Review of cooperative work on EDM in STCE of the CIRP

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1. Introduction

Cooperative research in the field of non-conventional machining processes is the responsibility of the Scientific Technical Committee E on Physical and Chemical machining of CIRP. The research on Electro-Discharge Machining (EDM) is one of the main activities of the Committee.

In a previous paper presented to CIRP [1] the history of cooperative work on EDM has been reviewed. A few lines from this paper may be cited as an introduction to the present review of this cooperative work.

In 1964 Professor Opitz proposed a programme for cooperative research on EDM, to be carried out in four sequential steps:

1. To agree on which parameters influence the process and to define these parameters.
2. To draw up the general research programme.
3. To carry out standard test programmes in order to obtain comparative results. A uniform standard procedure would be necessary to carry out the next step correctly.
4. The final research programme in which the participants would each carry out a part.

Steps 1 and 2 were mainly concerned with planning, and caused little difficulty. However, the results of the first standard tests of step 3 showed considerable divergencies. Although the pulse energy for the tests was decided beforehand, measuring these energies proved to be difficult, especially when relaxation generators were used.

In 1966 more detailed directions were drafted. New tests had to be carried out under more specified conditions, such as the pulse energy levels, pulse shape (rectangular) and pulse durations.

Experiments with relaxation generators were discontinued. During the next period a number of additional directions and proposals for improving measuring techniques became necessary.

In 1968 the results of the participating institutes were examined. The results are considered to show fair agreement, particularly in view of results derived earlier in the co-operative work. During the experiments it proved necessary to standardise (in addition to the above-mentioned parameters) the pulse duration time, polarity of the electrodes, type of flushing (pressure, velocity), and the geometrical configuration of the test electrodes. In order to determine the pulse current and the pulse efficiency, specially designed measuring devices have been developed and used by the participants.

When the first comparative experiments are completed the Committee intends to start step 4 of the Aachener proposal. The original intention was to explore the machining of cemented carbide at the low energy range (10 mJ and below). However, owing to the lack of suitable equipment, co-operative research on this subject was difficult. The tool servo-mechanism plays an important role here. Attention should be paid to this aspect.

Meanwhile a proposal was accepted to draft a test procedure for determining the machinability of workpiece materials with EDM. The aim was to provide guidance for industry in finding the optimum conditions for electro-discharge machining workpieces under certain described conditions.

2. Machinability in EDM

Operation parameters are dictated by the type of work to be carried out in terms of desired geometry of the workpiece, its maximum acceptable roughness and the metal removal rate. These parameters are interrelated, thus changes in one parameter will influence the others. The material parameters comprise these physical constants of the workpiece material which influence the thermal erosion process, and comprise pulse duration and pulse cycle time, pulse current and open generator voltage, polarity of the electrode gap conditions and flushing conditions.

For a given pulse energy the optimum pulse time (i.e. the pulse time for maximum material removal) can be determined. However, maximum material removal at a given energy is not necessarily a unique condition for optimum machining. Although pulse energy is a product of the pulse time, pulse current and voltage, these constituent variables do not individually contribute to metal removal in the straightforward manner implied by a simple product, and hence its practicability is limited. Thus 'erodability numbers' relating material removal simply to pulse energy, while useful in a general way, are insufficiently definitive. 'Better erodability' can be deemed to occur if, for a given surface roughness and relative electrode wear, material removal rate is higher, and similarly for other improved combinations of circumstances.

As with many types of machining, EDM metal removal rate being inversely related to the desired accuracy and roughness, it is necessary to separate the final finishing operation, which will be preceeded by one or more roughing cuts. A rigorous relationship between surface roughness and machining parameters is not yet clear. In theory a relationship between the roughness value and crater geometry can be derived, which in turn is related to metal removal per pulse (V_{wf}).

Tool-electrode wear is related to the accuracy of the machined part, and the maximum allowable relative tool wear can normally be derived from experience of given shapes.

The objective of cooperative research by STCE on the machinability of workpiece materials is to draft directives in order to establish machining nomograms of several workpiece materials uniquely by well defined experiments. For this reason standard tests to be performed by the participants in this research have been developed.

3. The Cooperative Work on the Machinability of Workpiece Materials with EDM

The present review will start with the proposal for the cooperative work originating from the Aachen University and presented to the Committee by the Technical Secretary in January 1970.

A short specification of the test conditions laid down in this proposal reads as follows:

Workpieces: circular rods of die steel 56NiCrMoV7, diameter 10 mm.

Electrodes: copper tubes, outer diameter 12 mm, hole diameter 34 mm.

Both workpiece and electrodes are mounted axially in line so that the working area remains constant during machining.

Flushing: die dielectric fluid is "Bepetan", pumped through the electrode hole into the working gap, pumping pressure 20 kN/mm².

Pulses supplied to the working gap:
rectangularly shaped, energy levels 3 - 10 - 30 - 100 - 300 - 1000 mJ. Open voltage 80 V, duty cycle 50%. Pulse durations are varied as much as possible. Polarity: electrode positive.

The tool servo system is adjusted for maximum relative frequency (maximum number of pulses which cause erosion).

Test performance: At each energy level a number of tests is run whereby the pulse duration is varied.

The duration of each test is 15 minutes.

Results: Mechanical data to be presented:
workpiece material removal rate, electrode wear rate, workpiece removal per discharge, relative electrode wear, roughness (CLA), dielectric flow rate and pumping pressure.
Electrical data: pulse energy, pulse current and pulse voltage (including their average values), open generator voltage, pulse cycle time and pulse duration, duty cycle, pulse frequency and effective pulse frequency, relative frequency.

The equipment to be used in the tests should at least comprise of an oscilloscope for observing the pulse shapes, counting logic for the observation of pulse-frequencies, tool-feed measuring equipment.

In January 1971 the first test results were obtained. From these results and subsequent discussion the following conclusions were drawn:

— The proposed pumping pressure was to high and in itself not relevant for the physical behaviour of the process. A constant dielectric flowrate of 0.2 cm^3/s for low energy settings and 0.5 cm^3/s for the higher energies was considered a better criterion.
— It proved to be difficult to carry out experiments at the specified energy levels. It was decided to perform series of experiments at current levels of 5 - 10 - 20 - 50 A. In each serie the pulse duration should vary between 5 μs and 2 ms.
— "Bepetan" as dielectric fluid was not suitable and not easily to obtain for all participants. The Committee advised to use synthetic dielectric fluid Shell Soll T.D.

Regarding the use of dielectric fluid and the effective pulse frequencies some complementary investigations were carried out by certain participants.

Table 1. Physical properties of dielectric fluids

Fluid	Bepetan	Shellsol T	Shellsol TD
Density (kg/m^3)	770	760	754
Viscosity (cP)	0.85 (20°C)	1.39 (25°C)	1.21 (25°C)
Flash point (°C)	54	53	46
Boiling temp. (°C)	146-194	172-210	165-191

4. Dielectric Fluids for Standardised EDM Tests

An investigation at Louvain (ref. 2) was undertaken to determine a most suitable experimental dielectric, and also to assess the influence of this factor experimentally. Brief details of the three fluids investigated are given in Table 1; "BEPETAN" had been used for the earlier CIRP cooperative tests, and was proved to have some general disadvantages for such purposes. Comparative tests with the three dielectric fluids were conducted under carefully controlled conditions to ensure comparability, at pulse durations of 5, 20, 100 and 500 μs, pulse current values of 10 A and 20 A, and a constant dielectric flow rate of 0,7 cm^3/s. Firstly, a test for repeatability with SHELLSOL TD established, see Table 2, that the confidence interval for workpiece metal removal rate was ±11% of the mean value at a confidence level of 95%, whereas for metal removal per pulse the confidence interval was ±16%. However for the tool-electrode these values were ±89% and ±120% respectively, illustrating the particular difficulty of obtaining reliable and repeatable results for the electrode at low wear ratio (3,5% in this case). By comparison, quite acceptable repeatability of the workpiece removal parameters can be expected.

From an inter-comparison of the results for the three dielectric fluids in terms of the relative differences in their metal removal parameters, the general conclusion can be drawn that the systematic differences are smaller that the expected statistical variations between tests. The choice of a fluid for experimental purposes in collaborative research in EDM can be made on grounds of common convenience for participants in the research programme [2].

Table 2. Repeatability test for SHELLSOL TD

Metal removal parameters	Vw (mm^3/sec)	VE (mm^3/sec)	Vwf (10^{-6} mm^3/pulse)	VEf (10^{-6} mm^3/pulse)
Mean value V	0.1031	0.0037	26.35	0.945
Standard deviation S	0.0040	0.0012	1.52	0.411
Process deviation s/V	3.8%	32%	5.8%	43%
95% confidence interval ±2.78 S/V	±11%	±89%	±16%	±120%

5. Effective Pulse Frequency and Pulse Efficiency

The electrical energy delivered by the generator is confined very locally within the gap enabling a small quantity of metal to be melted or boiled and subsequently removed. The discrete discharges therefore create small craters on the metal surface. With the high sparking frequencies normally used, the erosion results in substantial stock removal rates. Since a relation exists between the surface roughness and the crater geometry, the metal removal per pulse (V_{Wf}) is important. The product of the number of pulses per second which cause erosion (f_f) and the metal removal per pulse should give the metal removal rate Vw, thus

$$V_W = f_f \cdot V_{Wf} \quad .$$

The effective frequency is smaller than or almost equal to the number of pulses per second (f_p) supplied by the electrical generator, due to short circuits, open pulse etc. The ratio of the effective frequency to the (generator) pulse frequency is defined as the relative frequency:

$$\lambda = \frac{f_f}{f_p}$$

In the earliest CIRP comparative tests conducted by the participants in the cooperative experiments, fairly large discrepancies between the results of the participants were apparent. This was due to different values of the relative frequency achieved under the same nominal conditions. Subsequently these conditions (flushing, servo adjustment) were more exactly specified and controlled, and more consistant erosion parameters thus resulted.

Nevertheless the problem of how to define an "effective pulse" arose, viz a pulse which causes the effective erosion. In EDM the pulse supplied to the gap can be distinguished as falling into four categories:

1. pulses which cause effective erosion (effective discharges)
2. open-circuit pulses
3. short-circuit pulses
4. so-called static arcs, generally damaging the electrode surfaces.

In some cases, a combination of two of these categories is possible.

In the case of effective discharges, a pulse from the generator (duration t_i) causes, after a certain ignition delay time (t_d), a discharge to take place. The duration of this (effective) pulse discharge t_f is related to t_i and t_f by the expression:

$$t_f = t_i - t_d$$

The ratio of the discharge duration to the supplied generator pulse duration is defined as the relative discharge duration:

$$\varphi = \frac{t_f}{t_i}$$

and relates to a single pulse. Thus the average relative discharge duration can be defined as

$$\Phi = \frac{\sum^n t_f}{\sum^n t_i} \qquad \text{(n = large number of pulses)}$$

It is clear that the average relative discharge duration exerts a considerable influence upon the machining efficiency. The process (sero, flushing) has to be adjusted in such a way that Φ is maintained at a high value. However, too large a value of Φ implies low values of the ignition delay and thus introduces the risk of forming static ares.

Within the cooperative work of the Committee difficulties arose how to obtain suitable measuring equipment in order to measure Φ. Another problem is still how to define exactly the pulse discharge time t_f.

The question of effective discharge is related to the occurrence of static arcs and of quasi static arcs. The electrical behaviour of the latter is close to that of desired effective discharges, however their metal removal efficiency appears to be rather low. Research in this subject is still going on.

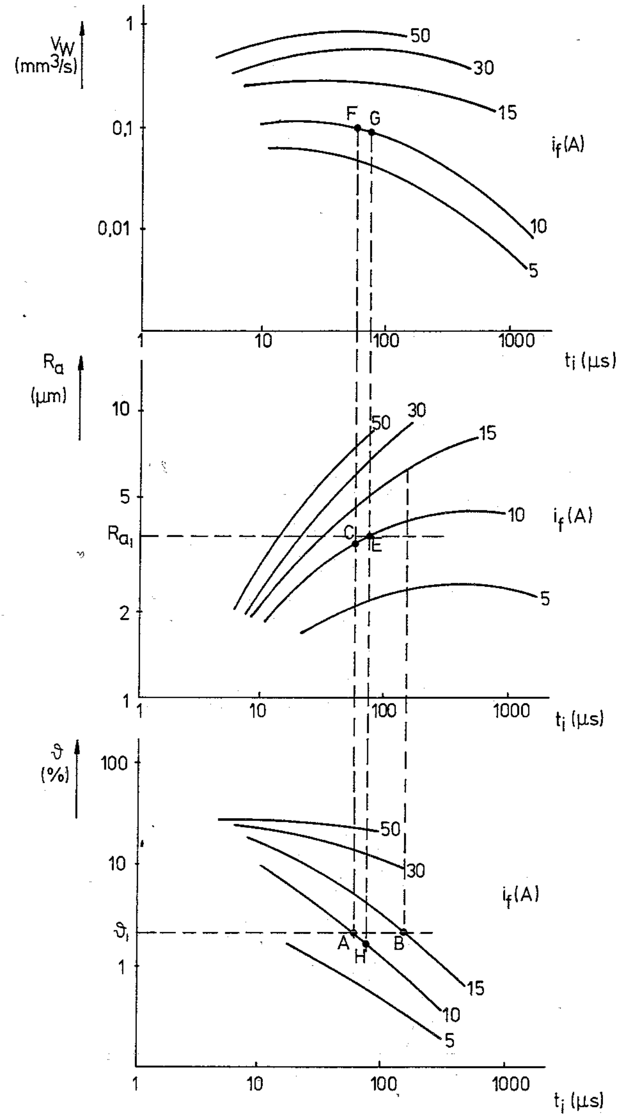

Fig. 1. Machinability nomogram.

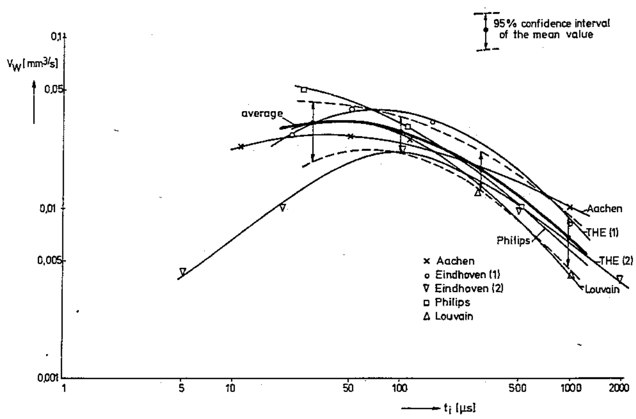

Fig. 2. Results of EDM machinability tests $\bar{i}_f = 5$ A.

6. Results of the cooperative experiments

As mentioned before, in 1971 the first test results were obtained. During the following years more participants joined the four which started the work. In this review the results of 7 participating institutes are presented.

These participants are:

University of Aachen (Mr. König)
University of Delft (Mr. Pekelharing)
University of Eindhoven (Mr. Heuvelman)
University of Krakow (Mr. Kaczmarek)
University of Louvain (Mr. Snoeys)
Centre for Technology of Philips (Mr. ten Horn)
University of Trondheim (Mr. Rasch)

A number of the participants carried out the experiments on more than one machine.

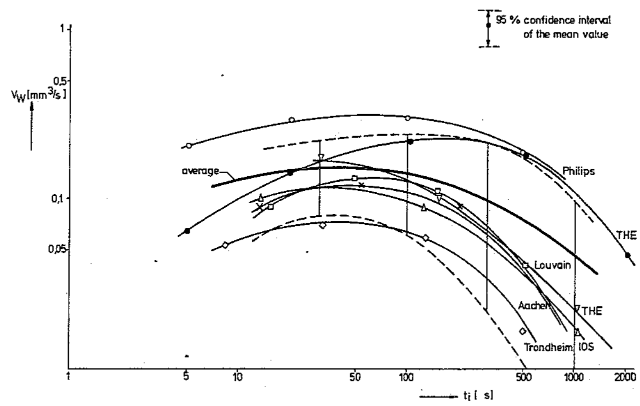

Fig. 3. Results of EDM machinability tests $\bar{i}_f = 10$ A.

At the meeting of the STC "E" in Krakow (1971) it was decided to present the results as a nomogram consisting of three diagrams. (See example in fig. 1). In the diagrams the metal removal rate Vw, the roughness value (R_a) and the relative electrode wear (ϑ) are plotted respectively in a relation to the pulse duration t_i with the pulse current (i_f) as parameter. The diagrams are on logarithmic scales The dotted horizontal and vertical lines give an example of how the diagrams could be used to find machine settings, in this case when the maximum allowable relative tool wear (ϑ) and roughness (R_{a1}) are specified. From the upper diagram the obtainable removal rate (point F) can be read. The nomogram holds for a duty cycle (pulse duration over pulse cycle time) of $\tau = 50\%$.

In figures 2, 3, 4 and 5 the results of the measurements of the metal removal rates of the various institutes are given. Each figure holds for a selected pulse current. In figure 6 the mean values of the test results are given, together with the 95% confidence intervals of these mean values.

This figure shows that the confidence intervals are rather wide. The high values of the confidence intervals can be imputed to the variations in the relative pulse duration φ (ratio of the effective pulse duration and generator pulse duration) which can be caused by the different characteristics and the adjustment of the tool servo system, the contamination of the dielectric fluid, variations of the open-generator voltages and of course by measuring uncertainties.

The participants in the cooperative research carried out measurements of the CLA-roughness values and the relative electrode wear. However, the variations in the results of the measurements are such that direct comparison as was done with

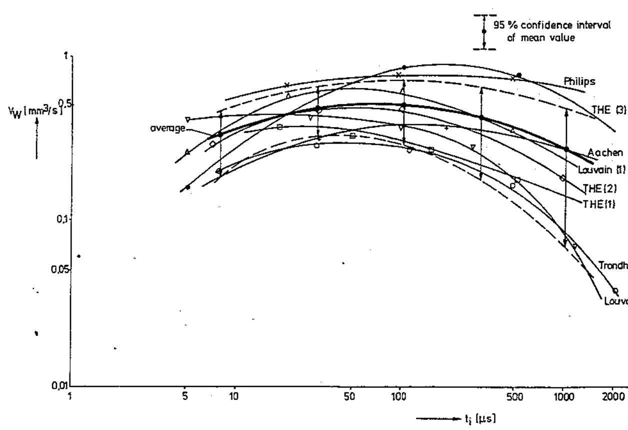

Fig. 4. Results of machinability tests $\bar{i}_f = 20$ A.

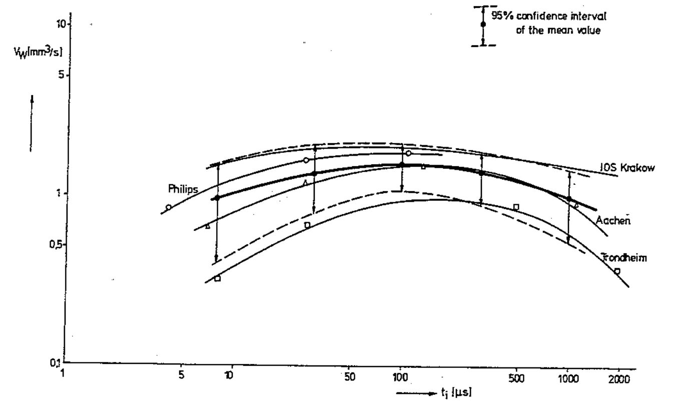

Fig. 5. Results of machinability tests $\bar{i}_f = 50$ A.

the metal removal rate figures, is not justified. The graphs of fig. 1, if not based on actual measurements, do give a realistic representation of the kind of relation that exists between roughness and relative wear on the one hand and pulse duration on the other.

In Fig. 1, the relation of roughness values are given in μm CLA (R_a). However, in a number of discussions of the STC "E" it appeared that the usual measurement of the R_a cannot be very reliable. The results of such measurements strongly depend on the stylus radius of the measuring equipment, the cut-off, the measuring length and sometimes on the location of the measurement on the machined surface. Therefore, in 1972, it was decided to use the VDI-roughness standard, or the R_a values connected to the class numbers should be used for the roughness values.

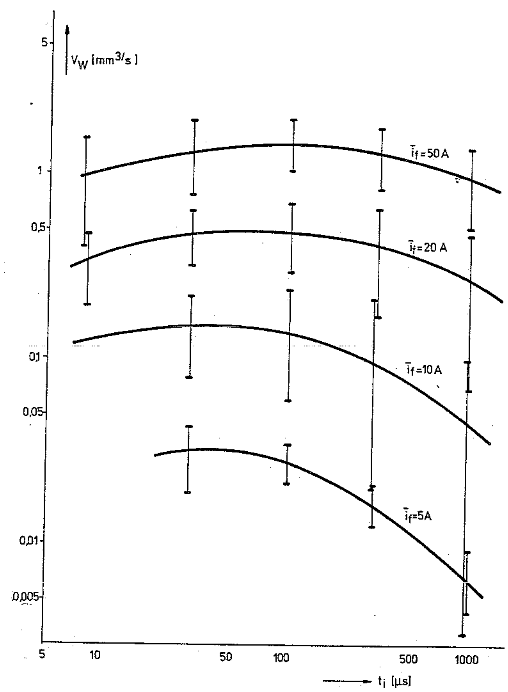

Fig. 6. Mean values of EDM machinability tests.

7. Conclusions and Prospectives

As mentioned before the objective of cooperative research of the CIRP Scientific Technical Committee E on the machinability of workpiece materials is to draft directives in order to establish machining nomograms for various workpiece materials by well defined experiments. The machining nomograms themselves should be made by machine suppliers and users. The latter can adapt the nomograms to their own specialized conditions, such as the current types of geometry and the materials used for electrodes and workpieces. A generalized machinability nomogram for one combination of workpiece- and electrode material covering all types of EDM cannot be produced since the relations given in the nomogram depend heavily on varying external conditions, such as the characteristics and adjustment of the tool feed servo system, the flushing and filtering of the dielectric fluid, the setting facilities provided on the machine in question etc. In addition the geometries to be machined will show great variations from one user to the other. This will profoundly influence the machining efficiency that can be expected from a given machine even at optimal settings. For instance, the flushing conditions are very different in the case of blind mould cavities as compared with the apertures to be machined in die plates for blanking tools. In the last case the side gap and side wear are essential factors to be controlled.

When the supplier or the user decides to compose a machinability nomogram for his own machine and particular situation, he should take the following into account:

A user producing mostly blind cavities should carry out his experiments on a cylindrically shaped workpiece using an electrode of somewhat smaller diameter. Workpiece and electrode should be aligned axially so that besides the frontal gap a side gap will develop in course of the machining operation.

In the case apertures in dieplates are the users primary interest the testpiece may consist of a plate of limited thickness e.g. 5 mm.

After machining a through hole in the plate, gapwidth is easily deduced from measurements of the hole and the electrode diameter.

Adequate flushing is necessary. When cylindrical workpieces are used central flushing through an axial hole in the electrode is suitable.

In the through hole type of test aspiration of the dielectric fluid through a central hole in the test plate is useful. In all cases the volumetric flow rate of the dielectric fluid should be kept as constant as possible. The suitable flow rate depends on the gap size and on the energy setting and must be determined in preliminary tests in order to assure stable machining conditions.

The experiments should be designed to cover the whole range of currents and pulse durations. The CIRP experiments are carried out at duty cycles of 50%. Higher duty cycles are of practical importance since these will lead to higher workpiece material removal rates. What value the optimal duty circle will be, depends on the actual machining conditions. In any case, when static arcs tend to occur frequently, the duty cycle must be decreased. The risk of static arcs also increases when the flushing conditions get worse as is the case with holes or increasing depth.

An experiment with one particular machine setting (current, pulse time) should be carried out at least three times in order to be sure that the obtained results (metal removal rates, roughness values) are reliable.

In the CIRP cooperative tests it was prescribed to adjust the tool servo system for maximum relative frequency λ. In that case the optimal rate of metal removal will be obtained.

However, equipment for measuring the relative frequency is not normally available. The same holds for equipment with which the average pulse efficiency can be determined. In practice, the servo system must be adjusted for stable working conditions. The tool servo systems of most machines provide the possibility to adjust the desired gap width and the servo amplifier gain. Unfortunately other indications for these functions are often used. (For instance "feed" for gap width and "stability" for servo amplifier gain). The gap width control has to be adjusted to produce the minimum number of short circuits (which indicates that the gap is too small) together with the minimum number of open circuit pulses (no current, indicating too large a gap).

With the gain control the total servo system can be adjusted for maximum reaction speed without overshoots or oscillations.

An oscilloscope connected across the gap in order to monitor the gap voltage will be a very suitable help in the correct adjustment of the tool servo system. Short circuits, static arcs and open circuits can easily be recognized on the scope.

From the cooperative experiments carried out up to now of the Scientific Technical Committee E in the field of EDM it appears that more research has to be carried out on the measurement of pulse efficiency, in particular in relation to the metal removal rates. Also the role of the tool servo is not too well understood, especially the influence of the gap width sensor and of the servo speed on the electro erosion process is not clear. The in-process measurement of the frontal gap and its relation to the side gap represent another important problem. The university of Aachen is carrying out research in this subject and presented a note to the Committee [ref. 3].

Up to now cooperative work has been carried out on die steel at normal machining conditions only. This year the Committee has started a cooperative research program on the machining of cemented carbides. Special attention will be paid to the occurrence of micro cracks in the machined surface. In the area of finish machining of die steels and cemented carbides much research has still to be done, especially concerning electrode wear. In this context work is in progress on the polarity effect in electro erosion [ref. 4] and will be carried out on the machining with demineralized water.

The problems connected with this particular section of EDM research do mostly not concern the experiments themselves but the availability of suitable measuring equipment.

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