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Simulation of energy consumption in electrochemical grinding of hard-to-machine materials

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Abstract The paper presents results of the simulation of the effect of some significant factors on energy consumption and specific energy consumption for electrochemical grinding and mechanical grinding of three hard-to-machine materials (sintered carbides B40, titanium alloy Ti6Al4V and steel 18G2A). The investigation has been carried out on models of energy consumption and specific energy consumption for electrochemical and mechanical grinding performed by the grinding wheel face. The results have shown that within the range of parameters and machining conditions employed, mechanical grinding of hard-to-machine materials is characterized by higher energy consumption than electrochemical grinding.

Keywords Electrochemical grinding · Energy consumption · Hard-to-machine materials · Modeling · Simulation

1 Introduction

Electrochemical grinding (AECG) is a typical example of hybrid processing because it constitutes a combination of electrochemical machining (ECM) and mechanical grinding (MG) [1, 2]. Advantages of this type of machining are: high yield, low tool wear, elimination of grinding burns and breaks on surfaces thus machined, as well as absence of surface distortions due to the heat generated in the process and absence of the hardened surface layer. Electrochemical grinding does not introduce significant stress into the work-piece and eliminates burrs on parts thus machined [3–5]. The improvement of precision and quality of machined surfaces and higher durability of the diamond grinding wheel is related to lower cutting forces and lower temperature within the working zone due to the synergic interaction of both component processes of AECG machining [1, 6]. Because of its merits electrochemical grinding is particularly recommended for the machining of hard-to-machine materials. Traditional methods of shaping such materials may be not economical and may also produce surfaces of unsatisfactory quality.

The aim of the paper was to examine which of the machining processes, i.e. mechanical grinding or electrochemical grinding, consumes more energy when applied to hard-to-machine materials, to determine the effect of the investigated factors on energy consumption in the processes examined and to compare the results obtained for various materials. The simulation of energy consumption in AECG and MG machining was carried out using three hard-to-machine materials: sintered carbides of B40 type (Table 1), titanium alloy Ti6Al4V (Table 2) and steel 18G2A (Table 3). It is assumed that cubic-shaped samples with a face surface of about 100 mm^2 are subjected to the machining, that the process is carried out in an electrolyte based on sodium nitrate (Table 4) and the tool employed is a diamond grinding wheel with a metallic matrix, diamond abrasive corn size 200/160 μm and with concentration 100%. It is also assumed that the machining is made on an electrochemical grinder of ESCB 40 type which performs the grinding using the grinding wheel face. In order to compare the energy consumption for electrochemical grinding and for conventional mechanical grinding, simulation of the effect of significant factors on energy consumption E and specific energy consumption e is made for both processes.

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Table 1 Composition and properties of sintered carbides B40 [14, 15]

Chemical composition (%)		Density (g cm^{-3})	Average size of corn × 10^{-3} (mm)	Resistance to bending (MPa)	Hardness HV	Poisson's coefficient υ	Young's module E (N mm^{-2})	Compression resistance (kN mm^{-2})
WC	Co							
89	11	14.4	2–4	2600	1150	0.22	575	4.0

Table 2 Composition and properties of titanium alloy Ti6Al4V [16, 17]

Structure	Temp. of phase transition $\alpha \rightarrow \beta$ (°C)	Content of alloy elements (%)			Content of impurities max. (%)					Density (g cm^{-3})
		Al	V	Ti	Fe	C	H	N	O	
$\alpha + \beta$	990	6.17	3.88	Rest	0.17	0.01	0.0012	0.009	0.172	4.42

Table 3 Composition and properties of steel 18G2A [18]

Chemical composition										Strength properties					Density ρ (g cm^{-3})
C	Mn	Si	Fe	P	Cr	Ni	Cu	S	Al	*Re* (MPa)	*Rm* (MPa)	*E* (MPa)	υ	*A* (%)	
0.15–0.2	1.0–1.5	0.2–0.55	Rest	0.04	0.3	0.3	0.3	0.04	0.02	320–355	490–630	2.1×10^5	0.3	22	7.85

Table 4 Composition and properties of electrolyte employed

Content (% weight)		pH	Conductivity κ (S m^{-1})	Oxidation (mg l^{-1})
$NaNO_3$	Na_2CO_3	8.4	6.6	8.2
8.5	2.5			

2 Modeling of energy consumption for electrochemical grinding

Energy consumption in the electrochemical grinding process is related to the energy demand from the component processes of AECG machining, i.e. mechanical grinding E_{MG} and electrochemical dissolution E_{ECM}, as well as energy consumption of auxiliary devices of the machine-tool E_D [7]. Therefore, the total energy consumption of the machining process can be described by the relation:

$$E_{AECG} = E_{ECM} + E_{MG} + E_D\,/\mathrm{J} \tag{1}$$

Energy consumption in the electrochemical process is expressed by the equation:

$$E_{ECM} = UIt\,/\mathrm{J} \tag{2}$$

where U is the inter-electrode voltage (V), I is current (A), and t is machining time (s).

In mechanical grinding, energy is mainly consumed to override the cutting resistance and to ensure feed drive for the specific axes. So energy consumption for this process can be represented by the relation [8, 9]:

$$E_{MG} = \int_0^t \left[F_c(v_c \pm v_p) + F_n v_f\right] \mathrm{d}t/\mathrm{J} \tag{3}$$

where F_c is the cutting force (tangential) (N), F_n is perpendicular force (N), v_c is cutting speed (m s^{-1}), v_p is work-piece speed (m s^{-1}), and v_f is feed speed (mm min^{-1}).

Because of the fact that energy consumption by the feed drives is significantly lower than energy consumption by the main drive of the machine-tool and the electrode power supply, it is neglected in the energy consumption model elaborated for the AECG process.

Energy consumption of auxiliary devices is related to the operation of equipment like the electrolyte pump, the fan motor for extracting electrolyte vapor, the power supplies for electronic control and measuring devices etc. It constitutes a small percentage of energy consumption due to the component processes of AECG machining and therefore is neglected in the present model. Because the auxiliary devices operate both in electrochemical and mechanical grinding, the above simplification does not have a significant effect on the later comparison of energy consumption for the machining under investigation.

Allowing for the above simplification, the general form of the energy consumption model for electrochemical grinding E_{AECG} assumes the form:

$$E_{AECG} = F_c v_c t + UIt/\mathrm{J} \tag{4}$$

Taking into account that electrochemical grinder ESCB 40 is used for machining the model (4) assumes the form:

$$E_{AECG} = \left(kb\left(\frac{a_p v_{f_x}}{v_c}\right)^z v_c + \kappa \frac{U^2}{\frac{1}{3}Z_i} ab \right) t/\mathrm{J} \tag{5}$$

where a is the thickness of work-piece being ground (mm), a_p is grinding depth (mm), b is width of work-piece being ground (mm), k, z are coefficients dependent on material being electrochemically ground (experimentally determined), κ is electrical specific conductivity of electrolyte (S m^{-1}), v_{fx} is longitudinal feed speed (mm min^{-1}), and Z_i is diamond corn size of grinding wheel (mm).

For the comparison of energy consumption of various processes, the specific energy consumption e constitutes a more objective indicator. It represents energy consumed by a machine-tool to remove unit volume of material [10]. The model of specific energy consumption for the electrochemical grinding e_{AECG} carried out in the conditions assumed has the form:

$$e_{AECG} = \frac{E_{AECG}}{V_{AECG}} = \frac{kb\left(\frac{a_p v_{f_x}}{v_c}\right)^z v_c + \kappa \frac{U^2}{\frac{1}{3}Z_i} ab}{\psi k_v \kappa \frac{U-E}{\frac{1}{3}Z_i} ab + c v_{f_x} b a_p} /\mathrm{J\ mm}^{-3} \tag{6}$$

where c is the coefficient reflecting the increase in mechanical grinding yield due to the electrochemical interaction, ψ is coefficient characterizing the electrochemically active surface of the grinding wheel, V_{AECG} is volume of the material surplus removed as a result of electrochemical grinding, and k_v is volumetric coefficient of electrochemical machinability, derived from the relation:

$$k_v = \eta \frac{A}{Fn\rho} /\mathrm{mm^3 A^{-1} min^{-1}} \tag{7}$$

where A is the atomic weight of the material being machined, F is Faraday's constant: 9.6485×10^4 (C mol^{-1}), n is valence of the material being machined, and ρ is density of the material (g mm^{-3}).

Energy consumption for mechanical grinding E_{MG} is calculated from the relation:

$$E_{MG} = k_1 b \left(\frac{a_p v_{f_x}}{v_c}\right)^{z_1} v_c t/\mathrm{J} \tag{8}$$

where k_1, z_1 are the coefficients depending of the type of material being mechanically ground (determined experimentally), t is machining time (s). Specific energy consumption for mechanical grinding e_{MG} is described by the equation:

$$e_{MG} = \frac{k_1 \left(\frac{a_p v_{f_x}}{v_c}\right)^{z_1} v_c}{v_{f_x} a_p} /\mathrm{J\ mm}^{-3}. \tag{9}$$

This significantly depends on the volume of the material removed.

3 Simulation

The simulation carried out aimed at determining the effect of significant factors in electrochemical grinding (cutting speed v_c, depth of cut a_p, longitudinal feed speed v_{fx}, and inter-electrode voltage U) on energy consumption for AECG machining. In order to compare AECG and MG machining with respect to their energy consumption, a simulation was carried out of the effect of the above factors on energy consumption of the machining types considered. Values of the individual factors employed in the investigation were determined based on the assumed experiment plan of PS/DS-P:α type (static, determined, selective, multifactor, orthogonal) [11–13]. The range of values for the factors employed in electrochemical and mechanical grinding is given in Table 5. The investigation made it possible to obtain a non-linear model in the form of a second order polynomial with the general form:

$$z = b_0 + \sum_{k=1}^{i} b_k x_k + \sum_{k=1}^{i} b_{kk} x_k^2 + \sum_{k\langle q}^{i} b_{kq} x_k x_q \tag{10}$$

where z is the result factor, x_k, x_q are investigated factors ($k = 1, \ldots, i$; $q = 2, \ldots, i$; $k < q$), i is number of investigated factors, and b_k, b_{kk}, b_{kq} are regression coefficients.

Based on this polynomial, 3-D diagrams were prepared of the effect of individual groups of factors considered on energy consumption E and specific energy consumption e.

3.1 Effect of cutting speed v_c and depth of cut a_p on energy consumption E and specific energy consumption e for AECG and MG machining

The effect of cutting speed v_c and depth of cut a_p on energy consumption E for AECG and MG machining of sintered carbides B40 is presented in Fig. 1. Figure 2 depicts how the above factors influence the specific energy consumption e for AECG and MG machining of the material. Increasing the cutting speed within the adopted limits

Table 5 Variability range of factors in the investigation of AECG and MG machining

Factors	Units	Range of values
v_c	m s^{-1}	20–32 (10–22)[a]
a_p	mm 10^{-3}	10–60
v_{fx}	mm min^{-1}	25–200
U[b]	V	4–10

[a] Cutting speed of titanium alloy

[b] Only for abrasive electrochemical grinding

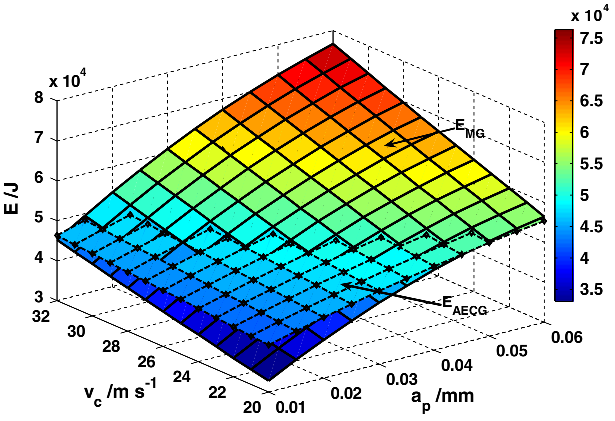

Fig. 1 Effect of cutting speed v_c and depth of cut a_p on energy consumption E for AECG and MG machining of sintered carbides B40, for $U = 7$ V, $v_{fx} = 112.5\ \mathrm{mm\ min^{-1}}$

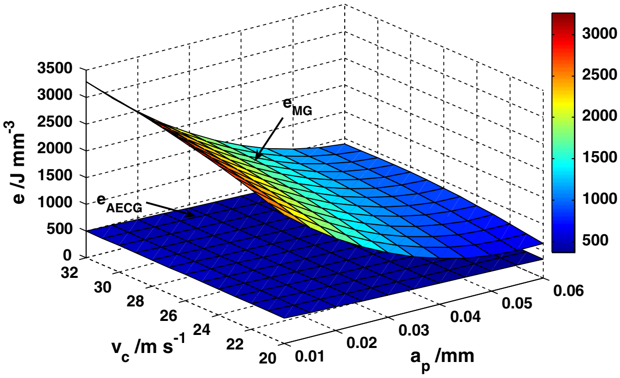

Fig. 2 Effect of cutting speed v_c and depth of cut a_p on specific energy consumption e for AECG and MG machining of sintered carbides B40, for $U = 7$ V, $v_{fx} = 112.5\ \mathrm{mm\ min^{-1}}$

resulted in an increase of energy consumption E in the case of both electrochemical and mechanical grinding. With increase in cutting speed in AECG machining, the energy consumption E increased insignificantly—less than 10% for B40 and 18G2A, and more than 30% for Ti6Al4V. For mechanical grinding the energy consumption increase E was greater: ca. 30% for B40, 70% for Ti6Al4V, 35% for 18G2A.

Increasing the depth of cut a_p resulted in an increase in energy consumption E for AECG machining on average by ca. 40% for B40, over 100% for Ti6Al4V and over 20% for 18G2A, and for MG machining by ca. 80% for B40, 70% for Ti6Al4V, 55% for 18G2A.

The investigation showed moreover, that electrochemical grinding of sintered carbides and steel with small values of the parameters considered resulted in higher energy consumption than that for MG machining. High values of the parameters reversed the relationship. Electrochemical grinding of the titanium alloy was characterized by lower energy consumption E than in the case of MG machining within the whole range of parameters employed. The highest energy consumption during both electrochemical and mechanical grinding was associated with the processing of sintered carbides B40.

Specific energy consumption for AECG machining of sintered carbides increases with cutting speed (by <10%) and decreases with increase in depth of cut (ca. 35%). For the case of AECG machining of titanium alloy, specific energy consumption increases with increase in cutting speed (over 30%). The increase within the adopted range of the depth of cut results in an insignificant increase in specific energy consumption (by <10%). From the results of AECG machining of 18G2A steel the conclusion is drawn that an increase in cutting speed results in an insignificant increase in specific energy consumption. For the case in question the latter decreased with increase in depth of cut (by ca. 50%).

For mechanical grinding the specific energy consumption increases with increase in cutting speed (by ca. 40% for B40, ca. 70% for Ti6Al4V and steel 18G2A). Increase in cutting depth results in a reduction in specific energy consumption (on average by ca. 3.5 times for B40, 4 times for Ti6Al4V and over 4.5 times for 18G2A).

Specific energy consumption for mechanical grinding turned out to be higher than that for electrochemical grinding within the whole range of parameters. The greatest differences are observed for low values of depth of cut; with its increase the difference in the respective values of specific energy consumption tend to decrease.

3.2 Effect of longitudinal feed speed v_{fx} and depth of cut a_p on energy consumption E and specific energy consumption e

Figure 3 shows energy consumption for AECG and MG machining of titanium alloy Ti6Al4V in relation to longitudinal feed speed v_{fx} and depth of cut a_p for constant values of inter-electrode voltage U and cutting speed v_c. Increasing both parameters results in increasing energy consumption for both types of machining. For the case of electrochemical grinding, increasing the longitudinal feed speed results in energy consumption increase by 50% for sintered carbides B40, 140% for titanium alloy Ti6Al4V and 25% for steel 18G2A, respectively. Varying the same parameter within the same range for mechanical grinding results in an increase in energy consumption by ca. 100% for sintered carbides B40, ca. 80% for titanium alloy Ti6Al4V and ca. 60% for steel 18G2A.

Figure 4 presents a 3-D diagram showing the dependence of specific energy consumption e on longitudinal feed speed v_{fx} and depth of cut a_p for AECG and MG machining of titanium alloy Ti6Al4V. AECG machining of titanium alloy, while increasing the longitudinal feed

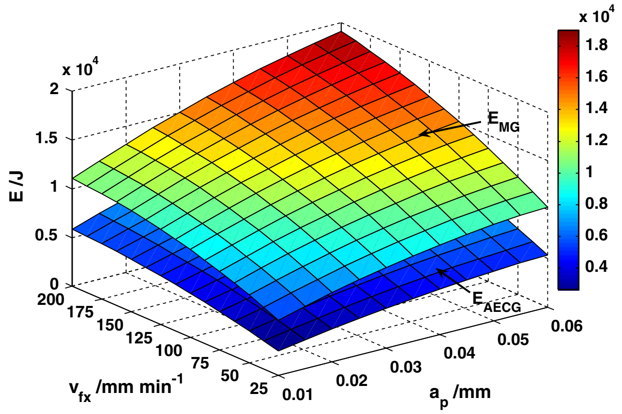

Fig. 3 Effect of longitudinal feed speed v_{fx} and depth of cut a_p on energy consumption E for AECG and MG machining of titanium alloy Ti6Al4V, for $U = 7$ V, $v_c = 16$ m s^{-1}

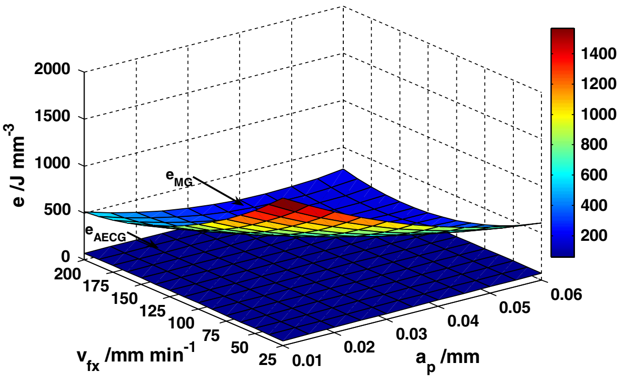

Fig. 4 Effect of longitudinal feed speed v_{fx} and depth of cut a_p on specific energy consumption e for AECG and MG machining of titanium alloy Ti6Al4V, $v_c = 16$ m s^{-1}, $U = 7$ V

speed, reveals an insignificant increase in specific energy consumption (by ca. 10%). For the case of AECG machining of sintered carbides and steel, the increase in longitudinal feed speed results in a decrease in specific energy consumption by ca. 40%.

Increasing the longitudinal feed speed v_{fx} during MG machining results in decreased specific energy consumption e (on average over 3.5 times for B40 and for Ti6Al4V and over 4 times for 18G2A). Within the whole range of the investigated parameters the specific energy consumption of MG machining turned out to be higher than that for AECG machining.

3.3 Effect of inter-electrode voltage U and depth of cut a_p on energy consumption E and specific energy consumption e for AECG machining

The effect of inter-electrode voltage U and depth of cut a_p on energy consumption E for AECG machining of steel 18G2A is represented in Fig. 5. An increase in both parameters results in an increase in energy consumption for AECG machining. The increase in inter-electrode voltage within the range 4–10 V was followed by an increase in energy consumption by ca. 180% for sintered carbides B40, 30% for titanium alloy Ti6Al4V and ca. 250% for steel 18G2A.

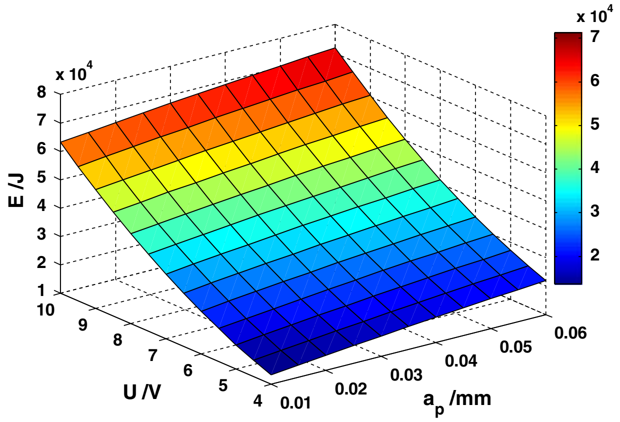

Fig. 5 Effect of inter-electrode voltage U and depth of cut a_p on energy consumption E for AECG machining of steel 18G2A, for $v_{fx} = 112.5$ mm min^{-1}, $v_c = 26$ m s^{-1}

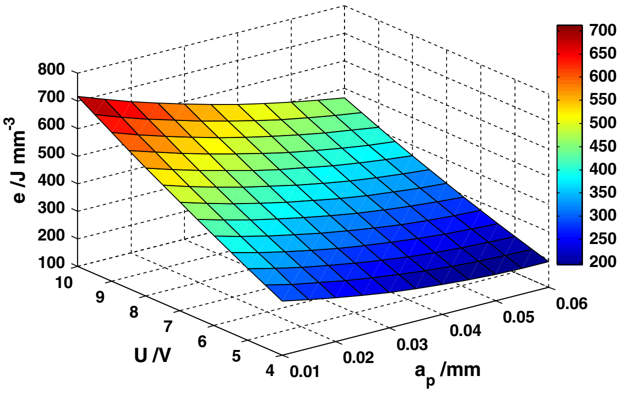

Fig. 6 Effect of inter-electrode voltage U and depth of cut a_p on specific energy consumption e for AECG machining of steel 18G2A, $v_{fx} = 112.5$ mm min^{-1}, $v_c = 26$ m s^{-1}

Figure 6 shows the effect of inter-electrode voltage U and depth of cut a_p on specific energy consumption e for AECG machining of steel 18G2A. For the case of sintered carbides B40 and steel 18G2A, increase in voltage within the range 4–10 V results in an increase in specific energy consumption by respectively ca. 65% and 160%. AECG machining of titanium alloy with the inter-electrode voltage increasing in the given range, was followed by a decrease in specific energy consumption by ca. 20%.

4 Discussion & conclusions

Electrochemical grinding of hard-to-machine materials constitutes a less energy-consuming process than traditional mechanical grinding within the range of parameters employed. This is clearly seen in diagrams of specific energy consumption e for both types of machining. Application of auxiliary electrical devices, like the electrode power supply, in electrochemical grinding, does not increase the energy consumption above the level obtained for conventional grinding, in spite of the fact that the electrochemical process plays a dominant role in removing the surplus material. Specific energy consumption for mechanical grinding was higher than that for electrochemical grinding on average by a factor of: for B40—ca. 4, for Ti6Al4V—over 6.5, for 18G2A—over 3. The specific energy consumption, that is the energy consumed by the machine-tool in order to remove a unit volume of material surplus, is a more objective indicator than the "pure" energy consumption E of machining. Nevertheless, the value of this indicator (E) has also not revealed an excessive energy consumption for AECG machining with respect to MG machining. The average energy consumption for electrochemical and mechanical grinding of sintered carbides B40 and steel 18G2A have a similar value (difference ca. 10%). Mechanical grinding of titanium alloy Ti6Al4V resulted in the average energy consumption being higher by ca. 70% than that for electrochemical grinding.

The main reason for the above results is lower cutting resistance in the electrochemical grinding process compared to conventional grinding. This is a characteristic advantage of AECG machining resulting from synergetic interaction of its component processes. This clearly lower specific energy consumption of AECG machining is also related to higher yield than that attained in conventional grinding of hard-to-machine materials.

An analysis of the effect of the investigated factors on energy consumption and specific energy consumption for electrochemical grinding and mechanical grinding of the sample hard-to-machine materials made it possible to draw the following general conclusions:

- An increase in cutting speed v_c produces an insignificant increase in energy consumption E and specific energy consumption e for electrochemical grinding and a much more pronounced increase for mechanical grinding (on average ca. 50%)
- Increasing the depth of cut a_p results in an increase in energy consumption E of both types of machining and in a decrease in specific energy consumption e (much higher for mechanical grinding)
- An increase in longitudinal feed speed v_{fx} produces an increase in energy consumption E for both types of machining and a decrease in specific energy consumption e (decidedly higher for MG machining)
- Increasing inter-electrode voltage U results in an increase in energy consumption E (more pronounced) as well as in specific energy consumption e for electrochemical grinding.

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