Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia CIRP 6 (2013) 5 – 12

www.elsevier.com/locate/procedia

The Seventeenth CIRP Conference on Electro Physical and Chemical Machining (ISEM)

Historical phases of EDM development driven by the dual influence of "Market Pull" and "Science Push".

B. M. Schumacher[a*], R. Krampitz[b], J.-P. Kruth[c]

[a] Prof.em. Dr.-Ing. Dipl.Wirt.-Ing., Via ai ciossi 4, CH6616 Losone, Switzerland
[b] Prof.em. Dr.-Ing., *Boardmember ENA GmbH*, Industriestr. 3, D-39443 Atzendorf, Germany
[c] *Prof. Dr.-Ir. Jean-Pierre Kruth, KUL Mechanical Engineering Dept.PMA, B-3001 Leuven-Heverlee, Belgium*
* *Corresponding author. Tel.: +41-91-7914250; schumabe@bluewin.ch*

Abstract

Electrical discharges are a well-known effect in nature and are accompanied by a lot of physical phenomena, such as light, shock-waves, electromagnetic radiation, high temperature, material transfer and noise. Benjamin Priestley recognized in 1751 marks of material removal as “footprints”, when electrical discharges take place between two electrodes. Josef Priestley described in 1766 the formation of ring-marks with discharges from “Leiden Jars”. Meritens started in 1881 the use of electrical discharges with material transfer for arc-welding purposes, but it took until years around World War 2, before electrical discharges were used for controlled metal removal operations. This application is today nearly 75 years going on and developed to an important industry-branch. The authors analyze the important development steps, driven continuously by two forces, the “Science Push” and the “Market Pull”. The history of EDM is proving the strength and effectiveness of a dual training for applied engineering, developing knowledge and experience in parallel. Important personalities, successful product-developments and applications, and recognized brands will be presented.

Selection and/or peer-review under responsibility of Professor Bert Lauwers

Keywords: Electrical Discharge Machining (EDM); History of process development; ED-Sinking; ED-Cutting; ED-Physics

1. Arcs or Sparks?

Lightning’s have all time made people fear the power of electrical discharges, phenomena occurring in nature but also created in laboratories while experimenting with electricity, either in gasses/air or under liquid. Robert Boyle (*1627/†1691) from Lismore/Ireland already reported on effects of material removal, later also called material disintegration, when searching to produce metal powder from solid rods. K. Kohlschütter, Professor at the University of Bern, described in 1917 effects of discharges for colloid chemistry and to pulverize metals. He also could observe the emission of gasses from electrode peaks under high electric tension. During the 1930ties (e.g. US-Pat.20035) first attempts were made to machine metals and diamonds with electrical discharges. The American company ELOX (H.V. Harding; V.E. Matulaitis) developed machines (US-Pat.1’556’325) using interrupted arcs to remove broken taps from valuable workpieces. They called their machine “Disintegrator”, principle still today in use in industry.

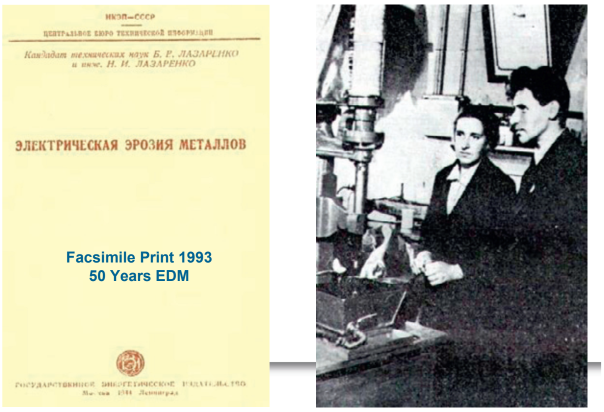
Distinguishing arcs and sparks in early times was not a question. Physicists until today are in trouble of definition. For Electrical Discharge Machining (EDM) this scientific judgment is of no importance, because in workshops “sparks” are defined as controlled discharges for precise material removal while “arcs” characterize a deteriorated process or are by intention used for rough jobs. We recognize here a good example to explain, that technical people need investigation as well as experiments to gain their knowledge and expertise, argument for the “Dual Education Principle”. The

Selection and/or peer-review under responsibility of Professor Bert Lauwers
doi:10.1016/j.procir.2013.03.001

authors use this understanding by the terms of "Science Push" and Market Pull" to describe the historical development of EDM pushed by research institutions on the one side and by industrial companies in fight for increased application on the other side.

2. Starting Electrical Discharge Spark Machining

During World War 2 the Russian physicist couple B.R. and N.I. Lazarenko were engaged with research, to minimize wear on electric power contacts and to find substitutes to precious materials. They applied an RC-circuit and charged defined energies in the capacitor. The thesis of B.R. Lazarenko in 1943 (Fig. 1) then proposed the use of the "Inversion of the effect of wear on electric power contacts for machining purposes" to turn the negative effect of electric contact wear into a positive effect for machining metallic workpieces.



1943 in Russian: B.R. Lazarenko: «Inversion of the Erosion of metals and measures against contact devastation.» Thesis, All-Union Electrotechnical Institute WEI; Moscow University / 1st publication 1944 in Russian [1] (1993 Facsimile, title page above)

Fig. 1: Start of precise ED-Machining

For the practical application of this idea, the Lazarenko couple developed and patented immediately an apparatus, see Fig.2, center. (SU-Patent 70010 / Priority 3.4.1943). As the Soviet Union was not member of the "Paris Patent Convention", the priority could not be maintained after the war in western countries because pre-published. Exception is GB for the rule of "insular novelty". The main driver for the application of EDM was the request to machine hard or hardened material and the demand for increasingly intricate part geometries. Fig. 2 (left side) gives some examples and shows further a sketch from the British patent of the original Lazarenko apparatus. The right side shows an machining apparatus invented by Dagobert W. Rudorff, later founder of Sparcatron Co. in Gloucester/UK, after ELOX in the US the second EDM-manufacturer in the western area. His patent is the first proposal to use wire electrodes for cutting selectable geometries by EDM.

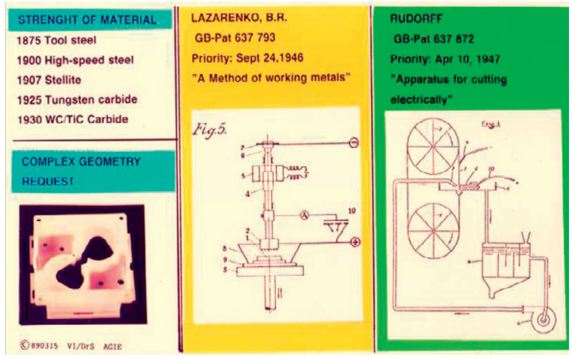


Fig. 2: Drivers for precise EDM and first patents

The late years of the forties after the disastrous war did not allow quick development of machinery but research on EDM started around the globe, predominantly in Russia. B.N. Solotych as assistant engineer with the Lazarenko's made the first systematic analysis and founded the theory of discharge ignition through cold emission of electrons by the high field-strength at surface peaks, narrowing the closest to the counter-electrode, published in [2] and there explained with sketch 14. (see Fig. 3).

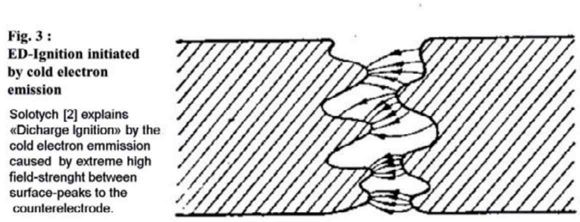


Fig. 3: ED ignition initiated by cold electron emission

Also effects from emission of gasses by the surface peaks, as observed by Kohlschütter[4], are taken in consideration. Solotych wrote the first general description on ED-Machining, published in Russia in 1952 [2]. The years of the fifties than became worldwide the pioneer-phase to transmit ED-Machining to practical application from laboratory to the workshop.

As what can be read from booming literature the researchers engaged on many fields: the physics of electrical discharges first, the metal removal process, the control of the gap during machining, thermal effects to the electrode materials. Russia and the socialist partners tried to stay ahead of the developments (Fig. 4 and 5), running theoretical research at many institutions.

During this period the socialist countries were in front of the market and many young researchers studied in Moscow, than coming home to develop the new technology in their home country. One example is Dr. Stanek from Czechoslovakia, who started EDM at VUMA in Novè Mesto nad Vahom but initiated also the ISEM Conferences in 1960 (First event in Prague).

Fig.4: Pioneers of the 50ties in socialist countries

The generator circuitry was quickly changed from RC-circuits to different combinations of RCL-circuits, thus increasing discharge rate and machining efficiency but risking imprecision, because the inductances resulted in wider variation of the peak-tension at the capacitor and this influences discharge energy and discharge gap. The Americans "invented" many circuitries either for the generation of proper discharges or process controllers. Colt Industries used their strong position for pressure on competition.

The ENIMS Research Institute in Moscow, in cooperation with a Machine-Tool Design Institute and a Generator Development Group (ZNIL-Elektrom), developed machinery, technology, accessories and electrode materials. Director of the EDM group, Prof. Livshiz, also published in 1957 a good survey on different variants of electro-machining and especially for EDM the early developments and applications [3]. As shown in Fig.5 at the right side, also cutting with wire electrodes was commonly in use. The machine basement shown in the original version is a precise Leitz measurement machine in cheek-rooms.

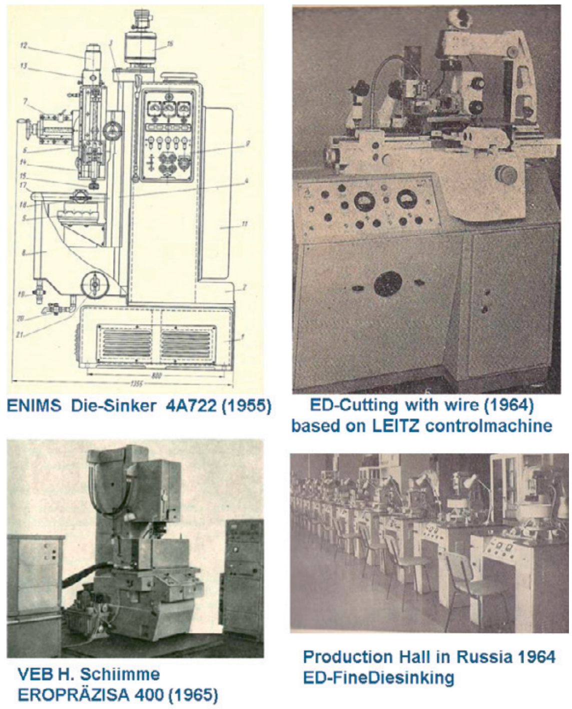


Fig.5: Machinery in socialist countries

The contour to be cut is read from a drawing and generated through XY hand wheels, with help of motors if parallel to X or Y axis. Later in use came an electric copying device from a template in size 1:1. Both methods were not very successful in economy and precision.

The next figures 6 and 7 describe the growing engagement of USA/GB and ASIA.

USA and Great Britain after the end of war had the best conditions to force innovation and to develop new manufacturing technologies. ELOX gained a dominating role in the market: in workshops "EDM-ing" became sometimes also named "ELOX-ing". The request for better control of the discharge cycle (on-time; on/off ratio) lead, other than in Russia, to the development of generator circuitry with radio tube switches. The important inductances and high open-voltage request of these components, besides heavy losses for cathode-heating, limited the success in the market. The high voltage caused wide discharge gaps and corner wear.

In 1954 the well experienced machine tool builders in the west European area restarted market presence by the 1st European Machine Tool Exhibition in Milano/Italy. Mr. Marc Bruma from France in a parallel conference presented a lecture on ED-machining and Sparcatron, AGIE and Charmilles presented newly developed machinery. Their novelties gained wide interest. Several research initiatives were taken. New competitors prepared market appearance (Cincinnati;

Wickman, also cooperating with ONA; Qualtex-Dunod; Languepin; AGEMA/AGEMAspark; AEG-Elotherm; Krupp-Nassovia; Fritz Düsseldorf; Dieter Hansen (Japanese manufacturers however came in only later during the 60ties.) while the applicants looked to make use of the EDM process advantages: machining independent of workpiece hardness, movement flexibility in any direction, sinking, cutting, grinding applications, machining in undercuts and eroding hole-structures like a worm through solid blocks. The fresh developed machines did not fulfill immediately all desires of the applicants and the generators circuitry looked like laboratory mock-ups. “The AGITRON” worked with a pneumatic servo cylinder, lifting the work tank and machining the part up against the fixed electrode.

Fig.6: Pioneers of the 50ties in USA and GB

Western Europe, to regain their traditional markets, started intensive research and also research cooperations.

(Fig. 8). The CIRP (Collège International de Recherche de Production / today “The International Academy for Production Engineering”) was founded in 1951 and started early in the sixtees also a scientific technical committee for Electro-machining (STC-E).

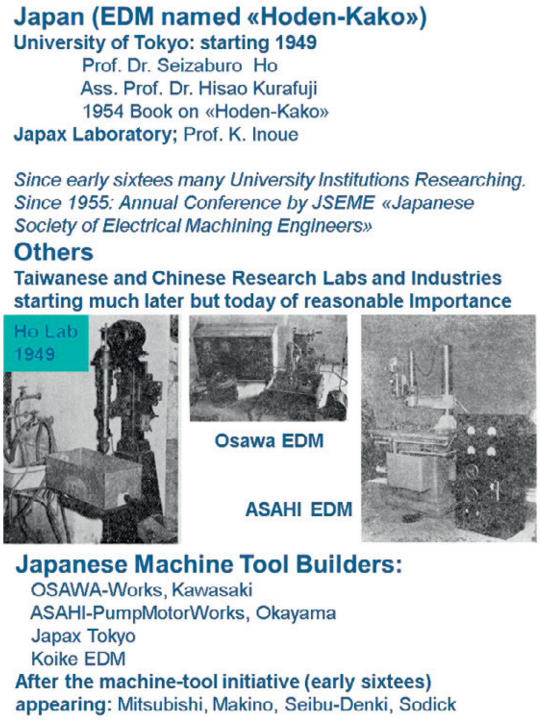


Fig.7: Pioneers of the 50ties Eastern Asia

3. The revolutionary Sixties and Seventies

Three important scientific developments of the sixties gave important push to EDM. In 1959 Hoerni and Noyce invented the **Planar Transistor.** This development created the base for **Integrated Circuit Technology**. Static pulse generators for EDM became reality. In 1965 Digital Equipment realized, based on integrated circuits, the first Process Computer, opening unexpected efficient development of compact machines and servo controllers as also program devices. In 1971 finally the Company Intel presented the first **Microprocessor**, a revolutionary help to develop numerical controls and programming methods for the working sequence of a machine.

The socialist countries did not immediately have access to such developments and this caused for them a big backstroke to participation in the international machine tool market. Their role became taken over by Japanese manufacturers in the sixties, on their way to change from heavy industries to specialized fine mechanics and electronics. Mitsubishi, Fanuc, Sodick and Seibu Denki entered the competition.

Fig. 8: Pioneers of the fifties in western Europe

AGIE and CHARMILLES from Switzerland were the first to equip static pulse generators to their machines with important advancement in higher machining rates, less wear and better precision, resulting from the reduction in open circuit voltage (70–100 Volts) and a reduced gap width.

The demand to improved servo control of the gap became partially compensated by the increased amount of debris, resulting from higher stock removal rates. The duty factor (with RCL-type generators less than 20%; end of discharge by relaxation) under roughing conditions could be increased up to 99%, depending however on the electrode materials. Motor generators (Fig.9) don't offer this possibility of flexible duty factor adaptation. Graphite proved to be an excellent tool electrode material, offering also the advantage of easy machinability by high-speed cutting, having however the disadvantage to be black and dirty.

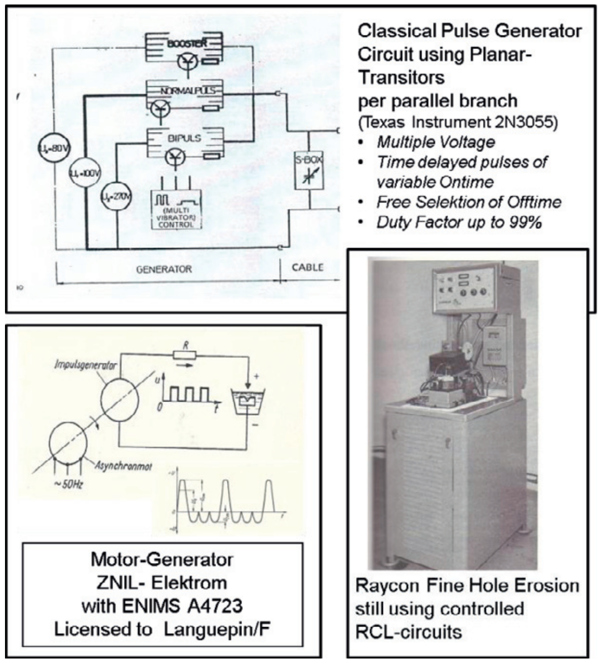


Fig. 9: Generator Circuit alternatives

Attempts to mold shaped tool electrodes from graphite by Fordath in England as by the US 3M-Company failed. For large applications sheet metal copper electrodes were developed by electro-chemical deposition, by shockwave forming or hydroforming, needing however complex backside support structures.

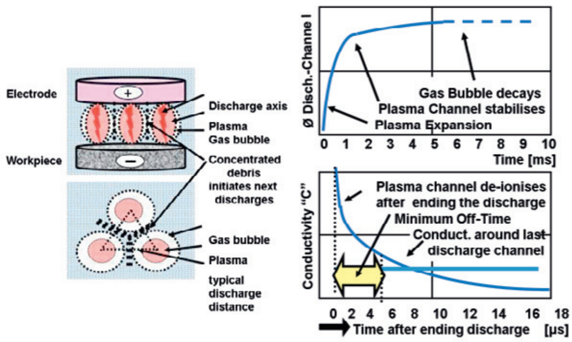


Fig. 10: Explanation of ED-ignition by particle bridges

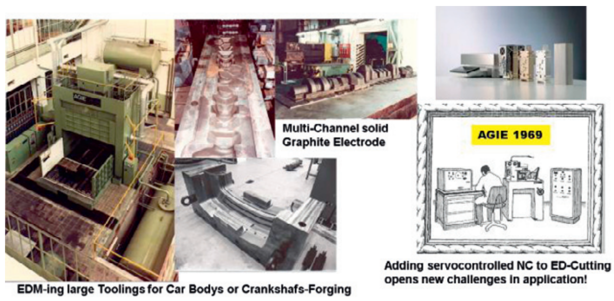


Fig. 11: New transistor and processor elements widen the field of application

Experiments with static pulse generators by Schumacher and high-speed film registration of discharges confirmed however a suggestion given by H. Müller [5,6,7]. There is evidence that the ignition of discharges starts by evaporation of a small particle bridge in the dirty gap (Fig.10). This is a similar proceeding like applied with "explosive wire" in shockwave forming. Many effects can be observed to support this theory: debris plays a high role for spark ignition and ignition can be eased by adding graphite powder, while sparking is difficult on the other hand when starting in clean filtered liquid. A minimum current has to be offered from the generator. Full power can only be applied, if the inter-electrode surface has the size of 3 cm2. Ignition spots have a characteristic distance, as also already observed by Solotych [14]. The reason is ignition by the higher debris concentration around a former discharge channel.

The static pulse generator advancement forced for a revision of the physical explanation of discharge ignition.

Until today most articles on EDM cite the explanation of Solotych (Fig.3) [2] describing ionization between surface peaks by high field strength, ion and gas emission.

Measurements of E. Kracht (Thesis at WZL Aachen) showed also the clear dependance of gap width on the generator settings. One should also not describe the servo control system as "setting the gap". It is the process, that is controlled by the servo device and the gap width derives from the machining situation (shape; current density, flushing).

Figure 11 shows in some machining examples what became possible with the introduction of the new technologies of the sixties. Today carbody dies and hughe toolings however are produced with high speed cutting, competition that developped in the seventies.

Continuous sophistication in the fields of application kept relaxation circuits alive for fine whole drilling or miniature parts. Also revised machines for "wire-cutting" used for a longer period relaxation-type generators.

The use of wire electrodes was known since the forties but missed an automatic path controller. AGIE presented at the European Machine tool Exhibition in Paris 1969 (with AGIEcut DEM15) a revolutionary new concept for ED-cutting, pushed by the new integrated circuit development. This start opened a great new ED-Machining field with wire tool electrode. (On workshop floor called "wire-cutting". The intention however is to cut workpieces with a wire by ED; the wire may become chipped behind the process). AGIE applied stepping motors to the X and Y axes, driven under servo control. To make this possible, ring memories were used to store the last 200 X-Y-steps of the pre-programmed cutting path, edited from another novelty to ED-cutting: "AGIEmeric" NC-controller. In case of process trouble the motors could servo-controlled step backwards following the cut slot. During the 70ties ED-cutting had a boom and developed quickly to reasonable cutting speeds, to applications for workpiece heights of 1000mm and workpiece sizes of m2. By the introduction of a double XY-slide it became possible, to move the upper and lower wire guide independently, resulting in taper cuts with variable slope corners in iso-radius (important for injection molds) or as conic section (forming tools). The servo-controlled action was applied also to the additional drives, as in iso-radius corners additional triangular surfaces had to be cut, avoiding "free-sparking", which would cause loss of precision, where the wire momentary does not move. The example in Fig. 11 (upper right) shows blocks with intricate meandered cuts, penetrating from several sides. This is to form a weigh beam for Mettler-Toledo laboratory scales.

4. New electronic components and software drivers

New semiconductor elements opened many ways for redesign of servo-control and generator circuitries within the seventies and eighties. To gain efficiency and precision with ED-cutting and ED-sinking [8, 9], the generators, the servo-controllers, the path controllers (NC's) and programming were continuously refined to widen the field of application and flexibility. Also the machinery became optimized with sophisticated drives for the wire electrode using heavy coils of stocked wire for autonomy. Wire guiding heads became also refined and equipped with pivoted wire guiding heads, enabling the flushing jet to follow the wire direction. The request for autonomous long run machining also needed the introduction of tool changers and programming of complete machining sequences (path, process, technological sequence, multi-whole path-sequences, fixing the core-piece when cutting closed loops and so on). Wire machines needed for autonomous operation automatic threading of the wire.

The years of the seventies brought many refinements also for die sinker machines. A support market developed for precise fixtures, for safe dielectric liquids, for effective filter devices, for supplies of pre-machined electrodes, for program preparation and so on.

Software became the new key development area for new functions. The appearance of powerful microprocessors enabled thyristor or transistor servo-motor drives with permanent-magnet rotors substituting hydraulic 4-way servo-valve drives, as commonly applied during the sixties. This development helped to introduce servo controlled axis to any slide of the machine, thus offering new applications in three-dimensional shapes, new challenges also to the engineers. The cost-driven request from the market, to enable the use of only one tool-electrode for rough and finish machining, lead to the development of planetary electrode movements, first as accessory device (offered by Herbert-Walter; EROWA, ISTEMA) but then integrated in many alternative combinations with the main axis of die-sinker EDM machines by use of electronic controllers.

An important development request was put on new generators for ED-cutting as well as for ED-sinking. Thermal losses of the power circuits were too high and switching mode power supplies became introduced. At the same time better "slope control" of the discharge-current pulses was introduced, diminishing the tool electrode wear rate and optimizing the metal removal rate. In the same attempt some competitors introduced selection algorithm for technological setting from a parameter memory.

A separate development area was introduced either for "Die-sinkers" as for "Wire-cutters" to gain adaptive self controlling of the discharge process by systematic analyses of the discharge parameters. Electrical discharge machining from its beginning offered good possibilities to sense process parameters during machining, as the full electric circuitry could be surveyed "on line" [11]. Process monitoring was implemented by sensing (at frequencies over 10 MHz) gap voltage and current, ignition delay time and ignition voltage, current/voltage rise and drop rate, voltage noise level, etc., and by defining several discharge categories that could be combined to represent objective functions like process efficiency, material removal or tool wear rates. A collaborative working group within CIRP resulted in guidelines (VDI and others) describing several discharge categories: Short-circuit, Low-voltage Ignition, Full-voltage-Ignition, Delayed-Ignition with variable delay, No-Ignition. In the 1970ties, the same working group laid the basis for advanced EDM process monitoring equipment (Philips, KU Leuven, RWTH Aachen, EDM equipment developers) that allowed to introduce "self-optimization" of the EDM process [10]. This evolution was supported by the already described new possibilities offered by data processing through "information technologies". Adaptive process control (AC, ACC-constraint, ACO-optimizing) was ideally possible with EDM as the difference between servo-drive-response in several milliseconds and the applied discharge frequency in the range from 10 kilohertz to 300 kilohertz allows detailed analysis of rather long discharge chains to characterize the process situation and its trends. Since then AC became common technology for EDM machines [10], whereas it remains exotic for other manufacturing equipment. It gradually expanded from sinking EDM, to planetary EDM, wire cutting EDM (including pulse location sensing) and milling EDM [12], including micro-milling EDM. Novel control techniques like expert systems, artificial neural networks and fuzzy control came to complement ACC and ACO systems [13].

5. EDM in the automatic factory

Running production facilities 7 days per week and for 24 hours is the new target to gain cost advantages, to manufacture and deliver "Just on Time" without buffer in stock, to offer shortest delivery deadlines. This all asks for comprehensive redesign to optimize efficiency and omit setting times, gain process time. Handling times should be organized parallel to process times.

Ambient respect is another important issue on the way, to integrate ED-machining completely with traditional equipment in line on the workshop floor. The use of inflammable liquids, the emission of electromagnetic radiation and expulsion of toxic gasses and all other safety regulations need respect. As a consequence a lot of additional sensors were installed and surveying software has to be added. Generally in modern installations the amount of software development becomes important. (Fig. 12)

REVOLUTION for CONTROLS Process (Servo), MachineTool Movement, Job Sequence, Planning			
Decade:	70ties	80ties	90ties
Applied to:	Machine	Mach.-Cell	Manuf.System
Paradigm:	Optimised Process	Utilisation Maximum	Factory Integration
Softwareportion: primary Target:	5% Economy	25% Economy + Autonomy	50% Econ.+Autonomy + Integration

Fig.12: Increasing importance of software development

6. Concluding remarks

The future factory is not a "**Mega-Machine**" but has to become structured as an intelligent Man/Machine-System. A minimum of interfaces will be helpful for best flexibility. Innovation in factory structures will ever more be analyzed for its sustainable value and environmental quality, but sustainability is not valid if there is no competitiveness.

Diminishing resources, intelligent design, energy-savings, re-use and re-cycling facilities are some of the challenges that keep equipment developers demanded. Especially the energetic un-efficiency of electrical machining processes, EDM at the front-end, request generator circuitries of a completely new layout.

On the other hand, the characteristic advantages of EDM in autonomous machining of complex forms and in independency from workpiece hardness will keep this process in front.

7. References

[1] B.R. and N.J. Lazarenko, 1944, *"Electrical Erosion of Metals"* in Russian: Gosenergoisdat Leningrad, 27 pages; 7 figures.

[2] B.N. Solotych, 1952, "Physical Fundamentals of electrical Spark Machining of Metals" Original in Russian; German Edition 1955 by VEB Verlag Technik, Berlin, 90 pages, 50 figures.

[3] A.L. Livshiz, 1957, "Electroerosive machining Metals" in Russian, German Edition 1959 by VEB Verlag Technik, Berlin, 145 pages, 62 figures; 7 charts.

[4] K. Kohlschütter, 1919, in German: "Studying Electrolytic Discharges to understand Electrical Colloid-Synthesis", Zeitschrift für Elektrochemie 1.10.1919 Vol.25 Nr. pp. 309-344.

[5] H. Müller, 1965, in German: "Contribution to clarify the process of Electrical Discharges", Zeitschrift Elektrowärme. Vol 23 Nr.3.

[6] B.M. Schumacher, 1966, in German: "Metalremoval Characteristic and Tool Wear when Electrical Discharge Machining by use of Relaxation- or Static Pulse Generators. PhD thesis at RWTH Aachen Machine Tool Laboratory WZL.

[7] B.M. Schumacher, 1990, "About the role of debris in the gap during EDM", Annals of CIRP, 39/1/1990.

[8] R. Krampitz; D. Heymann, 1975 (in German): "Level and Trends in sparkerosive machining of metals", ELEKTRIE /Berlin-East, 29(1975) Nr.9 pages 487–490.

[9] B.M. Schumacher; D. Weckerle, 1988 (in German), "EDM – right understanding and application", Technischer Fachverlag Velbert ISBN: 3-9801934-0-3.

[10] R. Snoeys, D. Dauw, J.P. Kruth, 1983, "Survey of adaptive control in electro-discharge machining", Journal of Manufacturing Systems 2(2) 1983, p147-164.

[11] J.P. Kruth, 1995, Chapter 5: "Automatic supervision in physical and chemical machining", in book: <Automatic supervision in manufacturing> (M .Szafarczyk, ed.) Springer Verlag, Series in Advanced Manufacturing, ISBN 3-540-19858-X, pp83-117.

[12] Ph. Bleys, J.P. Kruth, B. Lauwers: 2004 "Sensing and compensation of tool wear in milling EDM", Proceedings ISEM XIV, Edinburgh.

[13] J.P. Kruth, B. Van Coppenolle, 1995, , "New trends in automatic control of electro-discharge machining", Keynote, 16p, Proceedings of 4th Conf. on Monitoring and Automatic Supervision in Manufacturing (AC'95), Warsawa

[14] B.N.Solotych (in Russian),"Importance of individual craters upon quality of spark machined surfaces". Vestnik Masinostroenja 39(1959)Nr. 10 pp 58-61.