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Electrodischarge and electrochemical grinding of special materials

Abstract

In Electrochemical Machining (ECM), material is removed “atom by atom” as the result of an electrochemical dissolution process. Under optimal parameters for this process the tool has no wear and the quality of the surface layer, metal removal rate and accuracy are satisfactory for special application in the automotive or aerospace industries. However, ECM has also some limitations connected with electrolyte flow through interelectrode gap, machined surface passivation phenomena or heat and hydrogen generation, quick temperature increase and high probability of electrical discharges and difficulties with machining composite materials. In Electrodischarge Machining (EDM), material from workpiece is removed during electrical discharges occurring in the machining area as a result of material melting, evaporating and sometimes breaking as a result of high internal stresses. This way of material removal introduces significant changes in surface layer properties and reaching a satisfactory surface layer roughness and high accuracy is possible only for a rather small metal removal rate.

In order to overcome the above-mentioned problems, some hybrid abrasive ECM and EDM processes have been worked out and successfully applied in industry. Here, some results from the authors’ own research, industrial applications and data from the literature are presented.

Key words: Electrodischarge machining (EDM), electrochemical machining (ECM), hybrid electrodischarge grinding AEDM), hybrid electrochemical grinding (AECM), surface layer properties.

Szlifowanie elektroerozyjne i elektrochemiczne materiałów specjalnych

Streszczenie

W obróbce elektrochemicznej (ECM) materiał usuwany jest „atom po atomie” w wyniku procesu roztwarzania elektrochemicznego. W procesie tym przy zastosowaniu optymalnych parametrów nie występuje zużycie narzędzia, a jakość warstwy wierzchniej, prędkość usuwania materiału oraz dokładność są zadowalające dla specjalnych zastosowań w przemyśle samochodowym, lotniczym i kosmicznym. Obróbka ECM posiada też pewne ograniczenia związane z przepływem elektrolitu przez szczelinę międzyelektrodową, zjawiskami pasywacji obrabianej powierzchni, generowaniem ciepła oraz wodoru, szybkim wzrostem temperatury i dużym prawdopodobieństwem wyładowań elektrycznych oraz trudnościami w obróbce materiałów kompozytowych. W obróbce elektroerozyjnej (EDM) ubytek materiału z przedmiotu obrabianego realizowany jest podczas wyładowań elektrycznych występujących w obszarze obróbki w wyniku topienia, parowania, a czasem pękania materiału w wyniku dużych naprężeń wewnętrznych. Taki sposób usuwania materiału wprowadza znaczące zmiany właściwości warstwy wierzchniej, a osiągnięcie zadowalającej chropowatości warstwy wierzchniej i wysokiej dokładności obróbki jest możliwe przy stosunkowo niewielkiej prędkości usuwania materiału.

W celu przezwyciężenia powyższych problemów, opracowano i z powodzeniem zastosowano w przemyśle hybrydowe procesy ścierne ECM oraz EDM. Poniżej przedstawiono wybrane wyniki badań własnych autorów, jak również zastosowania przemysłowe oraz dane literaturowe.

Kluczowe słowa: obróbka elektroerozyjna (EDM), obróbka elektrochemiczna (ECM), obróbka hybrydowa – szlifowanie elektroerozyjne AEDM), obróbka hybrydowa – szlifowanie elektrochemiczne (AECM), właściwości warstwy wierzchniej.

1. Introduction

In modern automotive or aerospace industrial production there is an increasingly broad application of special materials. This is usually a consequence of their high mechanical or special chemical properties. Metallic alloys or metal matrix composites play a very significant role here. In manufacturing details made of these special materials it is usually necessary to take into account both the technical and economic aspects. So, it is necessary to reach as high as possible metal removal rate, required quality of surface layer properties, micro and nano-geometry and satisfactory accuracy. Because of these facts, very often the electrodischarge (EDM), electrochemical (ECM), classical grinding or hybrid manufacturing processes created between them are applied (Grzesik, Ruszaj, 2021; Kozak, 2018; Masuzawa, Takawashi, 1998; Ruszaj, 1999; Ruszaj, Grzesik, 2012; Ruszaj, 2017; Satyarthi, Pandey, 2013). In hybrid processes material is removed simultaneously as a result of melting and evaporating (EDM), electrochemical dissolution (ECM) or mechanical forces between the machined surface and abrasive grains (grinding). These processes can be applied in macro- and micro-detail manufacturing. The border between micro- and macro-machining is usually taken as one (1.0) mm. In industry, the application of the Micro-Electro-Mechanical Systems (MEMS) from one year to another significantly increases.

Here, we must very often apply mechanical parts smaller than 1 mm (microparts) and for their manufacturing in many cases classical manufacturing processes and their hybrid variants are applied, as well as electrochemical and electrodischarge grinding processes (Grabowski, Skoczypiec, Wyszyński, 2018; Grzesik, Ruszaj, 2021; Hackert-Oschaetzchen et al., 2012; Liu et al., 2014; Luo, Qin, 2018; Nagata et al., 2000; Ruszaj, Skoczypiec, Wyszyński, 2017; Ruszaj, Cygnar, 2019). Their application makes it possible to reach a relatively high metal removal rate with accuracy and with satisfactory surface layer properties.

In the paper below, based on our own research and the literature, the characteristics of the main phenomena occurring in the machining area and their influence on the properties of the machined surface and values of some technological indicators for hybrid machining processes such as electrodischarge and electrochemical grinding are presented and discussed.

2. Electrodischarge Machining – EDM

This process is applied for shaping electrically conducting materials as a result of material melting and evaporating during electrical discharges occurring in the dielectric fluid which has filled the space between the machined material and electrode-tool (Figure 1).

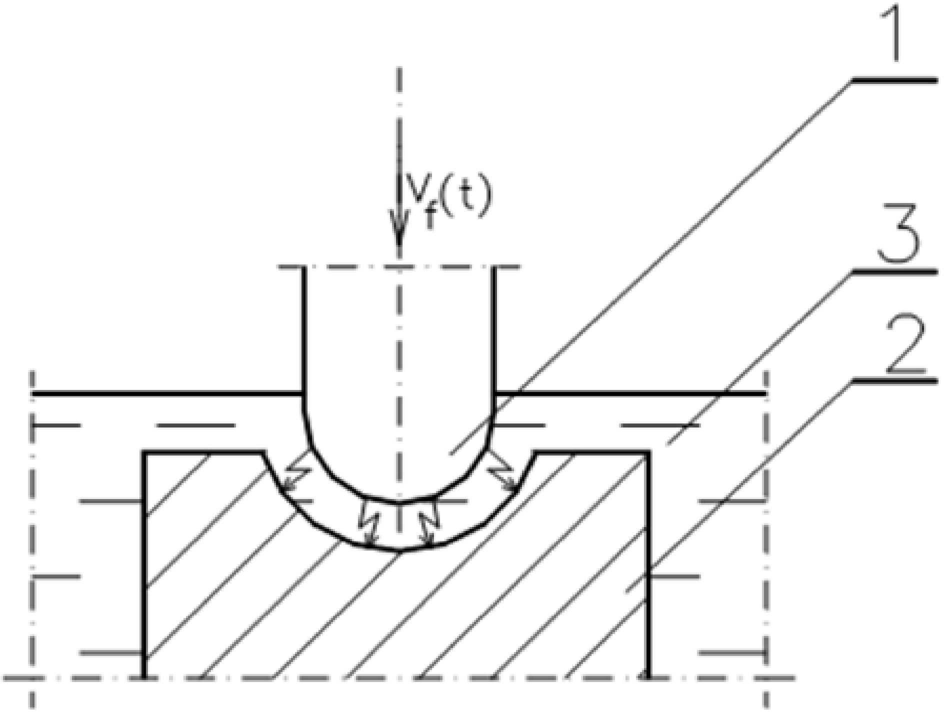

Figure 1. Scheme of Electrodischarge Machining (EDM): 1 – electrode-tool (cathode); 2 – workpiece (anode); 3 – container with dielectric: Vf (t) velocity of electrode-tool displacement

(source: Grzesik, Ruszaj, 2021; Ruszaj, 1999)

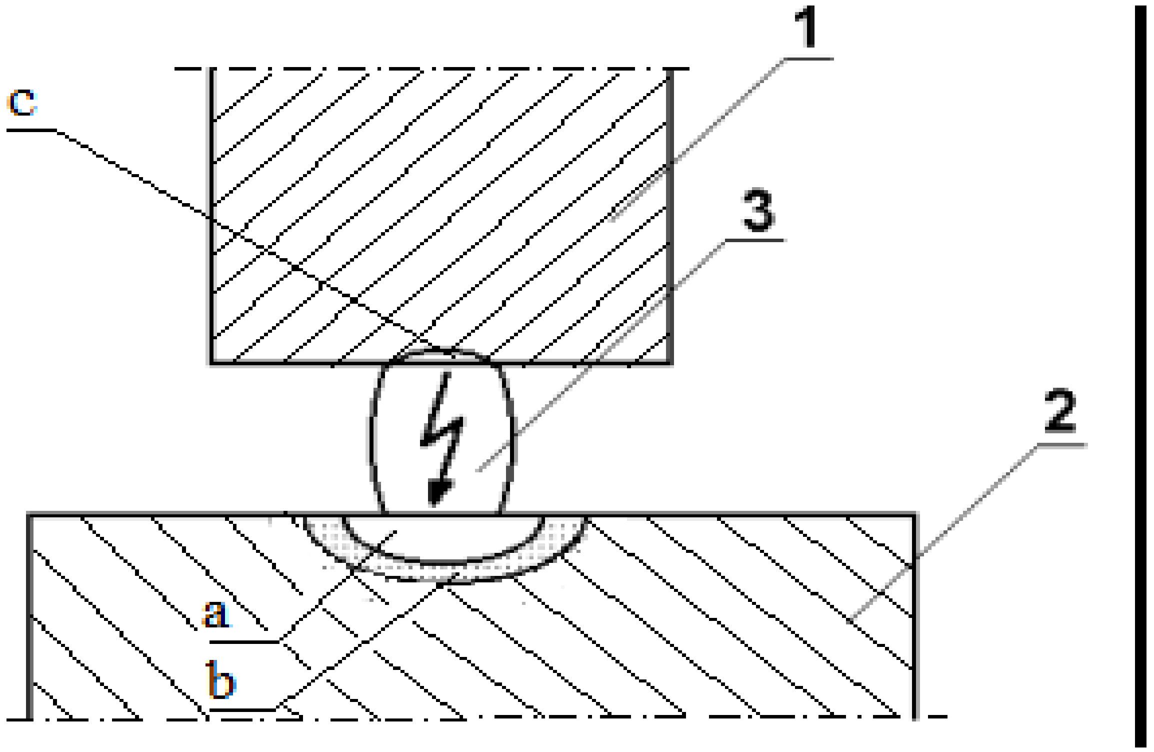

Figure 2. Scheme of area of one electric discharge: 1 – electrode-tool; 2 – workpiece; 3 – electrical discharge channel created in the dielectric between the workpiece and the electrode-tool; a – volume of machined material removed as a result of material evaporating; b – volume of machined material removed as a result of melting; c – volume of material removed as a result of evaporation and melting from electrode-tool – this is electrode-tool wear displacement

(source: Grzesik, Ruszaj, 2021; Ruszaj, 1999)

The above-described way of machining can be applied for shaping parts made of metals, alloys and conductive composite materials with a high metal removal rate independent of their structure and mechanical properties, and with an accuracy of T = 0.01-0.1 mm. This is in many cases satisfactory in processes involving plastic deformation (such as embossing, injection moulding. punching, stamping), alloying (casting moulding) or injection moulding. Very important is the possibility of shaping microdetails (usually smaller than 1 mm). Generally, EDM offers the possibility of machining with high reliability in material removal, which makes full automation of the production process possible (Grzesik, Ruszaj, 2021; Kozak, 2018; Ruszaj, 1999; Ruszaj, Grzesik, 2012).

The main disadvantages of EDM are: electrode-tool wear and surface layer properties that are poorer and significantly worse than in cutting processes. This results from the fact that material is removed as the result of melting and evaporation. So, in many cases it is necessary to apply finishing operations such as smoothing in order to decrease surface roughness or remove a compromised surface layer with low mechanical properties due to microcracks and sub-optimal metallographic structure, which increase the total time and costs of machining. The metal removal rate is satisfactory for shaping materials that are difficult to cut or with sophisticated sculpted surfaces (Grzesik, Ruszaj, 2021; Kozak, 2018; Ruszaj, 1999; Ruszaj, Grzesik, 2012).

In a majority of cases, fluids based on petroleum are applied as the dielectric. They are flammable and have bad influence on their environment. In many operations (for example, Wire Cutting EDM) distilled water can be applied as the dielectric fluid.

3. Electrochemical Machining – ECM

In the case presented in Figure 3, material from the workpiece surface is removed in the reaction: $Fe – 2e \rightarrow Fe^{++}$, basic cathodic reaction is hydrogen evolution in the reaction: $2H^{+} + 2e \rightarrow H_2$. This means that in cathodic reactions the dimensions of the working electrode do not change during the process, and this allows for the production of a large number of parts; for instance, aircraft engine turbine blades, using the same working electrode – there is no electrode-tool wear (Masuzawa, Takawashi, 1998).

This way of machining gives the possibility of a high metal removal rate for materials that are difficult for cutting or have a complicated shape. At the same time, thanks to the fact that material is removed atom by atom for optimal parameters of electrolyte flow, it is possible to achieve low surface roughness – the surface roughness parameter Ra is usually lower than one micrometre (1 μm).

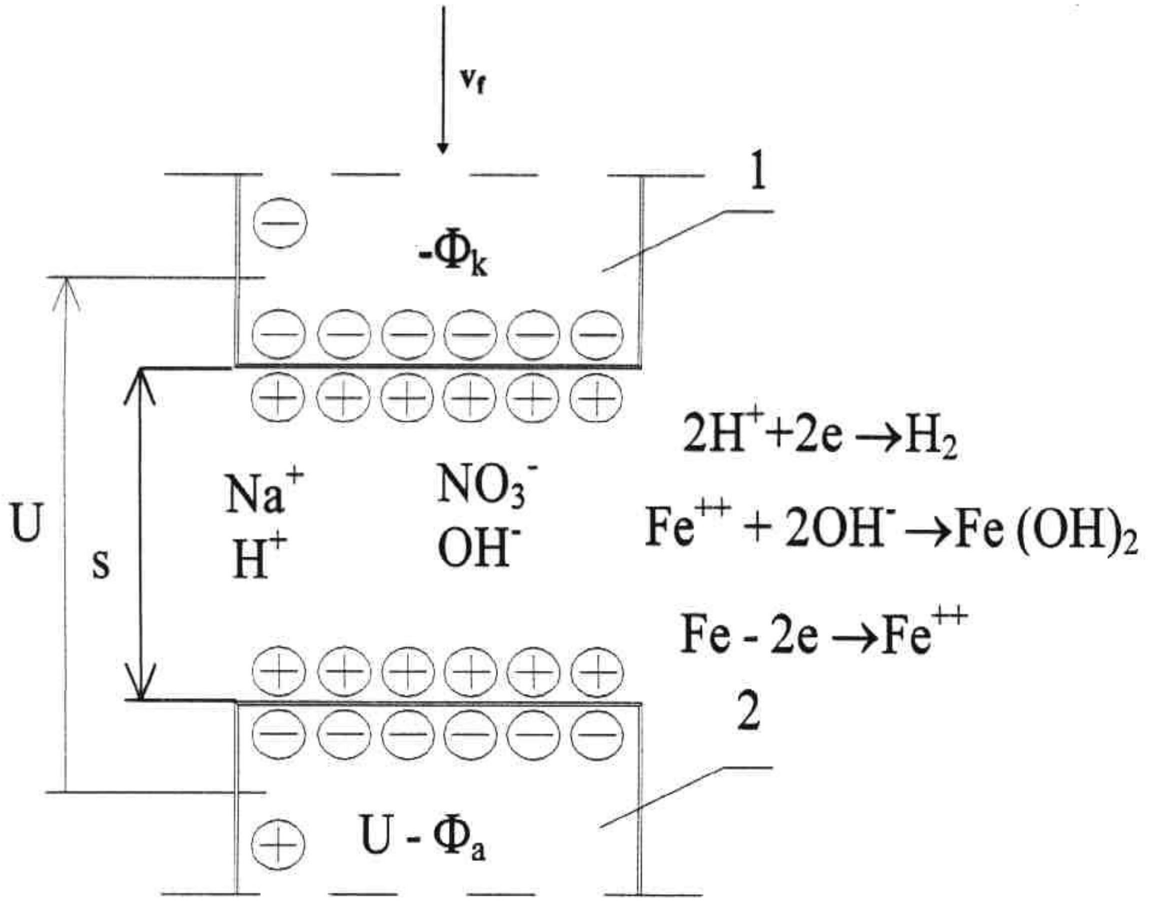

Figure 3. Simplified scheme of inter-electrode zone in ECM process in the case of machining iron element (Fe) using as electrolyte water solution of NaNO3: 1 – electrode-tool; 2 – workpiece; Φa, Φk – electrode potentials; U – constant or pulse interelectrode voltage; S – thickness of interelectrode gap

(source: Grzesik, Ruszaj, 2021; Ruszaj, 1999)

The ECM process has the following significant advantages (Grzesik, Ruszaj, 2021; Ruszaj, 1999; Kozak, 2018): no electrode-tool wear, high metal removal rate (significantly higher than in electrodischarge machining) and usually a good surface quality is achieved (machining allowance is removed atom by atom via the electrochemical dissolution process at a temperature lower than 100°C, which introduces no significant changes in the surface layer properties of the machined material). Additionally, machining productivity does not depend on the material's mechanical properties. The above-mentioned advantages make electrochemical machining (ECM) an important method in the macro- and micro-machining of 3D-sculpted surfaces. Any allowance in ECM micromachining can be removed by such operations as electrochemical sinking or milling with the application of a universal electrode-tool (3D-ECMM) (Grzesik, Ruszaj, 2021; Ruszaj, 1999; Kozak, 2018; Ruszaj, Cygnar, 2019).

4. Classical Grinding Process

In the classical grinding process, the tops and edges of abrasive grains are in contact with the workpiece material and, as a result of the cutting process, remove some volume of workpiece material. The abrasive grains are held together by a special material and create a special grinding "tool". In the grinding process the grinding wheel's interaction with the workpiece takes place as a relationship with each individual abrasive grain (Grzesik, Ruszaj, 2021; Ruszaj, 1999). The "lifetime of abrasive grain", as it is known, and machined surface quality indicators depend on the abrasive grain material, binder material, machined material properties and machined process parameters. The mechanical and physical properties of the machined material are very important. Because of this, in some cases the grinding process is combined with electrodischarge and/or electrochemical machining processes. The recent dynamic development of hybrid manufacturing processes is a consequence of the application in advanced industry of new alloys, composite and ceramic materials that are difficult for traditional machining (Grzesik, Ruszaj, 2021; Ruszaj, 1999; Ruszaj, Grzesik, 2012; Ruszaj, 2017; Satyarthi, Pandey, 2013). Important reasons in the development of hybrid processes are the increasingly high demands in the areas of detail reliability, dimensional accuracy and surface layer quality. Some hybrid processes, such as electrochemical grinding, have been used in industry for a long time. However, there are still some interesting aspects of this process in research and applications. The other hybrid processes such as, for example, electrodischarge grinding also offer new technological possibilities. The above-mentioned aspects of EDM and ECM hybrid processes development and applications are presented below.

5. Abrasive Electrodischarge Machining Process

It is worth to underline that in the Abrasive-Electrodischarge Machining Process (AEDM), material allowance is removed as a result of melting and evaporating during electrical discharges and micro-cutting by abrasive grains. These processes support each other.

The advantages of the process were the reason for starting investigations into the field of electrodischarge-grinding (AEDG) process development. In the Abrasive Electrodischarge-Grinding Process, as the tool is applied, the grinding wheel with metallic binder and interelectrode space is filled with dielectric fluid – as in the classical contactless EDM process. Electrical discharges occur between the grinding wheel's metallic binder and the workpiece. Machined material (allowance) is removed as a result of melting, evaporation and mechanical removal by the grinding wheel's abrasive grains. The advantages of introducing electrical discharges into the grinding process are as specified below (Grzesik, Ruszaj, 2021; Ruszaj, Grzesik, 2012; Satyarthi, Pandey, 2013; Ruszaj, Skoczypiec, Wyszyński, 2017):

- the products of micro-cutting are easily removed from the grinding wheel's working surface – however, this process significantly decreases the speed of the bonding process;
- new abrasive grains are disclosed on the grinding wheel's working surface;
- the empty free spaces between abrasive grains are increased.

Because of the above-mentioned reasons, when comparing classical grinding with AEDG:

- cutting grinding wheel properties are significantly better in comparison with the classical process and grinding wheel lifetime is usually increased;
- process energy consumption is decreased by 5 to 40 % – this is a result of the decreased frictional forces between the machined surface and the grinding wheel binder;
- there is a significant decrease (of 1.3 to 1.5 times) in the cutting forces.

Usually, the main disadvantage in comparison with classical grinding is higher surface roughness and the possibility of corrosion to metallic parts when a water-based dielectric is applied. Examples of materials machined efficiently in AEDG are: cemented carbide, magnetic or titanium alloys, composite materials on a metallic base such as AlSiC, PCD, Inconel 601, technical ceramic, Al-SC (Duralcan F3D 20S) Duralcan F3D 20S, ceramic materials such as: Si3N4 + TiN.

Each of the AECM or AEDM machining methods has its own optimal range of application.

For some modern materials, very efficient shaping can be a combination of the AECM and AEDG processes. In this case such processes as micro-cutting, melting, evaporation, microcracking and electrochemical dissolution take part in material removal (Grabowski, Skoczypiec, Wyszyński, 2018; Grzesik, Ruszaj, 2021; Luo, Qin, 2018; Ruszaj, Skoczypiec, Wyszyński, 2017).

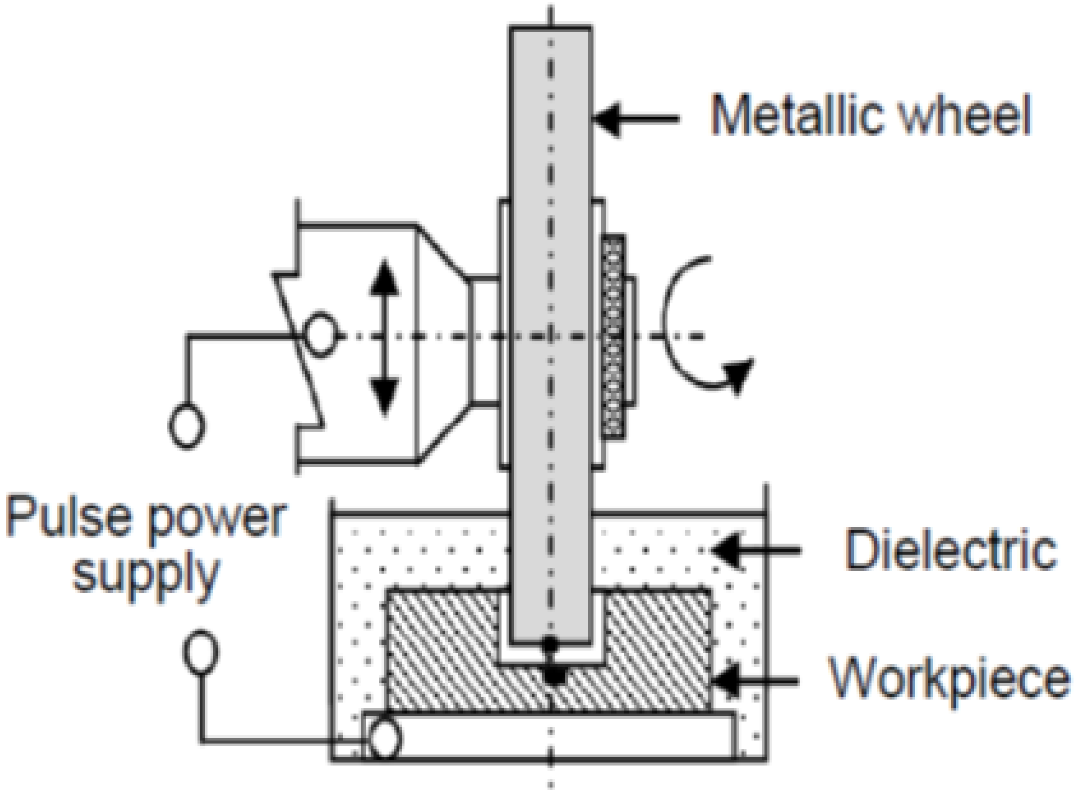

Figure 4. Scheme of electro-discharge grinding (EDG) process in classical flammable dielectric fluid

(source: Grzesik, Ruszaj, 2021)

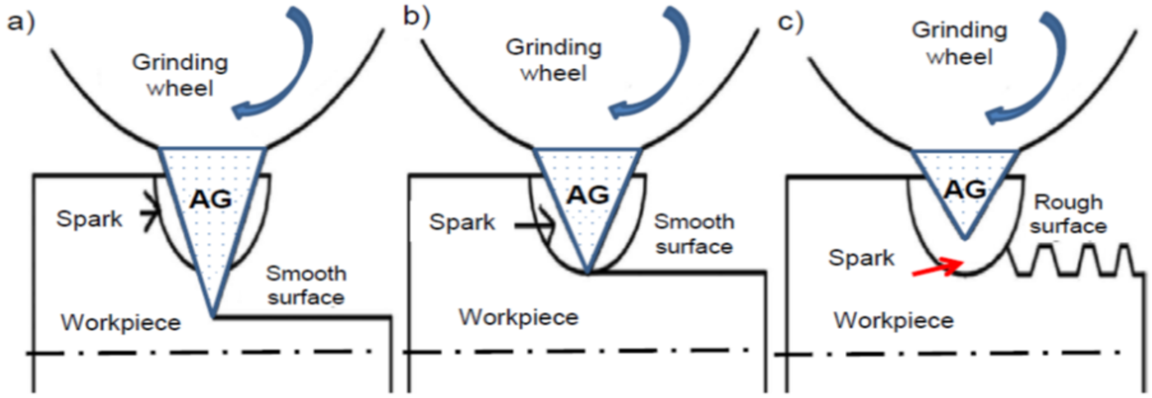

Figure 5. Mechanism of material removal in AEDG process schemes of various variants of electro-discharge grinding process: a) the machining depth is higher than depth of discharge craters; b) machining depth is equal to depth of discharge craters; c) machining depth is lower than depth of discharge craters. Symbol: AG – abrasive grain

(source: Nagata et al., 2000; Ruszaj, Grzesik, 2012; Grzesik, Ruszaj, 2021)

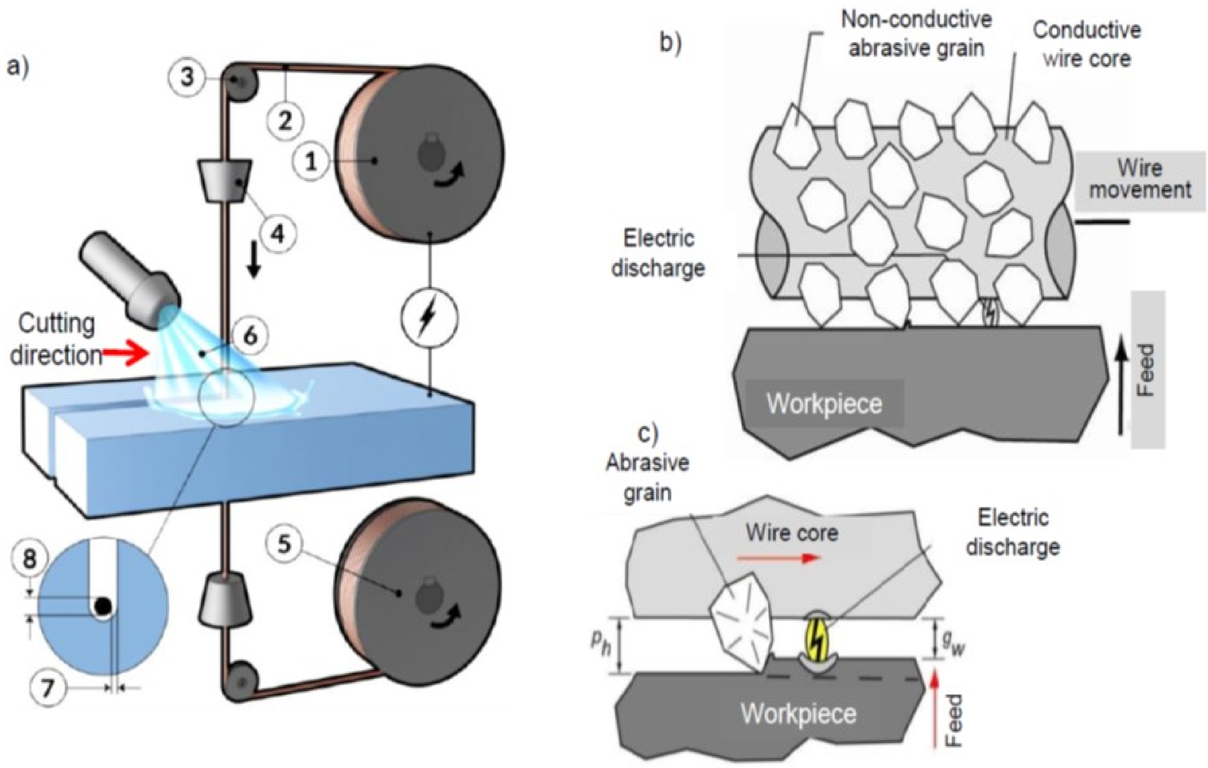

Figure 6. Abrasive-wire electro-discharge cutting: a) principle of the process when non-flammable dielectric fluid is applied; b) movement of wire with bonded abrasives; c) synergy between the grain abrasion and electric discharge [2, 8, 9]. Symbols: 1 – wire feeder; 2 – wire with bonded abrasives; 3 – tension roll; 4 – wire guide; 5 – tension roll for worn wire; 6 – dielectric jet; 7 – working gap (kerf); 8 – wire diameter

(source: Grzesik, Ruszaj, 2021)

When it is necessary to apply a WEDM process in the way presented in Figure 6, non-flammable dielectric (deionised water) must be applied.

6. Abrasive Electrochemical Machining Process

Electrochemical grinding has been applied in industry for many years; however, it is still connected with some difficulties, such as the working fluid (electrolyte) generating corrosion in machine-tools and equipment made of metallic materials. Because of this, machine-tools and technical equipment should be made of materials with high resistance to chemical and electrochemical corrosion. The electrochemical grinding machine tool must be equipped with a system for supplying and draining electrolyte, and because of this it is necessary to have a large space for its installation (Grzesik, Ruszaj, 2021; Ruszaj, 1999). Very often the products of electrochemical dissolution and grinding processes are hazardous to people's health. In addition, in the ECM grinding process the products of electrochemical dissolution are deposited on grinding wheel's surface which very quickly diminishes its cutting ability and increases the temperature in the machining area. Because of this the grinding wheel must frequently be regenerated in dressing process. Sometimes it is enough to apply (introduce) the EDM process from time to time and regenerate the grinding- tool's cutting ability.

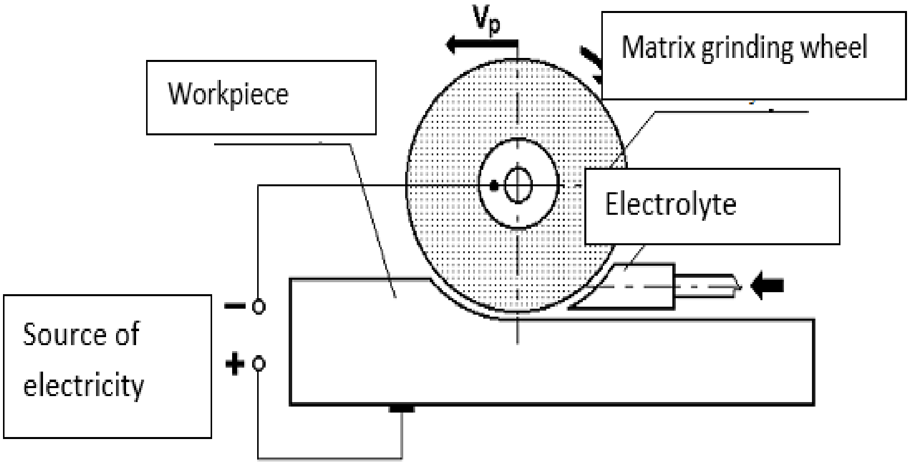

Figure 7. Scheme of electrochemical grinding process when using a cylindrical grinding wheel (source: Ruszaj, 1999)

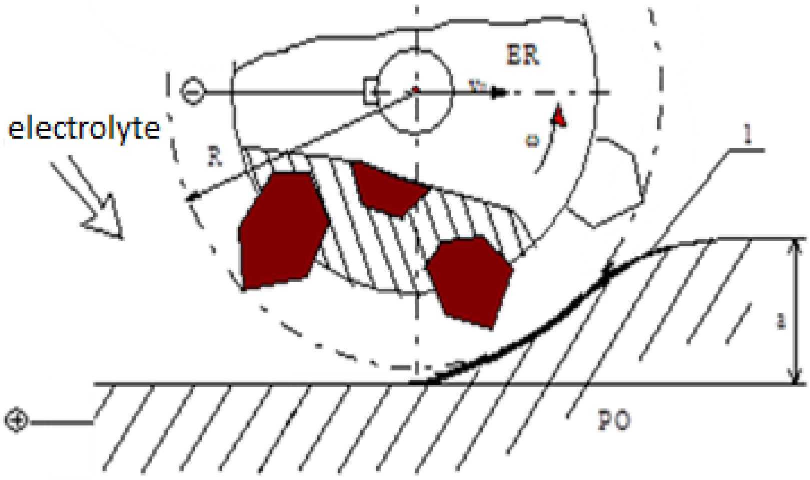

Figure 8. Scheme of machining area in electrochemical grinding process when using a cylindrical grinding wheel: 1– dissolute surface layer removed by abrasive grains; PO – workpiece; ER – electrode grinding-tool

(source: Ruszaj, 1999)

On the basis of information in the literature and our own research, the very important applications of electrochemical grinding process could be:

- ECM grinding of curved linear surfaces (Figure 9) when using a universal spherical electrode;
- grinding micro-surfaces – abrasive micromachining processes (Figure 10).

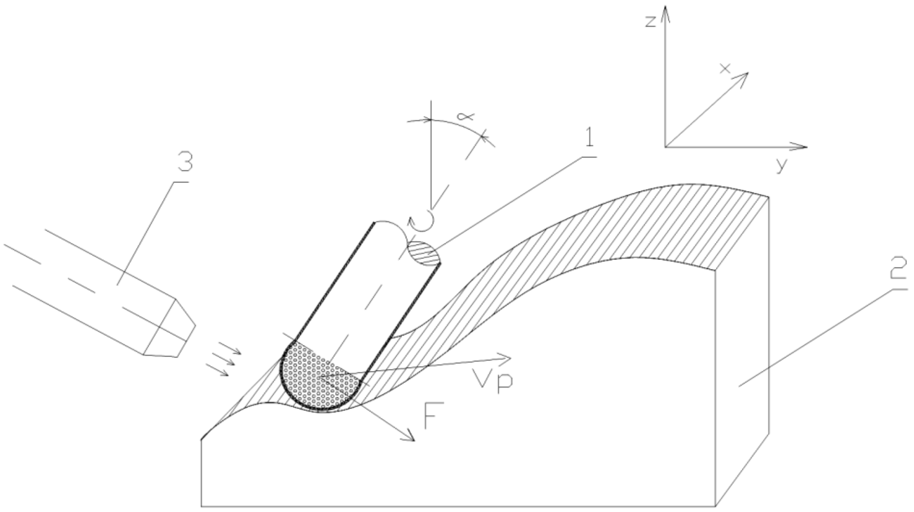

Figure 9. Scheme of machining (usually finishing) of curved linear surfaces: 1 – electrode tool, 2 – workpiece, 3 – Nozzle for electrolyte supplying; F – machine force, Vp – vielocity of electrode

(source: Grzesik, Ruszaj, 2021)

The main advantage of a spherical grinding electrode tool is the fact that it can be applied for smoothing curved linear surfaces. The spherical electrode tool can be displaced according to specially designed track, as presented in Figure 9. When the electrochemical grinding process is applied in the case described, the metal removal rate and the lifetime of spherical grinding tool are significantly higher than in the classical grinding process (Grzesik, Ruszaj, 2021; Ruszaj, Grzesik, 2012; Ruszaj, 1999).

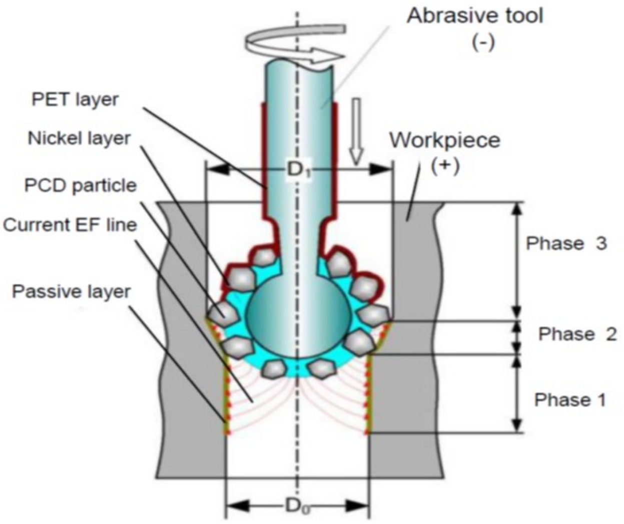

Figure 10. Scheme of finishing electrochemical grinding of micro holes with diameter D_o, 1, 2, 3 – stages of machining process, $D_1 = 0.6$ mm

(source: Grzesik, Ruszaj, 2021)

In the case presented in Figure 10, the application of the classical grinding process is impossible since because of the high micro-cutting forces the electrode-tool's lifetime is almost zero. The introduction of the electrochemical dissolution process decreases cutting forces and increases electrode-tool's lifetime and material removal rate (Grzesik, Ruszaj, 2021).

7. Conclusions

In recent years, the expansion of technology in production processes such as electrochemical machining, electrodischarge machining or classical grinding has reached a higher level of development and made it possible to achieve greater requirements related to the metal removal rate or accuracy of manufactured elements and machined surface quality. However, there are some limitations in the above-mentioned methods' development. These limitations can be overcome when ECM, EDM or (end) classical grinding processes are applied simultaneously for machining. These processes of simultaneous machining are named "the hybrid processes". Using these – as described in the paper – has made it possible to achieve a higher metal removal rate, higher accuracy and better quality of surface layer properties when machining special materials in special operations. In the case of machining curvy-linear surfaces using a spherical electrode, this is only possible in the hybrid AECM process, because in the classical grinding process the life of a spherical grinding tool is very low (Figure 9). Similarly, in the case of micromachining (Figure 10), the classical grinding process cannot be applied because the cutting forces are too high (Grzesik, Ruszaj, 2021).

Generally, each manufacturing process has some technological limitations for reaching higher accuracy or efficiency in machining. Hybrid machining methods which can reduce these limitations have been widely developed and used. By combining several energy sources in one process, a synergy effect is obtained. In turn, the obtained results in the form of, e.g., machining efficiency and accuracy or machined surface quality are greater than for each process carried out separately.

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