was filed and published – without naming the inventor – describing in detail welding with cathode rays - which are electron beams. This seems to have been known to CEA, as they made no effort to claim any rights from the Stohr patent [16], which was granted later on. At least Leybold-Heraeus had no trouble holding French customers harmless against all claims related to the CEA patent. Amongst the patents filed by K. H. Steigerwald and his co-operators at Carl Zeiss, the "deep penetration welding" patent, filed in 1959 [20] played an important role. All advantageous properties of electron beam welding depend indispensably on the phenomenon that the EB penetrates deep into the material via a vapour capillary, starting from a defined power density of the beam. Moving the beam relative to the work piece, material melts in front and resolidifies at the rear of the beam. The result is low heat input, fast welding and welding of thick sections.

When Hamilton Standard bought all activities from Zeiss, this included all the related patents, which later became part of the license agreements with their partners. Due to the significance of this, Hamilton Standard took great pains to have this confirmed nationally and internationally – initially with success. Among others, the German patent office confirmed it against all challenges.

The competitor Sciaky, after failed license negotiations, made actions for cancellation at the federal law court of Karlsruhe. Although the assigned expert, Prof. Eichhorn, pleaded in favour of the patent rights, Sciaky's clever lawyer was able to convince the judges, who were not familiar with the subject, to agree on a decision of annulment (1969). This judgement is still discussed controversially among experts. It is based on the assumption that deep welding is a non-patentable discovery of a natural phenomenon and not an invention. From that time on, every user of sufficiently high-density energy beams could produce deep welds without infringing a patent.

Leybold-Heraeus' Takeover of Hamilton Standards EB Department in January 1976 and the Establishment of Leybold-Heraeus Vacuum systems

Surprisingly, in the autumn of 1975, Hamilton Standard made an offer to Leybold-Heraeus for takeover of their EB department. This, and the existing good co-operation between the two firms enabled us to purchase Hamilton at reasonable conditions. Politically, it was in the interest of my company to get a stronger foothold in the U.S. market by increasing producing subsidiaries. Being the negotiator concerned, it was my intention to get hold of as many experienced colleagues as possible. The official inauguration of the new facility at Enfield, CT, with about 70 colleagues was celebrated by the state governor, Mrs. Ella Grasso (fig. 87). By virtue of this takeover, Leybold-Heraeus became licensor to Hawker Siddley Dynamics, Great Britain and Nippon Electric, Japan.

Fig. 86: Computerized EB welder with 15 kW, 60 kV (1984).

Fig. 87: Inauguration of Leybold-Heraeus Vacuum Systems in 1976 at Enfield/CT by the Governor Mrs Ella Grasso.

Fully Automated Large Chamber Electron Beam Welding Machine for Heavy Workpieces [65]

This machine went into production in 1983 with General Electric Large Steam Turbine Division, Schenectady, NY as a co-production between Leybold-Heraeus Hanau and Enfield. It had a chamber size of 36 m^3 for workpieces up to 3 m diameter and up to 13 t weight and it was an important machine, one of the most modern in the U.S.A. Its job was to weld vanes including chromium steel cladding into half-rings of turbo stators, with a continuous weld, up to 140 mm deep. After extensive tests, the EB generator with 60 kW power and all control functions including seam tracking was supplied by Leybold-Heraeus, Hanau; the chamber, pump station and software by Leybold-Heraeus Vacuum Systems. The stators were assembled in a jig on a run-out platform and, with a total weight of 35 t, were moved on an air glide into the chamber. The necessary vacuum of 10^{-4} mbar was achieved in 15 min. The weld position was "taught" by a seam locator and during welding any distortion was compensated for by the online seam tracker. This most powerful machine in the USA was transferred to General Electric Power Systems in Bangor, Maine, and is still in operation.

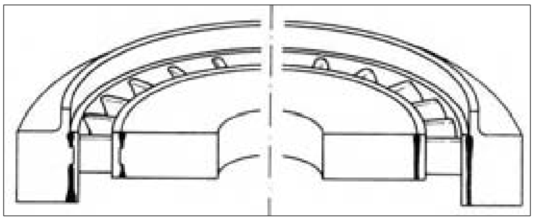


Fig. 88: EB welding of stator vanes for steam turbines. Left: 4 conventional welds. Right: 2 full penetrating deep welds.

Fig. 89: EB welding machine EBW 3600/ 60-150 CNC for automated welding of steam turbines.

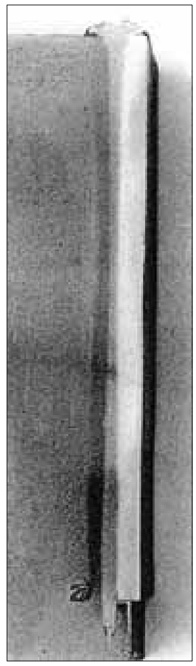


Fig. 90: Extreme deep welding (140 mm), 8 mm from the edge of the cladding.

My almost 30 years in management at the electron beam welding group at Hanau still fills me with gratitude today. I always had the full support of my superiors and a high standard of commitment from my colleagues. Some of my former customers I am now pleased to count among my friends.
Heraeus sold their Leybold EB welding activities, both in Germany and the U.S.A., in 1989 to PTR-Präzisionstechnologie GmbH, which now belongs to the AWT group

Walter Dietrich

Born in 1926. Dipl. Phys. Dr rer. nat. Dr h.c., Walter Dietrich studied physics at the Technical University of Stuttgart. After his diploma on metallurgy he worked for nearly one year as physicist with Carl Zeiss on the development of electron microscopes. He finished his doctoral thesis on high resolution electron spectrometry under Prof. Möllenstädt at the University of Tübingen.
He joined Heraeus in 1961 to takeover the responsibility in the field of vacuum processing plants with EB as a high power heat source. Besides melting, casting and evaporating this included especially EB welding. After having retired he held this responsibility for nearly 30 years.

The Development of Electron Beam Welding Technology in Japan

Hirosada Irie

The Beginnings of R&D on EBW

Although the fact that electrons with high energy can heat metal has been well known since the 19th century, and this knowledge was actually used to achieve welds in space in a science fiction novel before the second world war, it was not until 1960 that, stimulated by J. A. Stohr's presentation on the results of practical electron beam welding of zirconium at the Paris international "Fuel Elements Conference" in 1957 [14], the National Research Institute for Metals (NRIM), Dr T. Hashimoto et al, whose group had been promoting R&D work on welding technologies for nuclear power plant materials, finally tried to construct a low-power (60 kV, 3 kW) electron beam welding machine. This machine was designed and made by the Japan Electro-Optic Laboratory (JEOL) using their knowledge of electron microscopes. Its maximum power was 60 kV and 6 kW, but almost all the experiments were carried out at 3 kW, due to the heating problems of the electrodes. This machine was soon adapted from a hard-vacuum to a soft-vacuum welding environment as shown in fig. 93.

Soon afterwards, Ishikawajima-Harima Industries (IHI) (Tanashi Works) imported a full-vacuum electron beam welding machine from Sciaky, Chicago. The work it was involved in was not published, but it probably produced engine parts according to Air Force specifications. NRIM also introduced a machine of the same type – 30 kV (originally 15 kV) and 15 kW – from Sciaky, technically supported by Dengen-sha Co., Ltd. (whose main products were resistance welding machines).

Fig. 91: The world's first EB welder 1972 with 100 kV, 100 kW continuous power output at Osaka University [66].

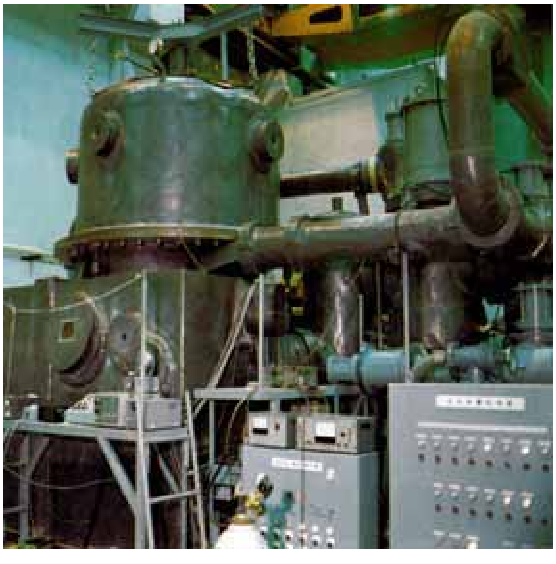


Fig. 92: In 1975 the voltage was increased to 300 kV, 100 kW [67].

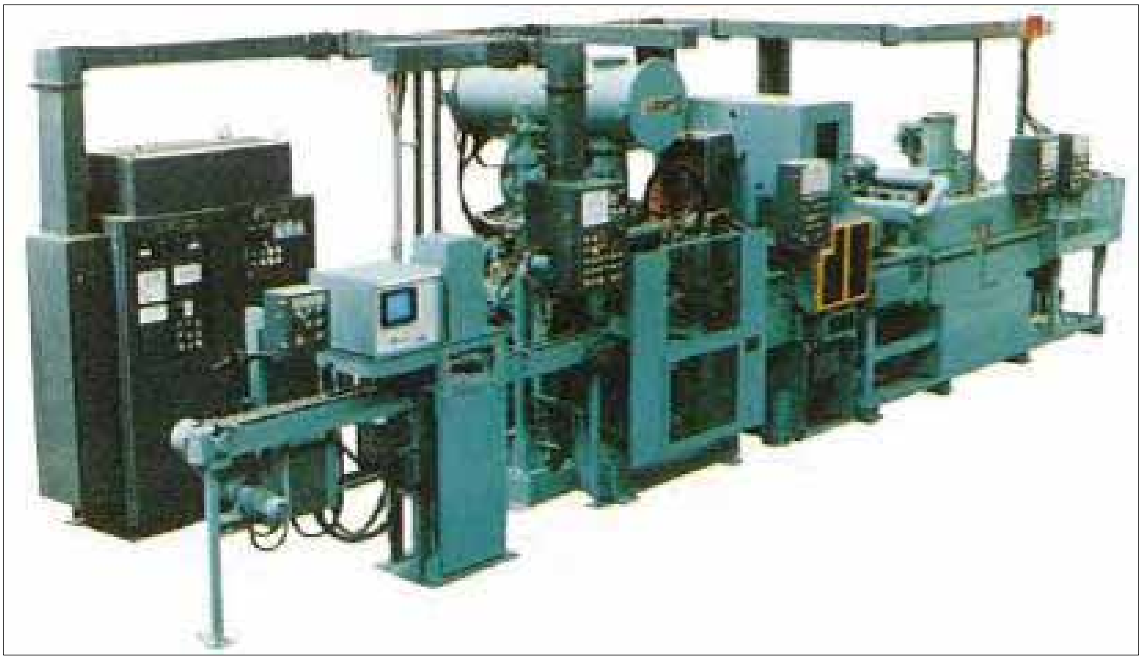


Fig. 93: The 1st EBW machine designed and produced by JEOL, which was adapted to soft vacuum (1959).

On the other hand, Osaka University (Prof. Dr Yoshiaki Arata), where research had been done on plasma and accelerators for fusion reactors, started research on electron beam welding, using its own 100 kW machine. [68]
As a result of the many successful domestic and foreign experiments and production processes using electron beam welding, the specific characteristics of electron beam welding compared to traditional arc welding processes was initially greeted by surprise in Japan, but soon widely recognized, and many companies actively carried out and developed the electron beam welding processes.
Against the background of these R&D results, the "Research Committee of Electron Beam Welding" was established in 1970 in the Japan Welding Society (JWS). Its first chairman was Prof. Arata. Since its establishment, a great number of R&D results – not only of machines and processes, but also concerning fundamental phenomena and the properties of welded joints – have been presented. [69, 70]
In general, firms using EBW machines, especially producers of small parts, for instance in the automotive industry, never publish their work in the EBW field. So our knowledge is necessarily very incomplete.
Here, typical R&D results will be briefly and roughly summarized, according to presentations in the EBW committee and other publications.

Development of Electron Beam Machines [71]

In Japan, both high-voltage type and low-voltage type electron beam welders have been developed and used. The high-voltage type has an accelerating voltage of more than 100 kV and the low-voltage type less than 80 kV. JEOL, Dengen-sha Corp., and MELCO (Mitsubishi Electric

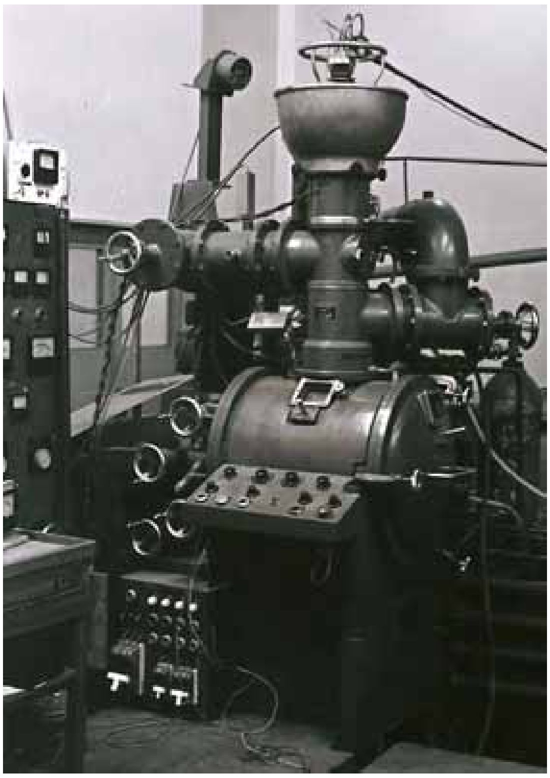


Fig. 94: An early mass-production machine (MELCO).

Corp.) have produced the latter type and NEC Corp. the former. Fig. 94 shows the early MELCO mass-production machine. Dengen-sha Co. Ltd produced these under license from Sciaky U.S.A. and has now ceased production, and NEC (Nippon Electric Corp) produced under license from Hamilton Standard U.S.A. However, after the expiry of their contract, NEC produced (and produces) its own high-voltage machines. Now only MELCO and NEC supply the market with EBW welding machines. Although each high-voltage and low-voltage type has its own characteristics of beam property, all the companies have used high voltage in high-power machines, such as those of more than 100 kW, because of the limitations of higher beam current.

Overcoming the Disadvantages of Electron Beam Welding

Electron beam welders have been mainly supplied by machine makers. However, many companies, especially in heavy industries, have produced their own machines using an electron gun supplied by machine makers.

According to many publications, R&D work [72, 73, 74] has been done in order to overcome the disadvantages of EBW and fully use the advantages such as deep penetration, a narrow fusion zone and HAZ, low distortion and high welding speed.

Time and Cost Saving for the Mass Production of small workpieces

Low-power electron beam welders such as 6 or 3 kW have been widely used in the automotive industry, the machine industry and so on. The development of these machines has focused on the shortening of tact time. A large proportion of the cycle time is taken up with evacuating and venting the welding chamber gas, so considerable energy has been invested in the adaptation of the “smallest chambers” possible, “soft vacuum” by mechanical booster pump, and “multi stage” of two or four stages to save preparation time. In such a system, a shutter separates the welding chamber from the electron-gun room, and, as soon as the welding chamber is evacuated to welding soft vacuum (c.1 to 10 Pa), the shutter opens and the electron beam is released. In this system, the tact time for each workpiece is designed to be 15 to 30 seconds. A typical machine is shown in fig. 95.

During the course of this development, many different types of production machines have been tried and tested. For instance, a rotary table with multiple chambers and a differential pumping system (NEC, Dengen-sha), and linear multiple chambers with a differential pumping system (MELCO) were envisaged and developed. With differential pumping systems, the evacuating and venting time of air is negligible.

Fig. 95: A recent multi-stage EBW machine (MELCO).

Fig. 96: The giant vacuum chamber EBW machine of c.280m^3 in volume and a workpiece for a nuclear power plant of 60-90 mm in thickness (MHI).

Limitation of Dimensions of large Constructions

The other disadvantage of EBW is the size of the welding chamber. Although EB can weld heavy section material with low distortion, for instance steel 150mm thick, the size of construction is limited by the size of the welding chamber. To overcome this disadvantage, three major systems have been proposed: a giant vacuum chamber, a local vacuum system and a non-vacuum system.
Mitsubishi Heavy Industry Co. Ltd (MHI) and Hitachi Co. Ltd each developed and constructed a giant vacuum chamber machine. The former developed the famous c.280 m^3 chamber (fig. 96) and produced a number of units for nuclear power plants, e.g., pressure vessels. The latter produced many precision machines for fusion and fission reactors of less than 3 m in diameter and for pressure vessels. In these machines, movable electron gun systems are used for three-dimensional welding.
Many heavy industry companies researched and developed local vacuum systems. Kawasaki Heavy Industry Co. Ltd (KHI) (fig. 97) and MELCO produced local vacuum-chamber systems for longitudinal seam welding for pipes of large diameter. MHI also constructed ring-type vacuum chambers for fission reactors with pre-TIG welding on the weld root side. Nippon Kokan KK (NKK) and Tsukishima Machinery Co. Ltd, co-operated with Steigerwald Messer Grießheim in Germany, and developed a local vacuum system for long linear welds. Recently KHI has successfully developed a new system for

circumferential butt welding of large pipelines for high-pressure fuel gas in the field, in which the electron gun is located inside the pipe and rotates (fig. 98). KHI experimented with non-vacuum welding, using a big accelerator imported from the Soviet Union. Sumitomo Metals Co. Ltd and Hitachi Ltd. introduced a Hamilton Standard machine. Osaka University also carried out scientific research from low-pressure to non-vacuum environment with an experimental machine it developed itself.

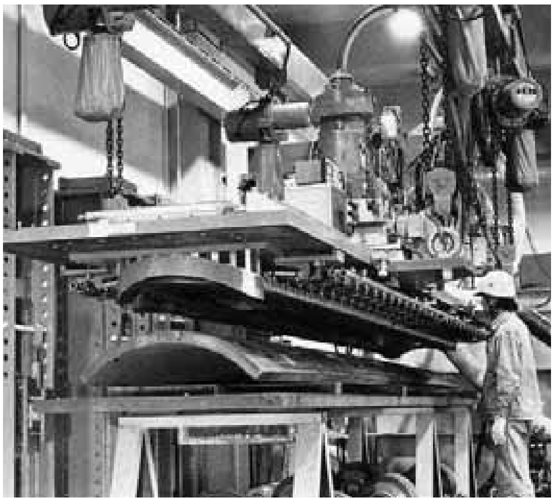


Fig. 97: A local vacuum EBW machine for seam welding of pipelines (KHI).

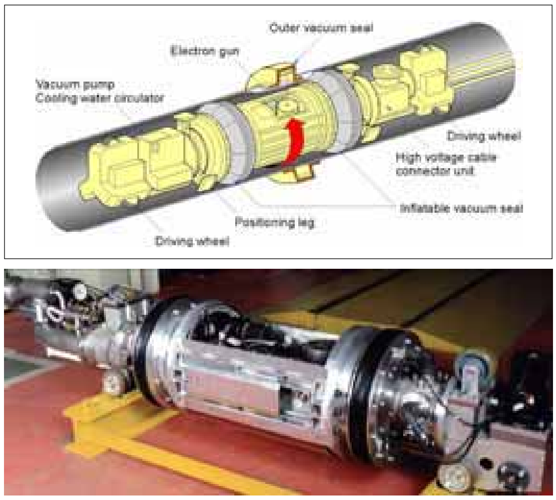


Fig. 98: Schematic diagram of a recently developed EBW machine for welding of high pressure gas pipelines in the field (above) and its realisation (KHI).

Prolonging Filament Life

One of the disadvantages of EBW is the life of the filament. When small parts were first welded, a life was required of more than 8 hours, the length of one shift of a day's production. However, longer life was, of course, desirable. MELCO developed a rod-type tungsten cathode, which is heated by electron bombardment from a heated tungsten wire. These can last for more than 500 hours in mass production (fig. 99). NEC developed a current-adjusting and controlling method for ribbon (thin plate) type tungsten filament which prolongs its life by more than a couple of hundred hours. Instead of tungsten cathodes, LaB6, which has high electron emission intensity, has also been investigated for longer cathode life.

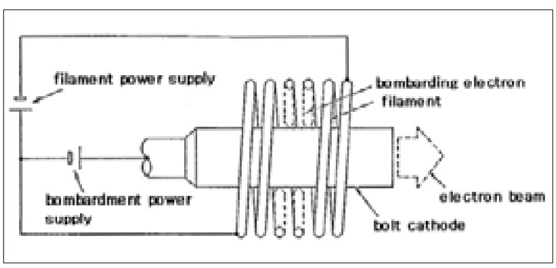


Fig. 99: Above: The rod type indirectly heated cathode (MELCO).
Fig. 100: Right: The most powerful EB welder in Osaka University, 300 kW, 600 kV, 1980.

Arcing

Arcing (spark discharge in electron gun) is a major problem in production, especially, during the welding of heavy-gauge workpieces. Many ways of solving this problem have been suggested worldwide. MELCO developed a non-stop power supply, in which arcing disappears in a short time, by the use of small capacitance in the power supply when it occurs; welding power comes back on soon after the disappearance. The voltage and the current present before arcing recover so soon that the problems that would be caused by actually stopping the EB process can be avoided. Hitachi, using Sciaky guns, developed a telefocus lens system, which has double lenses and by which the selection of a longer working distance from the gun to the workpiece could be carried out, resulting in a reduction of arcing and an interruption of welding. Of course, surge-absorbing devices imported from foreign countries were also investigated.

Extreme Challenge

In addition to conventional electron beam welding machines, two alternatives with extremely contrasting properties have been developed.

One is the machine with the highest accelerating voltage (fig. 100). Prof. Arata (fig. 101) and his group at Osaka University developed a 600 kV electron beam welding machine [75]. This is world-famous and presents the greatest challenge to EBW. Many scientific phenomena have been researched with this machine.

The other is a micro-welding system developed by MELCO for the welding of miniature and precise parts using high-speed deflection as a characteristic of electron beam welding (fig. 102).

Fig. 101: Above: Prof. Yoshiaki Arata.

Fig. 102: Right: The EBW machine for micro and precision parts. Size is c.900 W x 1630 H x 1500 D and specified for clean rooms (MELCO).

Hirosada Irie

1942 March	born
Diploma	1965 Bachelor of Electric Engineering (Osaka University) 1967 Master of Nuclear Engineering (Osaka University) 1979 Doctor of Welding Engineering (Osaka University)
1964 April	Start of research on electron beam welding in the welding division of the National Research Institute for Metals (NRIM)
1985 April	Research on material processing by high energy density beams (electron and laser beam material processing)
1997-2002	Director, Division of Mechanical Properties, NRIM
2002 March	Retirement from National Research Institute for Metals
2002-	Director, Japan Welding Technology Centre
2004-	Chairman of Board of Directors, Japan Welding Technology Centre Director, Prof., Japan Welding & Construction College
2004-	Director of Japan Welding Engineering Society
1993-2002	Chairman of Commission "Electron Beam Welding Research", Japan Welding Society
1997-2002	Vice Chairman of Commission IV of the International Institute of Welding.

The Early Days of the Electron Beam Welding Industry in Britain

David Wyatt

This short article documents and endeavours to illuminate some aspects of early electron beam welding industry in Britain. It concentrates on the work of native British enterprises, eschews complicated technical data, and notes that in the 1950s the early developments were all associated with the nuclear industry, that there was little or no fundamental research in this area in Britain and, further, that the British electron beam industry makes few pretensions to original invention in this field. However, applications research of a high quality was carried out by British technologists on machines imported from the European continent and due tribute must be paid to those scientists and engineers who, over the years, researched and developed the welding and heat-treatment capabilities of focused, high velocity beams of electrons, and whose ingenuity established these processes and ensured that they became an irreplaceable element in many areas of high precision engineering production. These scientists and engineers made important improvements to the individual aspects of the technology whilst producing dextrous control and multi-station tooling solutions to the difficulties inherent in the remote handling of workpieces in vacuum chambers [76]. In this context, the intellectual and practical input of the Welding Institute must be stressed. The electron beam industry owes a debt to this British institution for its objective inquiries and support over many years.

Fig. 103: TWI, EB welder 6m^3 chamber with 150 kV, 75 kW gun.

World-wide, the electron beam welding industry is small, with a global machine population, taking all builders into account, numbering only thousands. Its area of use is highly specialized, comprising in total a commercially unattractive technological niche market that can easily be satiated by expensive, long-lived, machines that, in most cases, require a minimum of maintenance during their extensive lives. As a direct consequence of this narrow market and its restricted demands, the few British companies that originally constituted the British section of the electron beam welding machine construction industry have ultimately, by purchase or merger, consolidated over the years into one

industrial unit. This single unit, built up by the cross-pollination, interaction and merging of engineering groups across Britain and in several other countries, now, post millennium, produces mass-production machines for a world market encompassing an immense range of applications which include, among many others, the welding of gears and turbo-charger fans, containers for powder metallurgy processes, the highly precise fabrication of delicate transducer and bellows assemblies for physical measurement, and the precision joining of components for gas turbine engines [77].
One derivative effect of the selling, design and construction of electron beam welding machines was the parallel need for in-house capabilities for the production and subsequent testing of samples for potential customers. This led to the establishment of separate sub-contract facilities and, in turn, to the founding of independent companies exploiting the electron beam welding process, so that, as the activity expanded, specialist organizations came into existence to market the process to industry at large and cater for all branches of the instrument and engineering industries [78].

In Britain, between 1965 and 1975, electron beam welding machine design and building resolved essentially into two main strands. These two strands comprised the building and exploitation of "low-voltage" (20 kV to 60 kV) full or partial vacuum machines for the instrument and mass-production industries and, secondly, a similar exploitation of "high voltage" (100 kV to 150 kV) machines capable of deep penetration, at longer working distances, in such operations as the welding of components in sophisticated alloy materials for gas turbine engines. Both low and high-voltage types utilized the same principles of generation and control of the electron beam and differed only in their areas of employment. In both of these strands there were intensive development programmes on the part of several manufacturers during this decade, which ultimately resulted in an extensive range of machines forming a spectrum ranging from inexpensive units with limited capability to high-cost units with very large work-chambers and complex numerical and automatic controls.

The group of British manufacturers that offered electron beam machines to industry were, in alphabetical order, British Oxygen (with its subsidiary Edwards High Vacuum electron beam processes), Hawker Siddeley Dynamics, Torvac (with its associated company Cambridge Vacuum Engineering) and Wentgate Engineers. In the early days, only the first two on this list were avowedly "high voltage" and of these, discounting the less significant early work of Edwards High Vacuum, the first in the field was Hawker Siddeley Dynamics, with Torvac occupying a similar pioneering position in the "low-voltage" area. It is worth noting that the first British-built "low-voltage" electron beam machines offered to British industry were produced by companies with basic expertise in vacuum technology:

Edwards High Vacuum, which later became part of British Oxygen, produced vacuum pumping equipment, and Torvac made machines which exploited low pressures in metal coating and heat treatment.

The first significant British commercial endeavour involving “high voltage” began in the mid-1960s with Hawker Siddeley Dynamics’ exploitation of a licence to build electron beam welding machines based on the Zeiss technology owned by Hamilton Standard, a division of United Aircraft Corporation in the United States of America. This initiative sprang from a long-standing collaboration between De Havilland Propellers in Britain, (later incorporated into Hawker Siddeley Dynamics) and Hamilton Standard Propellers in the U.S.A, a relationship originally based on the two companies’ mutual interest in airscrews.

The first machines built by Hawker Siddeley Dynamics, under the trade name “Dynaweld”, were the “433” (a reference to work-chamber size, in feet) of 6 kW power at an accelerating voltage of 150 kV. This versatile machine became popular and was sold widely to industry and to specialist welding sub-contractors. The various engine-building companies of the Rolls Royce and Bristol Siddeley complexes also set up electron beam welding departments using this equipment. Later machine designs, using different work-chamber sizes, designated “956” and “6000”, were built; the “956” accommodated large workpieces, and the “6000”, aimed at the automobile and similar industries, was a rapid-evacuation mass-production machine. Later, machines were offered with "1088" work-chambers and the "into air" facility for the continuous welding of tubing, and there was a collaboration with Leybold Heraus in which electron beam guns and high-

Fig. 105: Dynaweld machine with 3.5 m^3 vacuum chamber, 1967, 150 kV, 6 kW.

Fig. 106: Dynaweld, air to air, the tooling would be fitted under the nozzle, 1967/68, 150 kV.

voltage power supplies were supplied from Britain for incorporation into electron beam machines with German-built work-chamber and vacuum systems. Ingenious use of the Hamilton designs led to a domination of the British market by Dynaweld high-voltage machines which continued for some years. Sixty machines were built in the ten years from 1966, fourteen of which were sold to Rolls Royce for engine applications. By the early 1980s, having built over one hundred machines, Hawker Siddeley Dynamics' major interests in aerospace diverted emphasis from the building and servicing of electron beam welding machines, and, in 1983, Hawker Siddeley Dynamics left the market area and the Dynaweld enterprise, including the entire design dossier, was sold to the Torvac group of companies, where expertise and relevant experience relating to electron beam welding machines had existed from the late 1960s.

Fig. 107: British Oxygen chamber machine.

The next British company with ambitions to move into the high-voltage electron beam welding field was British Oxygen, which entered the arena with the purchase, in 1965, of Edwards High Vacuum, an enterprise specializing in the production of vacuum producing and pumping equipment, but with a minor interest in electron beam science and its industrial applications, resulting from their design and production of a 30 kV machine with a small work-chamber, targeted at the instrument industry. The acquisition of this relatively small company by British Oxygen resulted in the foundation, in 1969, of a subsidiary division of the Company registered as “Industrial Electron Beams”.

The objective of Industrial Electron Beams was to move into the market area discerned as occupied by British Dynaweld machines, and by European and U.S. imports, and to achieve this objective by substantially enlarging the electron beam activity already inherent in the earlier work of the Edwards group. Industrial Electron Beams’ intention was to colonize those areas of the electron beam welding industry that required large work chambers, high accelerating voltages and substantial beam power – machine characteristics that were regarded as concomitant with the longer working distances and deep weld penetrations essential for applications in the gas turbine and similar industries. Over the next few years, Industrial Power Beams sold and built two machines with Steigerwald gun systems and an experimental multi-station machine, which was never offered to industry. In addition, other possibilities were explored, and an electron gun system was sold to Heidelberg University for experimental work on bacterial sterilization. During this period, Industrial Electron Beams also had a liaison with Vickers Research, where an intensive development program exploring electron beam applications had been carried out, although Vickers had not exploited the research commercially to any major extent. The Vickers liaison did, however, bring to Industrial Power Beams technical information and elegantly designed prototype high-voltage electron gun components, but this particular avenue was not pursued, because, in 1976, the parent company, British Oxygen, left the electron beam field to concentrate its development elsewhere, and bought into Torvac as a convenient way to observe the electron beam market and its future potential. Thus in 1976 Torvac became responsible for the refurbishment and service of Industrial Electron Beams’ equipment and came into possession of all Industrial Electron Beams’ data and designs, including the Vickers prototype gun parts.

Fig. 108: Torvac machine with two chambers, 1978, 60 kV, 8 kW.

The Torvac group, with its associated company Cambridge Vacuum Engineering, had been involved with electron beam welding in the early 1960s, initially with Brad Thompson, U.S.A., and, later, in a complementary liaison with T.N.O., the Netherlands Institute for Applied Research. From these modest beginnings, Torvac built its own unique desk-type electron beam laboratory machine, rated at 60 kV, which was then re-designed as a compact production machine tool of great versatility, so that in the early 1970s, the high-voltage work of Hawker Siddeley Dynamics was matched by the activities of Torvac/Cambridge Vacuum Engineering in the low-voltage market area. During this period, Torvac sold 60 low-voltage machines with a variety of chamber sizes to universities, other higher education establishments and the instrument, automobile and similar industries. In addition, Torvac wisely built up lucrative electron beam welding and heat-treatment sub-contract facilities, which provided advertising and reinforcement for its equipment products. These sub-contract facilities eventually evolved into the separate "Thermal Processing Group".

Fig. 109: Torvac general-purpose machine, 1974, 60 kV, 3 kW.

Fig. 110: Torvac machine with 1 m^3 chamber, 1984, 150 kV, 10 kW.

In 1976, however, as previously mentioned, Torvac entered the high-voltage field as legatee of Industrial Electron Beams; much later, in the 1980s, when Hawker Siddeley Dynamics relinquished their electron beam activity, Torvac became responsible for the service of the 100 Hawker Siddeley Dynamics "Dynaweld" machines in existence and acquired, at the same time, the associated high-voltage machine designs (fig. 110). The result of these acquisitions and alliances meant that, from the mid 1980s, the Torvac product line included both high- and low-voltage electron beam machines with a comprehensive range of accessories and, further, that Torvac had the benefit of unlimited access to the Dynaweld network of existing and potential customers. The Torvac business expanded accordingly, and low-voltage "air-to-air" strip-welding units and high-voltage machines were built with a range of work-chamber sizes. In addition, international markets were developed via energetic sub-contractors selling and providing service for Torvac machines installed in companies working in the aerospace, weapons and nuclear industries worldwide. This potent consolidation of Torvac interests was recognized by the Thermal Scientific Group, which acquired the Torvac Group towards the end of the decade and soon reinforced the purchase by buying other, similar enterprises, heat-treatment and welding sub-contractors and machine builders, including Wentgate Engineers.

The last of the quartet of British companies, Wentgate Engineers, was not formed until 1967/68; it began as a venture aimed at providing competition in the low-voltage market. The machines first offered were "desk type" (fig. 111), with the electron gun pumped through the work-chamber. Later, these simple machines were followed by an improved range with larger chambers and higher beam power, with separate pumping of the electron gun. The Wentgate Engineers project, specifically to explore and develop the instrument and transducer industrys' potential requirement for small electron beam welding machines and competitive exploitation of that market segment, was only moderately successful and in 1987 Wentgate Engineers was bought by the Thermal Scientific Group.

Fig. 111: Left: Wentgate desk-type machine, 1975, 50 kV, 2 kW.
Fig. 112: Above: Wentgate Dynaweld general purpose machine with 1 cubic metre chamber,1988, 150 kV, 8 kW.

The Thermal Scientific Group merged Wentgate Engineers with Torvac under a new management structure, selling and building electron beam welding machines under the trade name "Wentgate Dynaweld" (fig. 112). This enterprise continued for two years until a further company re-shuffle returned the trade name "Dynaweld" to Torvac, within the holding company

"Cambridge Vacuum Engineering". Within two decades, Torvac/ Cambridge Vacuum Engineering had become the predominant British electron beam machine builder.

The Thermal Scientific Group management strategy of strategic sub-grouping of particular activities was highly successful. Eventually, the Thermal Scientific Group was purchased by Tube Investments, which later merged with Smiths Industries, becoming Smiths Group in the year 2000. Finally, the Smiths Group sold Cambridge Vacuum Engineering to Aquasium Technology Ltd in 2001.

Footnote by the editor

This British chapter would be incomplete without some additional remarks on the considerable influence The Welding Institute (TWI) [79] had on the development of electron beam welding.

TWI started its activities in the early 1960s and, due to its international contacts, created an interest for their high-power electron beam welding research programme. This resulted in a 75 kW, 150 kV machine which could weld 450 mm penetration in aluminium alloy and 300 mm in steel (fig. 103). TWI not only worked on applications [80] using new gun designs and various power sources, but also on equipment capable of welding at different pressures from high-vacuum up to atmosphere. Non-vacuum electron beam welds at 250 kV and 300 mA have successfully performed penetrations of up to 30 mm in stainless steel (fig. 113). Recently TWI discovered that a pulsed beam in atmosphere has a much reduced divergence and thus gives better penetration into the workpiece. [81] Excellent welding results have also been achieved at a reduced pressure in the range of 1 mbar (fig. 114).

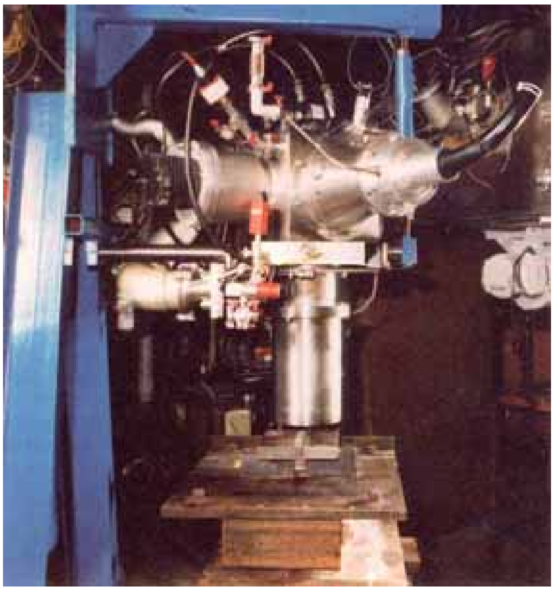


Fig. 113: NV EBW gun with high-frequency pulsing facility.

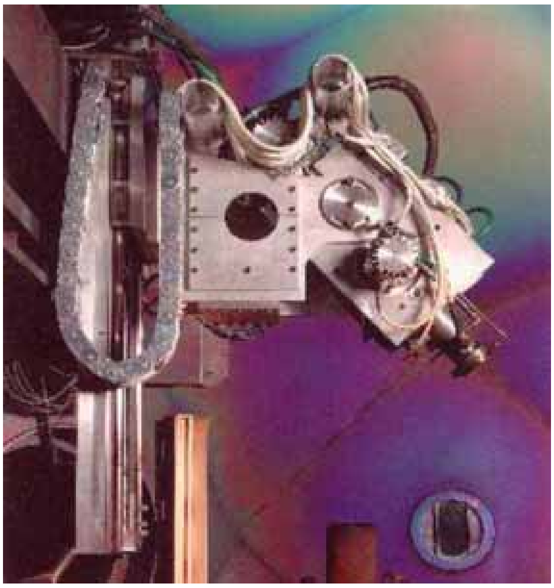


Fig. 114: Mobile reduced pressure gun capable of pulsing (2006).

A further area of interest is an electron beam technology called “surfi-sculpt” which uses the effect of the material’s transportation in the opposite direction of the weld movement due to a gradient of surface tension at different temperatures. [82] Starting a limited weld length many times at the same spot there is a build-up of material being transported from the “end crater” to the tip. By high-speed beam deflection and appropriate computer control, protrusions of many different shapes and in different materials can be performed (fig. 115, 116).

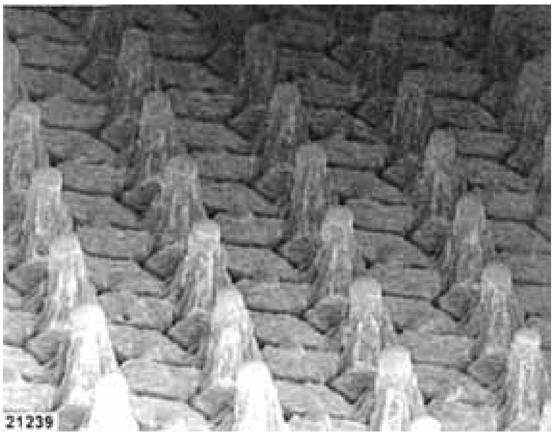


Fig. 115: Electron beam surfi-sculpt surface.

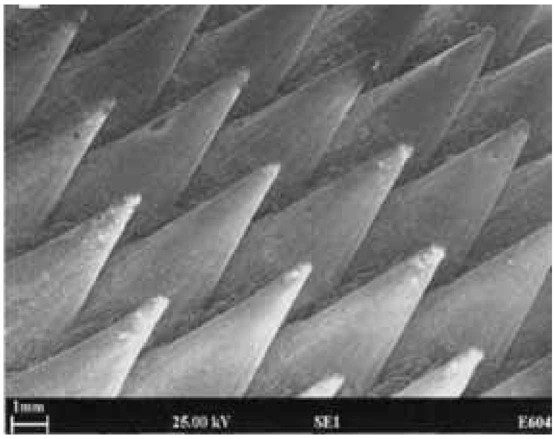


Fig. 116: Cones grown from titanium alloy surface.

Contrary to some players in the market, who are afraid of laser beam competition, Alan Sanderson and his expert team at TWI still see great potential in electron beam welding, when reinforced by intense R&D work.

David Wyatt:

David Valentine Wyatt, B.A. (Hons), C. Eng.

David Wyatt worked for 30 years in the electron beam industry, designing and developing electron beam welding machines; during this time held, in turn, senior posts in the electron beam activities of Hawker Siddeley Dynamics, the British Oxygen Company, and Torvac/Cambridge Vacuum Engineering, where he was appointed director in 1976. Later, he had similar responsibilities in the modern, re-named companies that emerged from the endeavours of this small group of pioneer British enterprises. Author of many papers on the practice and application of electron beam welding, which he promoted as “the aristocrat of welding processes”.

Electron Beam Welding in the Rest of the World

Dietrich v. Dobeneck

Besides the electron beam equipment manufacturers dealt with in the preceding chapters, I would like to mention a few more. In Germany there were companies such as FEP, ETC, Burkart, ELFEMA, Interatom or JRW each of which built 4-10 machines. Balzers in Lichtenstein was one of the early players. In the East, institutes and universities developed machines, e.g., 12 in Romania, ten in Poland [83], eight in Slovakia, nine in Bulgaria and four in Hungary. Quite a number of these machines were in industrial production. Dr Sobanski († 2006) from Wroclav, Poland, wrote that his institute (for radar electronics) was the first to develop EB equipment in Poland – nearly 50 years ago and said: “I am happy to hear that this technology is still alive and still expanding”. The voice of a true pioneer!

Whereas India has only about 30 electron beam machines, ten of which were built in the country’s own institutes [84], the EB-market in China is growing rapidly. Since 1980, EB-machines are being developed within the country [85]. There are at present five Chinese manufacturers, who have built about 120 machines, some with imported EB generators. Foreign companies produce vacuum chambers and motion systems for the local market in China. EB generators, too, are supplied from abroad. As far as I know, Korea is one of the big importers without any production of its own. South America and Africa run a few imported machines; in Australia there is not a single one.

Fig. 117: Beamstar made by Interatom.

Fig. 118: EB machine at Harbin Institute of Technology.

The Influence of Subcontractors and pro-beam's History

Besides the automotive, nuclear and aeronautic industries, subcontractors (job-shops) are the dominant users of EB equipment [86]. In the U.S.A. there are about 50 job-shops [87], in Europe about 20, most of them using several machines [88]. Their business begins with the evaluation of new applications, [89] and when the required volume for production is small, they will, from time to time, manufacture parts for their customers. If the welding process has to be certified according to some particular standard, this may mean test pieces for evaluation, or – more typically for automotive applications – endurance tests on a few 100 parts, before a decision on the acquisition of actual production equipment is made. Today, start-up production is still often at subcontractor level and the OEM company will only transfer the tuned-up process to its own production line after all the initial problems have been solved and the glitches removed. As the automotive industry is wary of any new investment, it even outsources high-volume production under the condition that there is complete back up at the subcontractor facility. That means the subcontractor has to provide a second EB weld capacity, preferably at another location.

In the life-cycle of a product manufactured at the OEM, there are sometimes periods of high production intensity, but also holiday periods, or repair-intensive times when a job-shop will get part of the production. And, when the product life has ended, there is still the need for spare parts, which the subcontractor may deliver on a regular basis. It is fair to say that job-shops are the door-openers for EB techniques to many users.

Fig. 119: Load lock cycle machine for rapid EBW of small parts in hard vacuum.

Most of the EB equipment manufacturers run their laboratory machines as a profit centre. So did Dr Steigerwald in the early 1970s. Customers who wanted to buy an EB machine required the supplier to demonstrate that he could do the job on demand. During the late 1960s and 1970s most applications needed long test-runs and evaluation of the welding task – which was not paid for. This meant that the "profit centre" made a loss. Therefore Steigerwald had the idea selling his two lab machines to me, one for welding and one for drilling [90, 91]. I agreed and founded pro-beam in 1974. The company grew and we started buying second-hand electron beam machines and by retrofits we made them more productive. The neverending requests from our customers for better quality in shorter delivery times and at lower prices, as well as increased competition from lasers brought us under considerable economic pressure [92, 85]. We had to think of new machine concepts and followed up the following ways of reducing costs:

- to build low-cost machines (fig. 119)
- to reduce or eliminate idle time for pumping and venting and to speed up workpiece positioning (figs. 120-122) and
- to increase welding speed (figs. 124-126)

I proposed a number of possible design concepts [93] to the OEMs, but there was no reaction. So in 1991 we built our first load-lock shuttle-machine ourselves as a particularly flexible system for job-shops. Then we realized that our CNC-systems were too slow to control production as fast as the electron beam was capable of working, so we started to manufacture our own pro-beam computer system, and finally, in 1999, we built whole EBW units ourselves. One major automotive manufacturer, Audi, asked us to supply equipment for fusion treatment of camshafts, and, shortly afterwards, they wanted production machines for sealing cooling channels in motor blocks. These crank-shaft housings were cast in England, machined in Hungary and electron beam welded in Munich in our job-shop, as many as three

Fig. 120: EB shuttle machine with simultaneous welding, evacuating and loading.

Fig. 121: EB transfer welder with pre- and post load-lock chambers and 2 EB guns.

Fig. 122: Twin chamber machines for EB hardening of cam-shafts.

Fig. 123: 45 m^3 + 10m^3 chamber for welding of satellite tanks.

truckloads a week, each full of 40 t of workpieces. Audi decided to stop this component-tourism. So pro-beam started a subsidiary at Chemnitz to build EB machines. Later, amongst others, Volkswagen, Bosch, EADS, Rolls Royce and Siemens followed. They realized that pro-beam was able to convert the experience of over 30 years of practical work with EB machines from eight different suppliers into advanced equipment and processes [84]. The investment for these machines was sometimes expensive, but the price per part came down considerably as productivity was increased, and the running costs were much lower in comparison to lasers.

In many cases it is impossible to increase welding speed for metallurgical reasons, e.g., hardening due to rapid quenching. The solution is to weld with multi-beams [94, 95]. This proprietary technology actually uses only one beam, which jumps so fast between several weld positions that the material does not recognize its short absence. The beam returns into the weld key hole so precisely and so fast that it has not yet closed. Jumping frequencies of the beam are up to 100 kHz.
When welding gears with, for instance, three beams, there is symmetrical heat input and therefore virtually no offset of the synchronizing ring relative to the gear, including reduced welding time. Multi-processes are also possible: The first beam pre-heats the material locally, the second beam welds and the third may perform a cosmetic pass or a post-heat-treatment.
Another even faster process is called flash technology. The complete contour of a joint or of several joints is welded within one instant. The contours are programmed and the beam follows them several thousand times per second. [96]

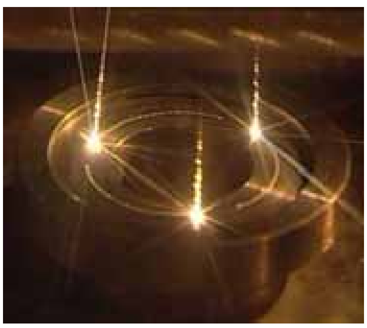


Fig. 124: 3 beam welding of gears.

Fig. 125: 60 beam welding of particle filters.

Fig. 126: EB flash welding of turbo-charger components.

Process observation and automated positioning are now done via light optics (telescope or CCD camera) and by the use of electron optics. Before the fall of the Iron Curtain, the majority of countries in the East used observation via electron optics, and countries in the West used telescopes or cameras. We were the first to succeed in combining the two systems on the same monitor – a huge improvement for practical work.
It is also of great importance to specify beam quality [97, 98]; today's international standards do not mention this topic. In order to reproduce a weld,

once performed and documented in the welding procedure specification, all parameters, including the emittance of the beam, have to be identical. We introduced this feature into production machines, which allows automatic beam adjustment and measurement of beam quality within two minutes.

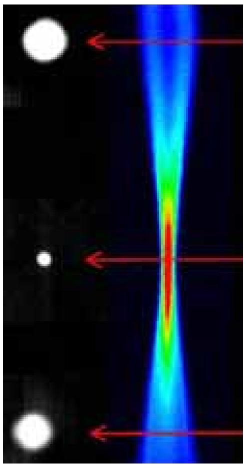


Fig. 127: Beam characterisation to determine emittance.

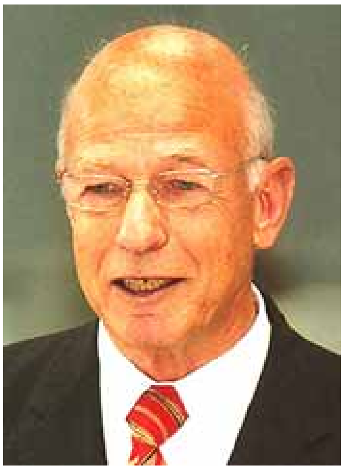
Today pro-beam employs a team of 250 people, 32 EBW units and five EB drilling machines many of them working three shifts, in eight different locations. Amongst these is the largest machine for civilian applications, with 16 CNC axes, a vacuum chamber 14 x 7 x 7 m and an articulated EB gun mounted on a five-axis robot, travelling on a gantry.

Fig. 128: 630 m^3 chamber with EB welded disc for Ariane tank.

Fig. 129: High-voltage EB gun mounted on a robot.

EB technology does not only have a fascinating, multi-layered history; with continuing innovations, depending on the development of computer controls, it will also have a bright future.

Dietrich Frhr. von Dobeneck



Born in 1938, studied physics at the Technical University Munich, where he stayed another five years as a postgraduate, working in plasma physics under Prof. Krempl.
In 1969 he joined Steigerwald Strahltechnik GmbH, where he was responsible for marketing and EB drilling. There he initiated rotogravure by means of an electron beam, a process which took 25 years of intensive R&D. 1974, establishment of pro-beam as a job-shop, and its general manager. 2001, chairman of the board of directors.

Selected Bibliography

List of Publications referred to in the text

[1] Crookes W.: Phil. Trans. Roy. Soc. Part I+II, 135+641, London (1879)
[2] Pirani M.v.: Siemens Patent DRP 188.4.66 (1905)
[3] Rühle K.: Verf. zur Verdampfung im Vakuum DRP 764.927 (1939)
[4] Busch H.: Ann. Physik 81, 974, (1926)
[5] Ruska E., Knoll M.: Z. f. Techn. Physik 12, 389, (1931)
[6] Urban K.: Der späte Nobelpreis (for Ruska). Phys. Jour. 6, Nr. 2 (2007)
[7] Ardenne M.v: Elektronenübermikroskopie, 162-165, Springer Verlag Berlin (1940)
[8] Brüche E.: Von Braun's Röhre zum Fernfokus. Zeitschrift für angewandte Physik 3, 88-90, (1951)
[9] Steigerwald K.H.: Ein neuartiges Strahlerzeugungssystem für Elektronenmikroskope. Optik 5, 469-478, (1949)
[10] Steigerwald K.H.: Materialbearbeitung mit Elektronenstrahlen. Physikalische Verhandlungen 4, 2, 123,(1953)
[11] Steigerwald K.H.: Das Bohren von Lagersteinen mit Elektronenstrahlen. Z. d. Deutschen Ges. für Edelsteinkunde 31, (1958)
[12] Steigerwald K.H.: Materialbearbeitung mit Elektronenstrahlen. 4. Internationaler Kongress für Elektronenmikroskopie, 276, Springer Verlag Berlin (1958)
[13] Schumacher B.W.: Dynamische Druckstufenstrecken für den Einschuß intensiver monokinetischer korpuskularer Strahlbündel in Gasen hohen Drucks. Optik 10, 116 (1955)
[14] Stohr, J.A.: (Nov. 1957) Fuel Elements Conference, Paris, TID 7546, Book 1, US Atomic Energy Comission, 0-17 (1958)
[15] Stohr J.A., Briola J.: Soudage des métaux sous vide Soudage et techniques connexes 12, 165-172, Institute de la Soudure (1958)
[16] Stohr J.A.: CEA Sacley, patent 1.41.535, Paris (1956)
[17] Purton G., Matchet R. L.: Electrons shot from guns make high purity welds. American Machinist 23, 95-98, (1959)
[18] Glaser W.: Grundl. der Elektronenoptik, Springer Verlag Wien (1952)
[19] Steigerwald K.H.: Elektronenstrahlen als thermisches Werkzeug. Neue Züricher Zeitung, 763-766, (1963)
[20] Steigerwald, K.-H.; Carl Zeiss Oberkochen: DBP 108.7295 (deep penetration welding) applied 20.02.1959
[21] Wabersich E.: Elektronenstrahlschweißen eines Treibstoffbehälters aus einer hochfesten Titanlegierung für die dritte Stufe der Eldo Trägerrakete. Luftfahrt-/Raumfahrttechnik 12, 48-53, Bremen (1966)
[22] M. Sciaky: L'impact industriel des faisceaux d'electrons - aujourd'hui et demain. 3ème Colloque International sur le Soudage et la Fusion par Faisceaux d'Électrons et Laser, 19-36, CISFFEL 3, Lyon (1983)

[23] Pierce J.R.: Theory and design of electron beams. Van Nostrand Publication (1954)
[24] Sayegh G.: Détermination des caracteristiques des faisceaux dans un canon à électrons. These de docteur en sciences physiques, Université de Paris sud, centre d'Orsay, (Septembre 1976)
[25] Two publications of SCIAKY S.A.: Le soudage par faisceaux d'électrons. Printed by Sciaky in 1968, Sciaky Electron Beam Welding 2d edition (1977)
[26] Sayegh G.: State of the Art of 'High Energy Density Beam' welding. Proceedings of the international conference on electron and laser beam welding, IIW published by Pergamon Press, Tokyo (1986)
[27] Wyman W.L., Steincamp W.I.: (April 1958) Rpt. HW 55667, General Electric Co.; also Welding Journal, Vol. 21, 49, (1958)
[28] Bunshab R.F.: The History of EB Technology in: Bakish R. (Editor): Introduction to Electron Beam Technology, John Wiley&Sons Inc., (New York / London 1962)
[29] Bakish R.: Twenty Five Years Electron Beam Welding in the U.S. CISFFEL 3rd Internat'l. Conf. on Welding and Melting by Electrons and Laser Beams, 895- 902, Lyon, France, (1983)
[30] Alvey J.W.: Automation Techniques Applied to High Production EB Welders,119-133
[31] Samuelson F.: Equipment and Applications for Partial EB Welding, 157-165, Electron Beam Welding Symposium, OSU Dept. of Welding Engineering, Columbus, OH (1966)
[32] Leonard L.H.: Electron Beam Welding at Atmospheric Pressure, 5th Annual Meeting of the EB Symposium, 378-394, Boston, MA (1963)
[33] Hanson R.C.: Private Communication to R. Bakish (Dec. 1982)
[34] Powers D.E.: Electron Beam Welding – An Overview, ASM Internat. Power Beam Conf., 25-33, San Diego, CA (1988)
[35] American Welding Society's C7.1 M/C7.1, 2004 Document, Recommended Practices for Electron Beam Welding (2004)
[36] Mayer R., Dietrich W., Sundermeyer D.: New High-Speed Beam Current Control and Deflection Systems Improve Electron Beam Welding Applications, Welding Journal Vol. 56/6, 35-41 (1977)
[37] Hinrichs J.F., et al: Production Electron Beam Welding of Automotive Frame Components, Welding Journal, Vol. 53/8, 488-493 (1974)
[38] Schollhammer F.R.: Hand-Held Electron Beam Gun for In-Space Welding, 4th Space Congress – Canaveral Council of Technical Studies, Cocoa Beach, FL (1967)
[39] LaFlamme G., et al: Hybrid EBW Process Joins Heavy-Duty Impellers, Welding Journal, Vol. 85/I, 44-47, (2006)
[40] Stecker S., et al: Electron Beam Free Form Fabrication Technology, IIW Doc. IV-911-06, IIW Comm. IV-Power Beam Processes, IIW Annual Assembly, Quebec City, Canada, (Aug. 2006)

[41] Olshanskiy N.A.: Welding method by electron beam in vacuum. Automatic welding, No. 8 (1959)
[42] Movchan B.A., Rabkin D.M., Gurevich S.M., Zagrebenyuk S.D.: Some technological peculiarities of welding by electron beam in vacuum. Automatic welding, No. 8 (1959)
[43] Kostyuk V.A., Kozlov Yu.M., Shuvalov A.V., Gerasimenko A.V.: Commercial machines for welding by electron beam. Welding Engineering, No. 1 (1961)
[44] Gorbanskiy V.V., Shubin L.V., Khudishev A.F.: Equipment for precision electron beam welding of refractory metals and alloys. Automatic welding, No. 6 (1961)
[45] Khavanov V.A., Bratchuk S.D., Seryoznov V.A., Kazakov A.V.: Equipment of NIKIMT for electron beam welding. Welding engineering, No. 9, 25-31 (2006)
[46] Kazakov V.A., Nazarenko O.K.: State-of-art and prospects of development of electron beam welding of aerospace vehicles, Proceedings from the conference “Welding in Space and the construction of space vehicles by welding”, 151-160, New Carrollton, Maryland, USA, ISBN 0-87161-375-6, (September 24-26, 1991)
[47] Nazarenko O.K., Povod A.G., Shnyakin N.S., Artamonov N.N., Kedman A.B.: Equipment and technique for electron beam welding of bulky workpieces. Automatic welding, No. 3 (1964)
[48] Glazov S.I., Lyushinskiy A.V., Magnitov V.S., Oboznov V.V., Chuklinov S.V.: Fundamentals of technology of electron beam and diffusion welding. Ed. O.S. Sirotkin and S.V. Chuklinov. Publishing house of research and technical board of SPA “Saturn”, town of Rybinsk (2001)
[49] Avvacumov J.V., Boykov L.V., Mikhailov V.I., Nazarenko O.K., Zamkov V.N.: Electron beam welding of joints made of titanium alloys. In: “Titanium ’99: Science and Technology”. Proceedings of the Ninth World Conference of Titanium Central Research Institute of Structural Materials (CRISM) “Prometey”, Russia, vol.3, 1742-1745, Saint-Petersburg, Russia, (7-11 June 1999)
[50] Nazarenko O.K., Kaydalov A.A., Kovbasenko S.N. and others: EB welding: Ed. B.E. Paton, 256, Kiev: Naukova dumka (1987)
[51] Nazarenko O.K., Lokshin V.E.: Dynamic characteristics of high-voltage power sources for electron beam welding. The Paton Welding Journal, 31-33, (January 2005)
[52] Nesterenkov V.M.: Technology and equipment for electron beam welding of power engineering components. In “Power Beam Technology”, 171- 179, Stratford-upon-Avon, UK, The Welding Institute, Abington Hall, Abington, Cambridge CB1 6AL (23-26 September 1990)

[53] Nazarenko O.K., Nesterenkov V.M., Neporozhny Yu.V.: Design and electron beam welding of vacuum chambers. The Paton Welding journal, 40-42 (June 2001)
[54] Paton B.E., Nazarenko O.K., Nesterenkov V.M., Morozov A.A., Litvinov V.V., Kazimir V.V.: Computer control of electron beam welding with multi-coordinate displacements of gun and workpiece. The Paton Welding journal, 2-5 (May 2004)
[55] Nazarenko O.K., Shapoval V.I., Loskutov G.A., Rybak V.N., Lanbin V.S., Khomenok A.V.: Observation of electron beam welding process and automatic tracking the butt joint. Automatic welding, No. 5, 35-38 (1993)
[56] Lorenz A., Dietrich W: DBP 1 087 723 applied 09.01.1953
[57] Lorenz A: Die Erzeugung sehr starker Elektronen-Strahlen mittels Druckstufenstrecken. Phys. Verhandlungen 7, 36 (1956)
[58] Kluger H., Dietrich W.: Elektronenstrahl-Schweißen an freier Atmosphäre. Schweißen und Schneiden 16, 10 (1964)
[59] Dietrich W.: Electron beam melting with multiple guns. 2nd Intern. Congress on Vacuum Science and Technology, Washington D.C. (1961)
[60] Dietrich W., Kluger H.: Rationelle Fertigungsmethoden durch Elektronenstrahl-Schweißen. G.I.T. Fachzeitschrift für das Laboratorium, Hoppenstedt Wirtschaftsverlag, Darmstadt, Fachberichte (1970)
[61] Dietrich W., Fritz D., Luxenburger R.: Das Schweißen von Lastwagenachsen in einer Fertigungsstrasse. DVS Berichte 36, Strahltechnik
[62] Mayer R., Dietrich W., Sundermeyer D.: New high Speed Current Control and Deflection Systems improve Electron Beam Welding Applications. Welding Journal 56/6, 35-41, (June 1977)
[63] Eichhorn, F.,Spieß, B., Ritz P.: Fugenspalterkennung und selbsttätige Nahtfugen-Nachführung beim Elektronenstrahl-Schweißen. Hochschulkolloquium, RWTH Aachen (22.03.1979)
[64] French patent N° 594.746, Soc. anon. des Établissements Gaiffe Gallot et Pilon, résidant en France (Seine). applied 6 June 1924 granted le 30 June 1925, Procédé et appareil pour la fabrication de pièces en métaux refractaires (published 17 sept. 1925)
[65] Powers D.E., Caroll M.J.: Fully Automatic EB Welding of Large, Heavy Section Pieces. Technical Paper MS 85806. SME Society of manufacturing engineers, Dearborn, Mich. (1985)
[66] Arata Y., Tomie M.: Trans of JWRI, 2-1 (1973)
[67] Arata Y., Tomie M.: Journal of JWS, 46-7 (1977)
[68] Okada M., Arata Y. et. al.: Reports on the first Symposium of Atomic Energy in Japan. 1, 409 (1957)

[69] Arata Y.: Development of Ultra High Energy Density Heat Sources and their Application to Heat Processing JWRI Osaka University (1984)
[70] Arata Y., Tomie M.: Beamdeflector. 2nd International Symposium of JWS (1975)
[71] Irie H., et. al.: Apparatuses and Applications of EBW in Japan. IIW Doc. IV-585-92
[72] Irie H., Hashimoto T., Inagaki M.: Journal of JWS, 46-9 (1977)
[73] Tsukamoto S., Irie H.: NRIM. Prevention of Welding Defects using modified Electron Beam IIW Doc. IV-577-91
[74] Irie H., Hashimoto T., Inagaki M.: Energy Density in Cavity during EBW. IIW Doc. IV-144-74
[75] Arata Y., Tomie M.: Journal of High Temperature Society 10-3 (1984)
[76] Chyle J.J.: Some Development in Metal Welding Processes. Machinery 95, 377, London (1959)
[77] Meleka H.: Electron Beam Welding. Principles and Practice, Mc Graw-Hill, London (1971)
[78] Adams M.J.: Brit. Weld. J. 15-3 (1968)
[79] Sanderson A.: Four Decades of EB Development at TWI. Welding in the World 2007, Journal of IIW, Vol. 51, 1/2 (2007)
[80] Sanderson A.: Metal Construction. Brit. Weld. J., 6-1 (1974)
[81] Sanderson A.: The development of RF excited guns for high power EBW. IIW Doc. IV-709-98
[82] Buxton A.L., Dance B.G.I.: Surfi-Sculpt – Revolutionary surface processing with an EB. Paper presented at ISEC 2005
[83] Dobeneck D.v.: Applications of Electron Beam Welding. Politechniki Wroclawski konferencje Nr. 3 (1979)
[84] Dobeneck D.v.: EBW – Applications and Equipment developed from 30 Years of Job-Shop Experience. Symposium on Electron Beam Technologies and Applications, Mumbay, India (2005)
[85] Dobeneck D.v.: Electron Beam Welding – Today's State of the Art and Trends of Development. Manufacturing Technology Conference, Kunming/China (2004)
[86] Dobeneck D.v.: Timesharing für Elektronenstrahlanlagen. Europa Industrierevue 1 (1976)
[87] Dobeneck D.v., Parella A.: Electron Beam Machining – the Process and its Applications. The Electr. Chem. Soc., San Francisco, CA (1974)
[88] Dobeneck D.v: Die Elektronenstrahltechnik – ein vielseitiges Fertigungsverfahren. Feinwerktechnik und Mikronik 77, v.3 (1973)
[89] Dilthey U., Woeste K.: Elektronenstrahlschweißen metallischer Werkstoffkombinationen. Schweißen und Schneiden 58, 6 (2006)
[90] Dobeneck D.v.: Abtragende Bearbeitungsverfahren mit dem Elektronenstrahl. Informationstagung für elektrische Abtragverfahren ETH Zürich (1971)

[91] Dobeneck D.v.: Wide Opportunities of Electron Beam Technique Application. State Com. for Science and Technology, Moskau (1972)

[92] Dietrich W., Fritz D., Kloss I., Reindl G., Schubert G.: Aktueller Stand der Elektronenstrahl-Schweißtechnologie in der Produktion. DVS Berichte, Strahltechnik (1986)

[93] Dobeneck D.v.: Schnelle Elektronenstrahlschweißanlagen als günstige Alternative zu Laserschweißmaschinen. Maschinenmarkt Nr. 7 (1997)

[94] Dobeneck D.v., Schultz H.: Neuentwicklungen und Einsatzmöglichkeiten des Elektronenstrahlschweißens. DVS Jahrbuch (2002)

[95] Dobeneck D.v.: Economizing Electron Beam Welding – Recent Developments and Future Trends. Proceedings of the IIW International Conference Prague (2005).

[96] Dobeneck D.v.: Those who rest will rust – The Development of Technology and Market for EB-Welding is being pushed by Economic Pressure. Proceedings of the IIW Intern. Conference Dubrovnik (2007)

[97] Eichhorn F.: New System for Precise Beam Diagnosis of High Power (> 30kW) Electron Beam Machines. IIW Doc. IV-378-84

[98] Löwer T.: Analysis, Visualisation and accurate Description of an Electron Beam for high Repeatability of Industrial Production Processes. 7th International Conference on Electron Beam Technologies EBT, Varna (2003), although IIW Doc. IV-934-07

[99] Schiller S., Heisig U., Panzer S.: Elektronenstrahltechnologie. Wissenschaftliche Verlagsgesellschaft, Stuttgart (1977)

[100] Schulz H.: Elektronenstrahlschweißen. Fachbuchreihe Schweißtechnik, 93, DVS Verlag (1989)

[101] Dobeneck D.v., Löwer T., Adam V.: Elektronenstrahlschweißen – Das Verfahren und seine industrielle Anwendung. Die Bibliothek der Technik Band 221, Verlag Moderne Industrie (2001)

[102] Dobeneck D.v.: Electron Beam Welding – Examples of 30 Years Job-Shop Experience. pro-beam AG & Co. KGaA (2005)

[103] Dobeneck D.v.: Electron Beam Welding – A Key Technology to Construct Vehicles for Road, Rail, Sea, Air and Space. pro-beam AG & Co. KGaA (2007)

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