Philips tech. Rev. 40, 199-203, 1982, No. 7

Three special applications of the Philips high-speed spark-machining equipment

J. L. C. Wijers

For some years the practical potentialities of 'spark erosion' have been the subject of extensive investigations at Philips. The article below gives some instances of this activity and shows that high-speed (micro)spark machining promises to develop into an advanced general-purpose machining technology. The examples given have been chosen to illustrate what can be done with a single relatively simple type of spark-erosion machine. The high-speed spark-machining equipment designed and built at the Research Laboratories — and the result of the combined effort of many people — draws attention once again to the advantages of efficiency and economy that can be achieved with a new general-purpose workshop technology.

Spark erosion

Towards the end of the sixties the first machines were developed at Philips Research Laboratories for machining materials by high-speed (micro)spark erosion. The principle of this workshop technology — the melting or vaporization of workpiece particles in a localized spark discharge and removal of the eroded material by flushing it away with a dielectric fluid — is now generally known; the spark discharge takes place between a moving electrode and the workpiece itself, which acts as the second electrode. The method has been described in detail in an earlier article in this journal [1]. Since then all kinds of machining problems of a rather experimental nature, originating from widely divergent areas of research and engineering, have been regularly tackled with our high-speed spark-erosion equipment and usually brought to a satisfactory conclusion. In this way our laboratories have gained a wealth of experience with spark machining, or 'sparking' as we often call it in the machine shop, as a method of machining materials. The method has been particularly useful for 'internal' work, i.e. for making cavities, channels or other recesses inside a block of material.

The 'tool electrode', which produces a 'negative' copy of itself in the material by spark erosion, is made by an *external* operation on the electrode material. Conventional workshop methods such as turning, milling and grinding are generally more suitable for external work than for internal work. Blind holes in particular give many problems when conventional methods are used. Spark machining provides a 'translation' from a relatively easily made external shape to a difficult internal shape.

Spark machining is often the only way of making shapes with accurate rectangular corners, without significant rounding. Another important advantage of spark machining is that there is no direct contact between the tool and the workpiece, so that no mechanical stresses are introduced. It is almost impossible to machine single-crystal aluminium, for example, in any other way without the danger of it becoming polycrystalline.

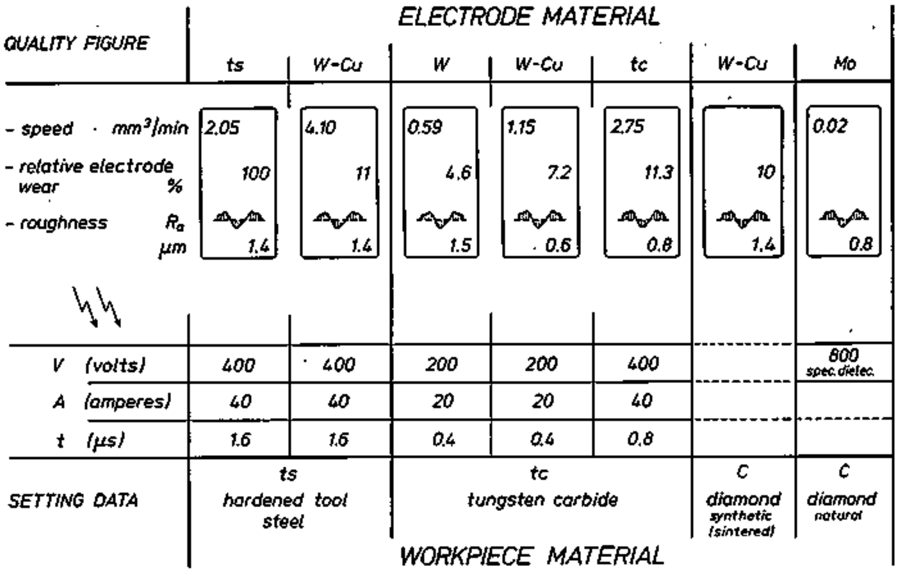
Fig. 1 gives an idea of what can be achieved with high-speed microspark machining, from data relating to the quality of seven combinations of workpiece and electrode materials now widely employed. 'High-speed' implies the removal of material in quantities of a few cubic millimetres per minute. At these rates a

---

Ing. J. L. C. Wijers is with Philips Research Laboratories, Eindhoven.

[1] C. van Osenbruggen, High-precision spark machining, Philips tech. Rev. 30, 195-208, 1969.

surface roughness of less than 1 µm can be achieved [2]. The exact values depend on the particular combination of materials. *Table I* and the photographs present some typical features of the machine used. In the design of this new high-speed spark machine the experience gained in the last few years has of course been used to the full in making the optimum compromise between machining rate and machining accuracy. Working with the machine has strengthened our view that microspark machining can be developed into a general-purpose method of metal machining.



QUALITY FIGURE	ELECTRODE MATERIAL						
	ts	W-Cu	W	W-Cu	tc	W-Cu	Mo
- speed mm^3/min	2.05	4.10	0.59	1.15	2.75		0.02
- relative electrode wear %	100	11	4.6	7.2	11.3	10	
- roughness R_a µm	1.4	1.4	1.5	0.6	0.8	1.4	0.8
V (volts)	400	400	200	200	400		800 spec. dielec.
A (amperes)	40	40	20	20	40		
t (µs)	1.6	1.6	0.4	0.4	0.8		
SETTING DATA	ts hardened tool steel		tc tungsten carbide			C diamond synthetic (sintered)	C diamond natural
	WORKPIECE MATERIAL						

Fig. 1. Seven suitable combinations of workpiece and electrode materials for use with the machine described in Table I. Each box gives the quality figures achieved. The figure in the top left-hand corner of a box gives the erosion rate in mm^3/min, i.e. the rate at which the workpiece material can be sparked away; the figure at the lower right is the surface roughness in µm; the figure in the middle is the relative electrode wear as a percentage, i.e. the loss of electrode material as a percentage of the loss of workpiece material. Also given are the machine setting data V, A and t: these are the no-load generator voltage, the r.m.s. pulse current, and the pulse duration, respectively. In addition to the combinations of workpiece and electrode materials given here, there are of course others that also yield good results, e.g. the tool steel mentioned here with electrolytic copper, and tantalum with tungsten.

This article will demonstrate some of the accomplishments of our highly skilled 'master-of-all-trades' by discussing two widely different workpieces and one rather unusual machining problem. The section that follows deals with the machining of a 'bonding bit' for joining together extremely small parts (0.01 mm) by thermocompression bonding. Next it is shown how spheres of single-crystal aluminium were made for certain material investigations. The final section deals with the machining of diamond for tools.

Miniature bits for thermocompression bonding

The manufacture of the IC bonding bit to the design shown in *fig. 2* is our first example here of high-speed spark machining successfully applied to a machining problem that would have been most difficult with conventional methods. This miniature tool — it is less than 2 mm long — is used for thermocompression bonding the electrical connections of an individual monolithic integrated circuit (IC). High-precision bonding with these bits is of course also intended to facilitate the automation of the assembly of ICs in their electronic 'environment'.

Integrated circuits, especially those for signals at very high frequencies, have little mechanical strength, and therefore it is much too risky to make connections by soldering or thermocompression bonding on the circuit itself. For external connections these ICs have a number of projecting gold strips ('beams', about 0.5 mm long, 50 µm wide and 10 µm thick), and an IC bonding bit can be used for joining the ends of the beams to the contact pins of the adjoining circuits — thus avoiding all danger of damaging the IC itself. The bonding edge (E in fig. 2), which is only 35 µm thick, forms a square into which the IC fits comfortably. When the bonding bit is moved this edge presses the ends of the beams accurately on to the contact pins. A brief application of pressure on the edge (about 0.4 N), with a local temperature increase of 400 °C, results in a firm bond between beams and pins.

Making a miniature tool of this type is an unusual problem if only because of the extremely small dimensions. Workpieces measuring about 1 mm are very difficult to set up and machine when conventional methods such as drilling or milling are used. While the bit is being machined, a pressure only slightly greater than it will encounter in thermocompression bonding could permanently damage its bonding edge, which is weak because of its small thickness and relatively large height. What is more, the inside surface of the workpiece requires a great deal of machining (fig. 2) to produce the sharp, rectangular transitions. Spark machining was the obvious method here.

In making the tool we started with small steel balls, as used in bearings. The steel of these balls readily meets a number of the requirements usually necessary for bonding bits. The accurately spherical shape and the smoothness are added advantages, since part of the surface can be used as the upper face of the bit without further machining. The spherical shape and smoothness permit a measure of self-alignment, automatically stabilizing the vertical position of a bit when pressure is applied during the bonding.

Table I. Some typical data for the Philips high-speed spark-machining equipment (upper photograph). This machine was designed and built in our own laboratories; it differs from the 'die-sinking' type commercially available mainly in having a smaller active electrode surface, a shorter pulse duration, a higher spark frequency and in the use of deionized water as the dielectric fluid and flushing agent. The lower photograph shows a later model of the electrode head of the machine with servo control and spark generator type EDM 81. Quality figures and machine-setting data are shown in fig. 1.

Spark capacity (sinking [a], wire sparking [b], rotary sparking, screw-cutting, copying)	max. 200 mm (x) max. 160 mm (y) max. 240 mm (z)
Clamping area	430 mm × 215 mm
Active area (electrode)	max. 80 mm^2 min. about 0.01 mm^2
Generator voltage (no load)	200, 300, 400, 800 [c] V
Pulse current (r.m.s.)	4, 20, 40 A
Pulse duration	0.2-3.2 μs
Repetition rate	2-250 kHz
Polarity	workpiece positive
Dielectric fluid	H_2O, deionized, conductivity 1 mS m^{-1}
Electrode servomechanism	electromechanical (stepping motor)
Smallest displacement	$\frac{1}{2}$ step = 0.625 μm

[a] In the 'die-sinking' process the electrode moves vertically (in the z-direction) and 'sinks' into the workpiece.

[b] In 'wire sparking' the electrode is a thin metal wire stretched over two guide rollers. While it is sparking the wire 'saws' through the workpiece and at the same time moves over the rollers (so that the electrode is continuously replenished).

[c] This value is only attainable if a special transformer is used.

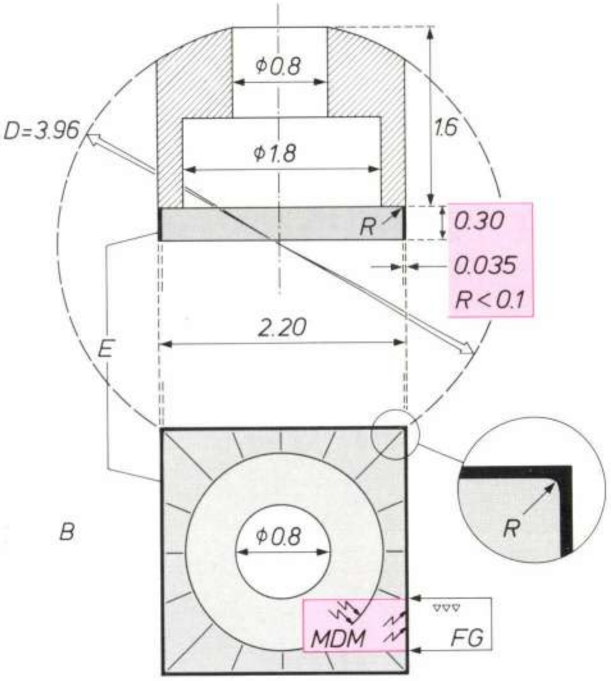


Fig. 2. Dimensional drawing (vertical section, *B* view from below; measurements in mm) of an IC bonding bit. *E* bonding edge, height 0.30 mm and width 0.035 mm. *R* radius of curvature of the right angles formed by *E*. This miniature tool was made from a steel bearing-ball of diameter *D*. Because of the great deal of internal work, the nearly rectangular corners, and above all the two small dimensions of the bonding edge, microspark machining (sometimes called microdischarge machining, *MDM*) is the only suitable machining technique. The outer face of *E* is ground (*FG*). The total machining time is about 25 minutes.

---

[2] The roughness values given in this article are R_a-values, which are usually about a quarter of the corresponding R_{max}-values (peak-to-valley). A definition of these values will be found in the 'Tool Engineers Handbook' (ASTE), McGraw-Hill, New York 1959, and in the provisional standard ISO/DIS 468 (1980).

Aluminium test spheres

The second manufacturing problem we shall look at here is spark machining of spheres from a rod of single-crystal aluminium. This problem was encountered at the Research Laboratories when it was necessary to find out whether the result of a particular electroplating process depended on the crystallographic orientation of the aluminium used. Small spherical samples were required for the investigation. We started with cylindrical rods of the material made in our laboratories, each rod consisting of a single crystal of aluminium. The sparking hardly affected the single-crystal nature of the material [3].

Fig. 3 illustrates how we solved the problem of machining the rod to leave a small sphere with a stem. The original rod, fixed in a holder that can rotate about its axis, acts as a rotary anode. The speed of rotation is about 50 revolutions per minute. The axis of rotation has a fixed position in the horizontal plane. The cathode is a tube with a groove cut into one side, and can be displaced vertically. (The width of the groove determines the final diameter of the stem.) The servomechanism of the machine ensures that the sparking edge of the cathode always remains at the same distance from the anode. The rotation of the rod ensures that its entire circumference is exposed to the sparking.

The combined fast rotation of the rod and the slow vertical movement of the cathode eventually leaves a perfect sphere. The entire process takes only an hour. The diameter of the sphere is approximately 0.1 mm smaller than the inside diameter of the cathode, and its roughness is about 1 μm. The wear of the cathode does not adversely affect the dimensional accuracy, provided that the cathode is *long* enough; the active length of the cathode should be greater than is necessary for sparking the complete sphere.

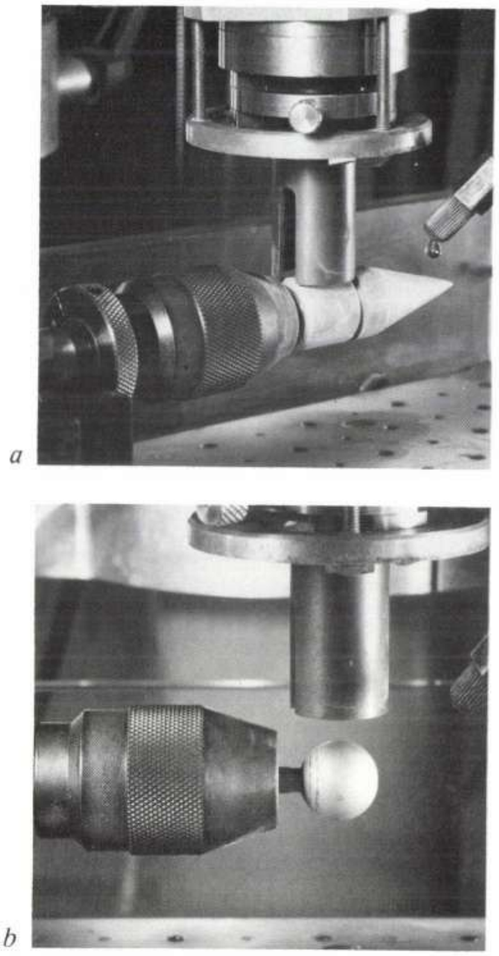


Fig. 3. Making aluminium test spheres (diameter about 17 mm) by rotary sparking. The spheres are formed from a rod of single-crystal aluminium. The electrode has a groove cut in it, so that the test sphere finishes up at the end of a stem. *a*) Intermediate stage. Sparking produces no significant stresses in the material, which therefore remains of a single-crystal nature. *b*) The final situation.

Spark machining of diamond

The idea of machining diamond, the hardest known material, by spark erosion looks at first sight unrealistic. With the exception of a very rare semiconducting variety, diamond is an excellent insulator. However, it is in fact suitable for spark machining, but ingenuity is necessary. A thin coating of adhesive containing powdered silver is applied to the surface of the diamond. The silver makes the coating conduct electrically, and the spark-machining process can be started. When the coating has been eroded away the process does not stop, but continues. The theory of this effect is that after the removal of the top layer the very high temperature (a few thousand kelvins) in the discharge channel continuously converts the newly exposed material into a graphitic form — which is a good conductor.

Another method for starting the spark-machining process is to heat the diamond material in a carbon-rich atmosphere to a temperature high enough (about 1100 K) to produce a sufficiently conducting graphitic structure on the surface.

If the spark machining of a diamond and the removal of the eroded material from the discharge gap are to proceed in a stable manner, it is important to use the correct dielectric fluid (the 'sparking fluid') in the gap between electrode and workpiece. A concentrated aqueous solution of sodium hydroxide in paraffin (kerosene) with certain additives proves satisfactory. The no-load voltage of the spark generator should be at least 800 V to produce spark pulses, of about 1 μs duration, that have sufficient energy.

The knowledge that diamond can be spark machined — and with great accuracy — has meanwhile acquired considerable technological significance. At Philips tools are now widely used in which an extremely accurately dimensioned natural or synthetic diamond determines the quality of the work. Familiar examples are diamond-tipped tools for machining optical surfaces [4] and cutters for producing smooth fractures in optical glass fibres [5]. Diamond is also widely used for wire drawing. Instead of natural diamond the material now chosen for the actual drawing die (*fig. 4*) is often a composite of a metal alloy containing a polycrystalline form of synthetic diamond.

Making a diamond-tipped precision tool [4] by conventional methods is an exceptionally laborious and highly specialized job, largely because of all the grinding, and can take at least 50 hours. The high precision that has now been reached in the application of high-speed spark machining is such that the total machining time can be considerably curtailed; at present grinding is necessary only in special cases as a finishing operation. In this way it takes only a few hours to make the complete tool — only about a tenth of the time previously necessary.

A diamond of 1 to 3 carats is used for a precision tool. A chip about 1 mm thick is 'sawn' by spark machining: the electrode is a molybdenum wire of diameter 0.2 mm. The flat chip thus obtained is brazed to the shank of the tool at a temperature of 1300 K. The desired shape of the cutting edge (and of the flank) is obtained by copying a standard shape, again by spark machining with a wire electrode; this takes about 30 minutes. The resultant surface is finished with a polishing operation. For minimum wear of the tool the primary face of the chip, its top surface, should have the same orientation as one of the crystal planes of its cubic crystalline structure, within a tolerance of a few degrees. This orientation is determined beforehand by X-ray diffraction.

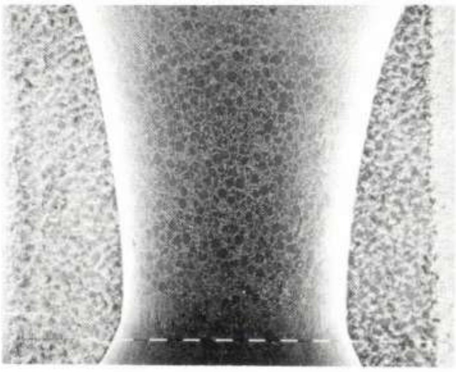


Fig. 4. Photomicrograph of a cross-section of a diamond die. The bell-shaped channel, designed for drawing wire of diameter 1.3 mm, is produced by means of a sparking process. The diamond is a polycrystalline synthetic product. Each dimensional step is 100 μm. The die was sawn through — by wire sparking — to enable roughness measurements to be made and to give a better view. The picture was made with a scanning electron microscope (SEM).

The high-speed spark machine shown in the photograph above Table I can also be useful for 'conditioning' grinding wheels that have lost some of their abrasive power, especially wheels in which the diamond grains that serve as grinding material are contained in a layer of metal, e.g. bronze. The conditioning is sometimes done in two stages. Here the high-speed machine is ideally suited for the second stage, the finer finish. The design of the machine, with removable electrode head, offers the added advantage that the grinding wheel does not have to be taken out of the grinding machine, so that the rotational accuracy of the disc is more easily preserved. In such situations the dielectric fluid is simply sprayed between the electrode and the grinding wheel.

Summary. Three practical cases are described to illustrate the usefulness of high-speed (micro)spark machining as a general-purpose workshop technology. They are the manufacture of a bonding bit for connecting up individual ICs by thermocompression, the manufacture of single-crystal aluminium spheres from a rod of the same material for investigating electroplating behaviour, and the machining of diamond for tools. The high-speed spark-machining equipment built at our laboratories for such machining and manufacturing problems and its principal features are briefly described. The machining rate is a few mm^3 per minute, the attainable surface roughness (R_a) is less than 1 μm. Diamond can be spark-machined after providing it with a conductive layer. With an appropriate spark-generator voltage and dielectric fluid, spark erosion continues after the conductive layer has been eroded away. The machine can also be used for conditioning diamond grinding wheels.

---

[3] In the electroplating process no dependence on the crystallographic orientation of the aluminium was found.

[4] T. G. Gijsbers, COLATH, a numerically controlled lathe for very high precision, Philips tech. Rev. 39, 229-244, 1980.
J. M. Oomen of these laboratories has made a substantial contribution to the further development of the method of manufacturing diamond-tipped precision tools.

[5] A neat illustration of the smooth fracture of a glass fibre accurately perpendicular to its axis by a rotating diamond cutter can be found in Philips tech. Rev. 39, 245, 1980.