Adaptive Control System for Optimizing the ECG Process under the Overcut Constraint

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One of the main limitations in Peripheral Electro Chemical Grinding (ECG) is the overcut phenomenon. The dominant parameters which govern the dimensions of the geometrical overcut are the voltage and the feedrate. This paper deals with the development of an empirical model which describes the overcut as a function of the dominant parameters. Based on this model an adpative control system was built and experiments in Profile Peripheral ECG were carried out. A comparison of the results obtained with and without the adaptive control system is presented as well as the relationship between the side and bottom overcuts. According to the above an adaptive strategy to control the geometrical overcut in Profile ECG is suggested.

THE ECG PROCESS

The Electro Chemical Grinding (ECG) process has been described in detail by other authors [1-4]. In this paper we shall briefly summarize the principles of the process concentrating on the peripheral ECG and give special attention to the overcut phenomenon and other aspects of the process on which our optimal adaptive control system was based.

The material removal in the ECG proces is based on the principle of anodic dissolution during electrolysis combined with an abrasive grinding operation. In the electrolysis process, the workpiece is used as the anode while the grinding wheel is used as the cathode; both of them are, of course, electrical conductors. The eltctric tension between the two electrodes is insured by a D.C. (generally rectified) power supplier. The anode is held at a positive potential relative to the cathode, which is practically grounded. A salt solution (usually consisting of $NaNO_3$, KNO_3 and their buffers, $NaNO_2$ and KNO_2) is inserted into the gap between the two electrodes in order to create the working zone (sometimes called the working gap) in which the electolysis process takes place. A fundamental description of the ECG setup is shown in Fig. 1.

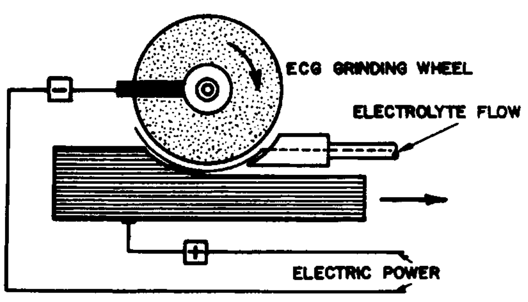

Fig. 1: Fundamental description of the ECG process

The electrolysis process in which atoms from the metallic workpiece move into the solution is described for Ferum, as an example, by eqs. (1-5).

Anode: $F_e \rightarrow F_e^{++} + 2\bar{e}$ (1)

Cathode: $2H_2O \rightleftarrows 2H^+ + 2(OH)^-$ (2)

$2H^+ + 2\bar{e} \rightarrow H_2\uparrow$ (3)

Solution: $Fe^{++} + 2(OH)^- \rightarrow Fe(OH)_2\downarrow$ (4)

and totally: $Fe + 2H_2O \rightarrow H_2\uparrow + Fe(OH)_2\downarrow$ (5)

The electrolysis process, which is usually governed by Faraday's law of electrolysis, is disturbed by the hydrogen produced beside the cathode as well as by the passive layer (sometimes called the anodic layer) which coats the anode. Both of these phenomena disturb the motion of the charged ions into and in the solution and finally stop the anodic dissolution. It is the grinding wheel's task to replace the electrolyte in the working zone as well as to scrape off the passive layer.

THE OVERCUT PHENOMENON:

One of the main limitations of the ECG process is the overcut (O.C.) phenomenon. The overcut may be defined as undesired and uncontrolled electrochemical overdissolving of the workpiece. The phenomenon occurs beneath and on the sides of the grinding wheel during and immediately after grinding. The overcut phenomenon is limited in its dimensions and decays as the overcut increases. As a consequence, a meaningful geometrical deviation between the ground profile and the grinding wheel profile can easily be obtained. Moreover, the electrochemical etching occurs both on and underneath the surface causing geometrical overcut and selectively etching the subsurface layers destroying their qualities. The undersurface selective etching occurs particularly in grinding of composite materials and relates to a single "preferred" phase like the Co phase in the case of sintered carbides [5,6]. The geometrical overcut effects, on the other hand, are usually emphasized in grinding of more homogeneous materials like steels. In this paper the discussion is limited to the geometrical effects of the overcut phenomenon. The overcut phenomenon is affected by almost all the parameters and variables involved in the ECG process [7], beginning with the grinding machine, the power supplier, the grinding wheel (type, grain size, and profile) and the workpiece (material, pretreatments and shape) through the electrolyte (type, ph, pressure, temperature, and concentration) and ending with the feedrate, the voltage across the electrodes and the depth of grinding. Many investigators were aware of the fact that for a certain machine and a given setup and job, the dominant parameters are the feedrate and the voltage across the electrodes.

THE AIM OF THE WORK

Although not many of the investigators studied the problem of the overcut [7,8], yet, it is well-known that the overcut is one of the main limitations of the high-potential process - the peripheral profiled ECG. Most of the research expresses in one way or another the importance of being able to predict, control or reduce this phenomenon.

It is mentioned many times [7,8,9], that in order to minimize the overcut dimensions, one should increase the feedrate and decrease the electric tension between the electrodes. That trivial solution actually means an increase in the abrasive component of the process at the expense of the electrochemical one, and leads to conventional abrasive grinding. Such a solution can in no way be an index of performance when dealing with an electrochemical process. In our opinion the process should operate on the optimal loci (as described by the authors [10,11] and will be briefly repeated herafter) with the additional constraint of a given maximum permitted overcut. In other words, the optimal working point (WP) on the optimal loci should be defined and determined by the maximum permitted overcut.

The development of such an adaptive strategy, self-defined and converging to the optimal operating point is the goal of this work. The system should converge from any starting point (SP) to the optimal operating point (WP) for any given task and independently of the threesome: the workpiece, the grinding wheel, and the electrolyte.

THE ECG OPTIMIZATION

At the first stage an optimal control system was built based on the concept of maximizing the removal rate under desired and programmable constraints. The control plane is defined by the two dominant and independent control parameters: the feedrate V_f and the operating voltage U. The working region is bounded by five constraints as shown in Fig. 2: minimal and maximal (U_{min} and U_{max} respectively) electric tension (r.m.s.-scaled), lines E-A and D-C; the near sparking curve(called sparking constraint) defined by B-C; the maximum grinding wheel power C-B; and the Faraday constraint O-D.

The five constraints create five extremal points of which three, A,B,C, have a practical meaning. Point A: lies in the intersection between the power and the minimal voltage constraints. The material removal rate (MRR) is maximized under the limitation of being pure abrasive. Point A is therefore distinguished by: very low electrochemical efficiency, high wear rate

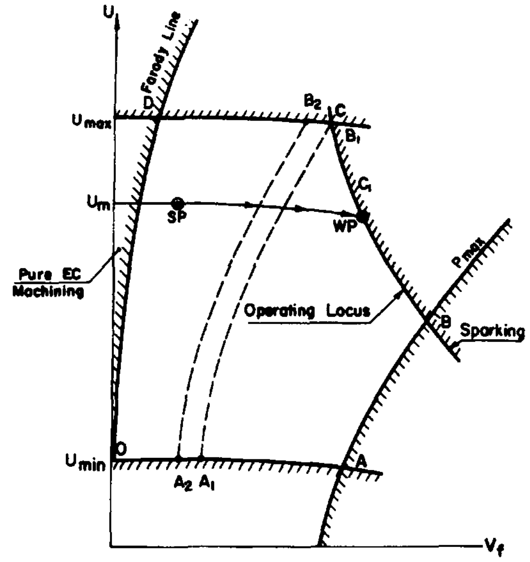

Fig. 2: Description of the constraints and the extremal points on the control plane.

of the grinding wheel, very low overcut (if any), good surface finish, and quite low MRR. Point B. (or point B_1 in cases where the power is limited by the operator due to fragile material, etc.): being able to move on the sparking constraint (by changing the limit level). Point B can't be characterized by any quality except that it always represents the maximum MRR. The material is removed by a combined operation of both the abrasive and electrochemical components. Point C: Unlike point B, point C is static and defined by the intersection of two constant and fixed constraints: the maximal voltage and the sparking line. Point C, therefore, represents the situation (in general) of maximum MRR in the maximal tension and under the sparking constraint. This point is distinguished by high electrochemical efficiency, low wheel wear and relatively high overcut. Point C_1: is the operating point and is free to move along the optimal frame (D)CBA. In a majority of practical cases, C_1 would be between points B and C. In profile grinding in particular, one would prefer to work in the area of Point C in order to prevent superfluous wear on the grinding wheel.

It was shown by the authors [11] that the sparking line (and practically a line near the sparking line whose distance from the sparking line is predetermined by the operator) together with the power limitation produce the optimal working loci.

The reader should be aware of the fact that the moment we accept the sparking and the power constraints to define the optimal loci, the two dominant parameters - operating voltage and feedrate - are no longer independent. For each adjusted voltage U_m there is only one adapted optimal feedrate. On the other hand, for each fixed feedrate there is at least one optimal voltage. At the design phase, the first step must be to find out the degree of influence of changing each of the two parameters on the overcut. For that purpose, a peripheral ECG with zero depth of grinding was selected as a preliminary study case.

EQUIPMENT

In order to emphasize the geometrical overcut and minimize the influence of the grinding wheel wear on the results, steel (4340) workpieces and diamond wheels were selected. The Agathon Electrolytic-125E grinder with wheel power of 2HP and constant rotation speed of 5000 r.p.m. was used. The power supplier was the Elyform Ely 300 generator (full wave rectifier with maximal output power of 2.2 KW emitted at nominal rated voltage levels of 7.5, 10, 12.5 and 15V). As an electrolyte, we used a water solution of commercial salt (42% by weight $NaNO_3$; 42% $NaNO_2$; and 16% anti-corrosion additions) with density of 1.04 gr/cm^3. The drive system was based on a stepping motor mounted directly to the worktable lead screw causing movement of 0.0159 mm per pulse.

FIRST STAGE EXPERIMENTS - PLANAR PERIPHERAL ECG

Type of grinding: planar peripheral ECG
Grinding wheel: DD 100-100/M, ϕ125 mm, 7 mm in width
Workpiece: steel (4340), 59 mm length, 5 mm width
Depth of grinding: zero
Adjusted voltage: 7.5, 10, 12.5V
Constant feedrates: 0.16-1.28 mm/s in steps of 0.16 mm/s

Procedure: After 35 mm of ECG along the workpiece, the electrical power was stopped and the grinding process was continued without the electrochemical component but with the same feedrate.

Measuring: The bottom overcut δ_y produced during the ECG operation was measured on half of the workpiece width $x = x_c$ (relative to the zone that was ground without the electrochemical component) along the longitudinal axis (feed direction) by a Tallysurf Surface Analyzer with vertical magnification of x100. The results obtained are summarized in Table 1.

Table 1: The bottom overcut, in the peripheral ECG, vs. the adjusted voltage for different constant feedrates.

V_f^* \ U_m	δ_y $(x = x_c)$						
	0.16	0.32	0.48	0.64	0.80	0.95	1.27
7.5	5.5	4	3.5	3.2	3	2.5	2
10	10	7	6	5	4	3.5	3
12.5	14	11	9	7.5	6	5	4

$^*V_f$ (mm/s), Um(v), δ_y (mm 10^{-2})

EMPIRICAL MODEL

Although it can be easily seen that the most dominant parameter relating to the bottom overcut is the adjusted voltage, and although one may easily conclude that in an adaptive control system it would be natural to fit the feedrate to the adjusted (or operating) voltage, yet, there are still some good reasons to construct a model describing the overcut behavior.

a. The results obtained from the model can be used as initial conditions for the adaptive control system.
b. Trial and error methods can be used according to the model in cases where an adaptive control system is not available.
c. A mathematical model can be accurately analyzed to define the degree of influence of each parameter on the overcut.
d. By statistical analysis, on the other hand, we can determine to what extent the phenomenon is described by the model.

It can be shown that the results obtained in the experiment are described by:

$$\delta_y = K \cdot \text{EXP}\ (b_0 + b_1 U_m + b_2 V_f) \tag{6}$$

where:

δ_y (mm 10^{-2}) - bottom overcut
$b_0(-)$; $b_1(V)^{-1}$; b_2 $(mm/s)^{-1}$ - coefficients
$K \triangleq 1$(mm 10^{-2}) - dimension factor

Writing eq. (6) in linear form by taking ln of both sides:

$$\ln(\delta_y) = b_0 + b_1 U_m + b_2 V_f \tag{7}$$

By means of regression and linear curve fitting we get:

$$b_0 = 0.641 \quad b_1 = 0.163\ (V)^{-1} \quad b_2 = -1.021\ (mm/s)^{-1} \tag{8}$$

According to eq. (6) and the coefficients (8), iso-overcut curves can be calculated. Such calculated lines and the practical result are shown in Fig. 3.

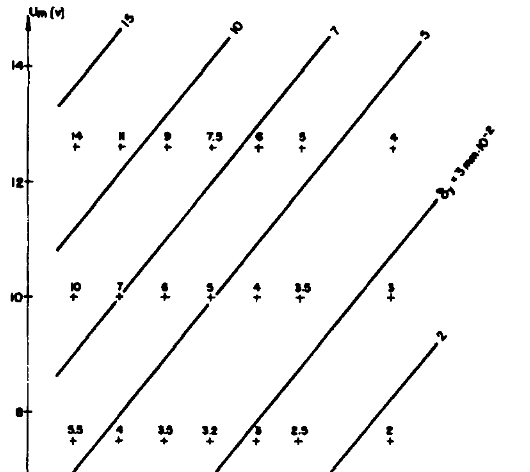

Fig. 3: Calculated iso-overcut lines and experimental results.

ANALYSIS

Based on the results and some statistical investigation (analysis of variance and factorial analysis for 3^2 design), important conclusions can be reached.

a. The results confirm the assumption that the bottom overcut increases when increasing the adjusted voltage and decreases when increasing the feedrate. This phenomenon is confirmed all over the investigated region.
b. The influence of the adjusted voltage is much more significant than that of the feedrate. The influence of the adjusted voltage decreases in low voltage levels ($b_1 U_m \approx -b_2 V_f$), but for practical representative conditions, i.e. $U_m \approx 10V$ and $V_f \approx 0.5mm/s$, the proportion is changed $b_1 U_m \approx -3b_2 V_f$ where the minus sign indicates opposite influences.

c. From analysis of variance (Table 2) we see that the bottom overcut in the case of peripheral ECG with zero depth of grinding is really dominated by the adjusted voltage and the feedrate. All the other parameters concerned taken together have a negligible influence and the variance ratio is about 286.

Table 2: Analysis of Variance

SOURCE	SUM OF SQUARES	DEGREE OF FREEDOM	MEAN SQUARE
Due to regr.			
b_0	53.885	1	53.885
b_1, b_2	5.148	2	2.574
About regr.	0.157	18	0.009
TOTAL	59.190	21	

* In all statistical computations the feedrate V_f was taken in mm 10^{-2}/s and the variance ratio is: 2.574/0.009 = 286

* All computations are related to ln (δ_y).

d. Based on factorial analysis for 3^2 design [11], we can see that the mutual influence and the cross effects between the adjusted voltage and the feedrate (linear and quadratic) are very small and practically negligible.

Relying on the above analysis, three important operational conclusions relating to the optimal adaptive control system may be reached.

a. The adjusted voltage is the most dominant parameter. It is therefore essential to grind under a constant voltage level in order to ensure and achieve: the desired overcut, a more uniform overcut and surface, a better correlation with the model and a better repeatability. This last point practically means small standard deviation over a batch. Assuming normal distribution and demanding:

$$P(\delta \le \delta_{max}) = 0.95 \tag{9}$$

the programmed permitted overcut δ_n is given by:

$$\delta_n = \delta_{max} - 1.645s \tag{10}$$

where:

δ_{max} - maximum permitted overcut
δ - practically obtained overcut
s - estimated standard deviation
p - probability

It can easily be seen from eq. (10) that decreasing the standard deviation enables one to increase the programmed overcut without breaking the severe constraint of the maximum permitted overcut. Therefore, the adjusted voltage might be increased causing reduction in the wheel wear as a consequence.
b. It is necessary to continuously adapt the feedrate to the adjusted voltage in order to keep the process on the optimal loci, prevent arcing (over feedrate) or over electrochemical etching (low feedrate).
c. The adaptive control system that was developed by the authors with [11] or without [10] the control loop for the wheel power limitation can be used as the adapting (feedrate to the adjusted voltage) unit in the whole system.

ADVANCE TESTS

In the second experimental stage, tests relating directly to profile ECG were performed.

Experiment Conditions:

type of grinding: Profile peripheral ECG
grinding wheel: DD 100-100/M, 7 mm width
depth of grinding: 1.6 mm
grinding profile: Rectangular 1.6x7 mm with rounded corners
workpiece: Steel 4340, 3 mm width
results: At least 6 results for each tested machining condition
adjusted voltage: 7.5, 10, 12.5V (5V with current limitation)
feedrates: Constant 0.10, 0.16, 0.24, 0.32, 0.40 mm/s, and variable feedrate obtained by the adaptive control unit.

Experiment Description:

In each test (setup) there were 4 3mm wide workpieces. Each of the four was assigned a Roman numeral (Fig. 4). The 4 workpieces were held by two supports (one on each side) each of 6mm width to insure stability for the ECG operation. In each tested group, 4 grooves with different adjusted voltage U_m were ground. As a reference groove, one of the 4 grooves ground without tension U_m=0, was used. From the four workpieces 3 were randomly selected and measured.

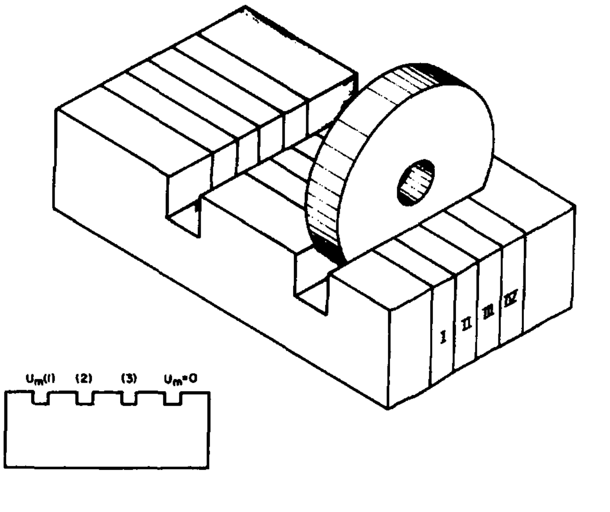

Fig. 4: Description of the profile grinding test.

The side and bottom overcuts were measured by a profile projector (Johnes & Lamson) with magnification of X50. For each groove both the reference profile and the tested one were drawn.

Data Collection:

The measuring method and the data collecting procedure will be briefly summarized. For each tested groove and operating condition (certain adjusted voltage and feedrate) a six row table was completed. For each case, the left and right side overcut dimensions were indicated as function of the height of the measuring point y. As mentioned before, each set of 4 workpieces was ground at a constant given feedrate under three different non-zero adjusted voltages, and a reference groove was ground without tension. The workpiece was mounted on the sliding table of the profile projector and the reference groove was copied on to a transparent paper. The workpiece was then moved by the table until the profile of the tested groove was aligned as symmetrically as possible with the reference groove. Measuring horizontal and vertical axes on each side (denoted by X_L, Y_L, X_R, Y_R) of the copied groove were drawn. The origin of each of them was well-defined by the intersection of the measured profile and the reference one. The bottom and side overcuts were measured at defined points along these axes and were related to them. Due to errors which occurred during the measuring process and caused by the alignment procedure, the need for correction of the results was essential. The correction was performed by a mathematical procedure of centering the results without losing the statistical distribution. Once the centering operation had been completed, the source of the results, in the sense of left or right side, was ignored. Therefore the R and L indexes were omitted and x and y were referred to as the measurement axes in general.

The Side Overcut:

The measured side overcuts for tests performed with different adjusted voltages and with different constant feedrates are shown in Fig. 5 for y=1mm. Each drawn point is the mean of 6 measured overcuts. The results obtained for a wide range of feedrates were put on a semi-logarithmic scale as function of the operating voltage only according to the equation:

$$\delta_x = b_0 EXP(b_1 U) \tag{11}$$

where:

δ_x (mm 10^{-2}) - the side overcut
b_0 (mm 10^{-2}) - coefficient
b_1 $(V)^{-1}$ - coefficient
U(V) - operating voltage (differs from the adjusted voltage by the programmable parameter DU($U=U_m-DU$))

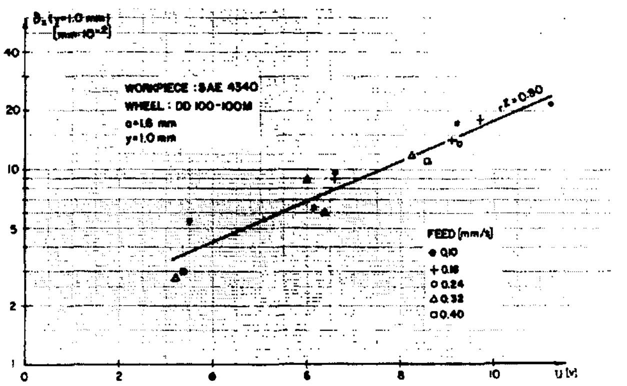

Fig. 5: The side overcut vs. the operating voltage for different feedrates and y=1.0mm.

This equation is of the same form as eq. (6) which describes the bottom overcut. The difference between the two equations is that in eq. (11) the influence of the feedrate was ignored in order to meet the demands of the optimal adaptive control concept. As mentioned before, the feedrate would automatically be adapted' to the adjusted voltage. Although the feedrate was not taken into consideration, relatively high regression coefficients were achieved, as shown in Table 3.

Table 3: Coefficients and regression factor obtained in different measuring heights y

y (mm)	b_0 ($mm\ 10^{-2}$)	b_1 $(V)^{-1}$	r^2 (-)
0.2	1.35	0.2	0.71
0.4	1.47	0.22	0.82
0.6	1.58	0.23	0.87
1.0	1.6	0.24	0.90

The dependence of the side overcut on the feedrate in the higher points (near the original surface) v is very low. The regression coefficient increases with the height of the measuring point.

The side overcut behaved in the same way as the bottom overcut in the planar peripheral ECG, but its dependence on the operating voltage is stronger (b_1=0.23 against b_1=0.163). It is obvious therefore, that the side overcut and the bottom overcut are not independent.

The slope of the overcut function was all around b_1=0.23 and only in the case where y=0.2 (near the corner) was b_1 different and decreased to 0.2.

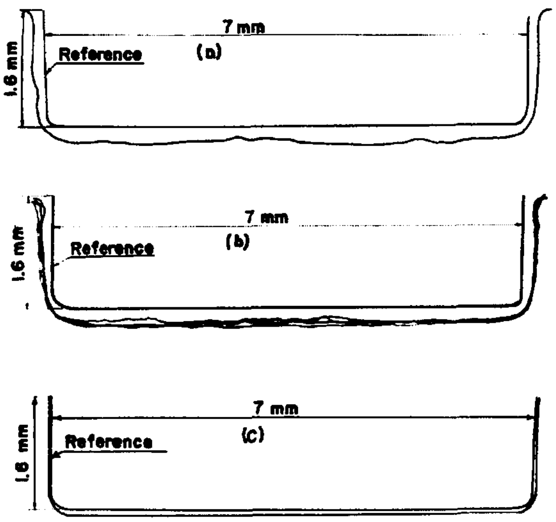

Fig. 6: Overcut that has been copied from the profile projector:
(a) U_m=12.5v Vf=0.16mm/s
(b) Same as (a) for 4 different parts
(c) U_m=12.5v with A.C.

Based on the experiments carried out, there were some expectations concerning the side overcut which would be obtained under the optimal adaptive control.

a. Working with constant tension insures good prediction of the overcut dimensions and repetition of performance.
b. The distribution of the overcut over a batch would be reduced and the surface would be improved.
c. Changing the feedrate during the ECG process would hardly affect the dimension of the overcut or its character.
d. As the influence of the feedrate on the overcut is small, the time during which the wheel is over the workpiece will also have a low influence on the overcut. It is expected, therefore, that the "walls" would be more upright.

The grooves as copied from the profile projector are shown in Fig. 6. Profiles obtained with and without the adaptive control are compared.

Table 4: Comparison of the resulting side overcut with and without the adaptive control system.

U_m (V)	V_f (mm/s)	$\bar{\delta}_x(y=1)$ ($mm\ 10^{-2}$)	s ($mm\ 10^{-2}$)
12.5	0.10	21.50	3.55
12.6	0.16	18.33	4.89
12.6*	- AC-	7.13	3.40
10.1	0.10	17.33	3.23
10.1	0.16	14.17	2.77
10.1	0.24	13.83	1.16
10.1	0.32	12.00	1.70
10.2*	- AC-	6.00	2.14
7.4	0.10	9.67	2.11
7.5	0.16	9.00	2.61
7.5	0.24	6.17	1.14
7.4	0.32	5.00	1.06
7.6*	- AC-	2.88	3.00

*with the adaptive control unit

By examining the side overcut obtained we may conclude that the overcut was significantly reduced by using the adaptive optimizing system.

The Bottom Overcut

The dimension of the bottom overcut, its uniformity, distribution and repeatability over a batch were the main characteristics we were interested in. The maximal bottom overcut (δ_y) was always obtained in the half of the workpiece width ($X=X_c$=3.5 mm.)

As before, in the first stage the cases of constant feedrate for different operating voltages were investigated. The bottom overcut for these tests is described in Fig. 7 on a semi-logarithmic scale according to eq. (12). this equation is similar to eq. (6) which satisfied the bottom overcut for zero depth of grinding neglecting the feedrate influence.

$$\delta_y = b_0 \cdot EXP\ (b_1 U) \qquad (12)$$

The obtained coefficients according to the least square approximation were:

$$b_0 = 2.95\ (mm\ 10^{-2}) \qquad b_1 = 0.20\ (V)^{-1} \qquad (13)$$

with regression factor of r^2=0.77

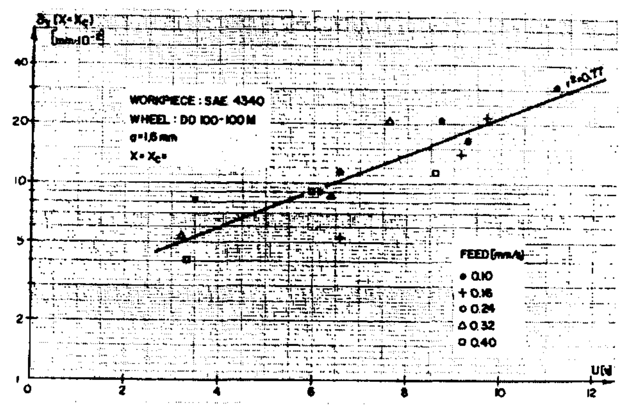

Fig. 7: Bottom overcut vs. applied voltage for different fixed feedrates.

Table 5: Comparison of the resulting bottom overcut with and without the adaptive control system

U_m (v)	f (mm/s)	$\bar{x}_y(x=x_s)$ (mm 10^{-2})	s (mm 10^{-2})
12.5	0.10	30.00	5.37
12.6	0.16	16.67	3.33
12.6*	-AC-	8.50	0.53
10.1	0.10	17.00	6.26
10.1	0.16	14.00	2.28
10.1	0.24	20.67	2.73
10.1	0.32	20.67	4.50
10.1*	-AC-	12.75	2.31
7.4	0.10	11.67	2.88
7.4	0.16	5.33	2.07
7.5	0.24	9.00	1.55
7.4	0.32	8.67	4.23
7.6*	-AC-	3.75	2.87

*under adaptive control

In relation to the bottom overcut, it can be seen that working on the optimal loci significantly reduced both the overcut itself and the standard deviation.

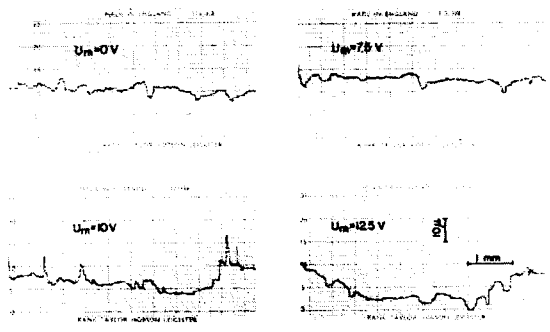

Fig. 8: Typical bottom overcut for different adjusted voltages under adaptive control.

Typical bottom overcut surfaces obtained by a Tallysurf (with vertical magnification of X100 and horizontal magnification of X20) with and without the adaptive control system are presented in Figs. 8,9. In these figures the significant contribution of the adaptive control is well-seen. In Fig. 10, two half photographs of the ground groove, one under the adaptive control and the other without adaptive control are presented. Both were ground with the same adjusted voltage, U_m=12.5V. There is a clear connection between the bottom and side overcuts. The investigation of the correlation between them is out of the scope of this work. But it should be noted that it clearly seems that the bottom overcut is more sensitive to changes in the feedrate.

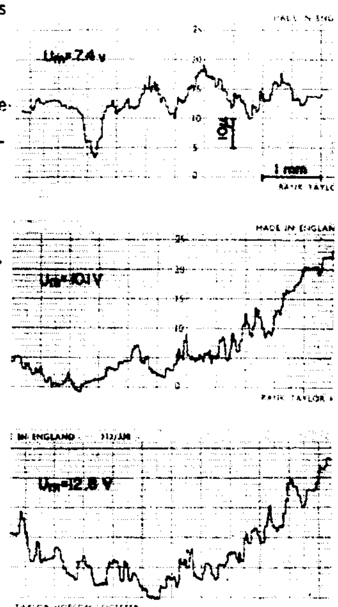

Fig. 9: Typical bottom overcut with V_f=0.16 mm/s obtained for different U_m.

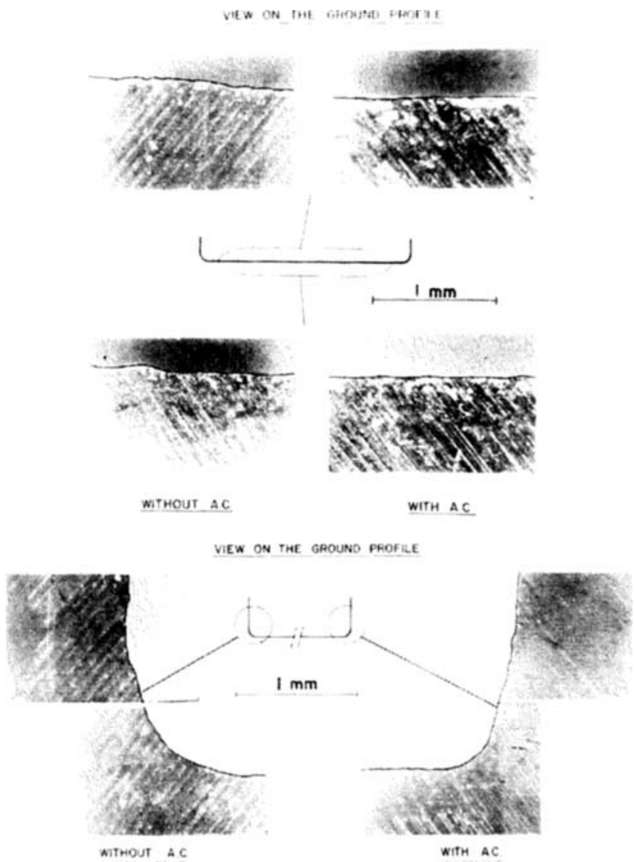

Fig. 10: Overcuts with and without the adaptive control.

The Optimal Adaptive Control System

Concept: the concept according to which the optimal adaptive control system was developed and built was:

a. The adjusted voltage should not be changed during the grinding operation.
b. The adjusted voltage should be changed if necessary in the intervals between grinding of two consecutive stepping workpieces according to the measured and permitted overcut.
c. The feedrate should be continuously and automatically adaptively changed by the optimizing unit in order to keep the working point on the optimal loci. The system may be treated as a double adaptive control system as it includes two adapting loops. The first adapts the feedrate to the adjusted voltage in order to meet the optimal loci. This phase is performed continuously, automatically and on-line. The second loop changes the adjusted voltage as dictated by the adaptive strategy.

Description: The optimal adaptive control system is presented in Fig. 11. The system consists of two loops. The first one is the feedrate adapter. The operator determines the distance of the operating loci from the sparking line by selecting DU. (Recommended values are between 0.5 and 0.75 volts).

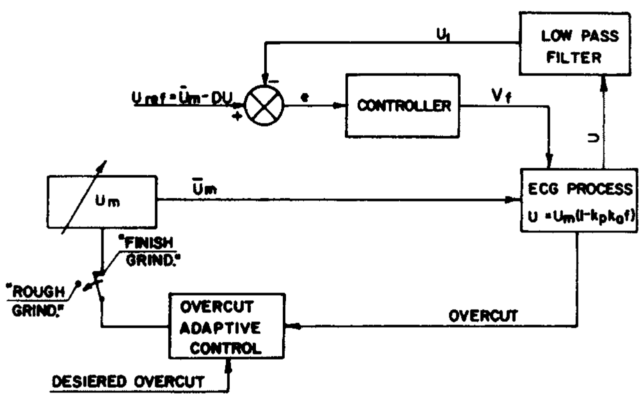

Fig. 11: The optimal adaptive control system.

The system would converge to the operating voltage U which should be equal to Uref. As the power supplier is rectified a lowpass filtration was needed. The controller (a special numerical controller was designed for this purpose) emits pulses to the driving system with the frequency proportional to the required feedrate. The actual operating voltage U differs from the adjusted one U_m due to the feedrate V_f (causing a voltage drop). During the grinding operation the adjusted voltage U_m is held constant. After the grinding operation had been terminated, the overcut was measured and the adjusted voltage U_m for the following workpiece was determined according to the strategy to be described by the second adaptive loop.

Suggested Strategy

The programmed overcut should be determined according to eq. (10) in order to insure that 95% of the parts will be ground with smaller overcut than the maximum permitted one. A dead zone in which U_m would not be changed was defined. The dead zone is used as a filter which prevents the control system from following the distribution of the obtained overcuts. The algorithm for correcting the adjusted voltage is based on the measured overcut and the approximate relation which describes the overcut of all types (OC) and given by:

$$OC = b_0 EXP(b_1 U_m) \qquad (14)$$

As has been shown, b_1 is almost constant for the bottom overcut all over the working region. Therefore, if index n denotes the next part and 1 denotes the previous one, the relation between the next and previous overcuts is given by eq. (15) and the coefficient b_0 vanishes.

$$\frac{OC_n}{OC_1} = EXP\,[b_1(U_m - U_{m1})] \qquad (15)$$

or: the next adjusted voltage should be:

$$U_m = U_{m1} + [\ln(OC_n/OC_1)]/b_1 \qquad (16)$$

For the case studied, the mean value of b_1 was 0.23. In order to always stay on the safe side two gain values of b_1 should be used. We selected b_1 to be 0.26 when increasing the adjusted voltage and 0.22 when decreasing it. The principle of convergence is shown in Fig. 12.

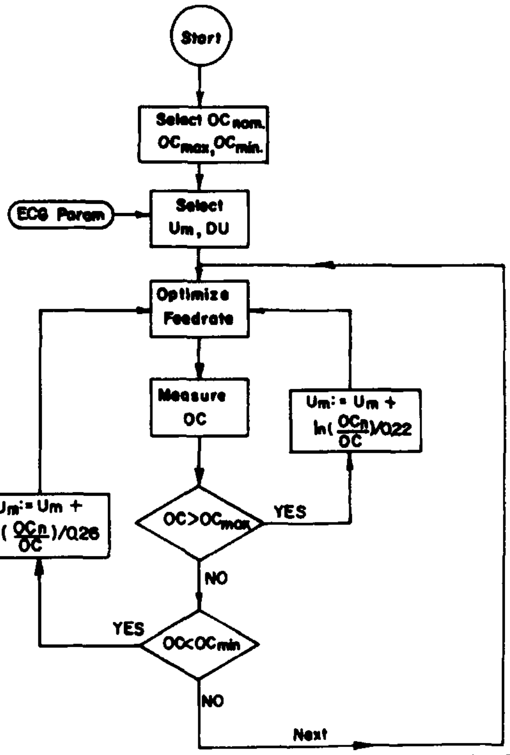

Fig. 12: The adaptive strategy optimizing the adjusted voltage.

SUMMARY

An optimal adaptive control system based on three test levels was presented. Tests in *Peripheral Profile ECG* were carried out and the behavior of the bottom and side overcuts was investigated. Based on the results an empirical model, which describes the different types of overcuts was developed and tested. The model was found to be easy to construct, valuable, and accurate enough for adaptive control purposes.

The control plane was defined by the two most dominant parameters of the process, i.e. the operating voltage and the feedrate. The working area was bounded by the sparking, the power and the machine constraints. Consequently, the optimal operating loci was defined.

Results obtained with the optimal control system (variable feedrate) were compared with the results obtained with constant feedrates. The comparison showed a significant reduction in the overcut and a great improvement in the distribution and uniformity of the process under the optimal control. The behavior of the overcut along the optimal loci was described and an adaptive control strategy to limit and control the overcut was suggested.

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