Application of laser and electrochemical interaction in sequential and hybrid micromachining processes

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Abstract. One of the research and development trends in nowadays manufacturing technology is integration of different manufacturing techniques into single machine tool. In the first part of the paper possibilities, goals, reasons and advantages of thermal and electrochemical interaction have been characterized. As literature review indicates such a connection can be realized as sequential or hybrid machining. The second part of the paper focuses on detailed analysis of laser assisted electrochemical process. For this purpose, the mathematical model of workpiece heating has been developed. Based on obtained results and literature review possibilities of technical realization and potential application have been discussed.

Key words: laser beam, electrochemical machining, hybrid machining process.

1. Introduction

Production of micro-details is a dynamically developing area of production technologies application. In serial production the most popular methods are micro-cutting (turning, milling and drilling), micro-plastic forming and micro - laser beam machining. One can state that in the group of micromanufacturing methods application of unconventional technologies, such as electrochemical and electrodischarge machining, has a special place because of their high efficiency in shaping 3D structures. It is also worth to underline that this methods are not suitable for serial production and potential area of application is prototypes, technological tooling, MEMS parts and tools manufacturing.

As in the macromanufacturing, advanced materials play an increasingly important role in shaping microparts. The improved thermal, chemical, and mechanical properties of the material gives substantial benefits to the product design and performance, however makes the traditional machining processes unable to machine them in an economical way or to machine in general. Therefore, in the group of methods dedicated to machining of technological equipment, MEMS parts, functional prototypes and tools for micro-casting and micro-forming special attention is paid to the application of microcutting and unconventional processes such as the laser beam, electrodischarge and electrochemical machining. The recent development is focused on manufacturing of 3D-shaped surfaces. In case of microcutting the main problem during machining is connected with a size effect [1, 2]. Significant resistance limits its application to machining of 3D parts made of soft materials and dimensions $> 50\ \mu$m. Because of this fact a special attention is paid to unconventional processes such as: electrochemical (ECMM) and electrodischarge (EDMM) micromachining, however its disadvantages such as low precision and low productivity also affect quality of machining [3, 4].

One of the research and development trends in nowadays manufacturing technology is integration of different manufacturing techniques into a single machine tool. The goal of such a solution is to increase machining efficiency or shorten a production chain. In this aspect integration is defined as combination of different manufacturing technologies in a single workstation to obtain a product with high and clearly defined features. Such a solution can be justified by economical or synergetic reasons. In the first case it results in combine or complete machining and in the second one it leads to a hybrid process.

The combine machining involves at least two different machining technologies on the single machine tool or it links two different machine tools in production chain to obtain highly advanced product. The complete machining is connected with full shaping of the part on the single machine without fixing change. With application of combine and complete machining following advantages are connected: decrease of machining time (minimization of setup time), machining costs reduction and increase of product quality.

While the hybrid machining process (HMP) can be defined as a combination of different machining actions or phases to be used on the material being removed. The reasons for developing HMP are to make use of the combined or mutually enhanced advantages, and to avoid or reduce some adverse effects the constituent processes produce when they are individually applied [3–5]. An adequate selection of mechanical, thermal and chemical interaction on the machined material gives possibility to obtain beneficial technological solutions. As an example on can indicate ultrasonically assisted electrodischarge machining, ultrasonically assisted electrochemical machining, abrasive electrochemical grinding, abrasive electrodischarge grinding or electrochemical discharge machining [6, 7]. In the group of combined effects the special place takes thermal and electrochemical (especially laser ra-

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diation) interaction. Such combination can be implemented as sequential (complete or combine) machining or as hybrid machining process.

2. Electrochemical machining

Electrochemical machining (ECM) is an important technology, especially in machining difficult-to-cut alloys and to shape free form surfaces [3]. In ECM, material is removed by the electrochemical dissolution process, so part is machined without inducing residual stress and without tool wear. In comparison to conventional methods, the main advantages of ECM are as follows: material removal rate does not depend on material hardness, there is no tool wear during machining (when machining parameters are optimal), good surface quality after machining (there is no significant changes in surface layer). Such advantages make the electrochemical machining one of the most attractive method for manufacturing of micro 3D structures made of conductive materials [4, 8]. The one of the main problems in ECMM is to achieve high localisation of dissolution process, what define limits of machined detail accuracy and dimensions.

In order to improve the precision and efficiency of the ECM the electrochemical dissolution must be controlled and limited. One way to improve machining resolution is to locate process in the specific areas. Several studies aimed at improving the conditions of electrochemical dissolution were conducted. They include, among others: application of smaller inter electrode gaps, the use of insulated electrodes, processing with use of rotating electrode or the use of short voltage pulse processing [9–12].

One of the solutions to improve electrochemical machining accuracy can be integration with other technologies. In the next paragraphs the possibilities of laser beam application for this purpose has been discussed.

3. The possibilities of laser radiation and electrochemical dissolution interaction

The combination of the laser radiation and electrochemical impact on the machined material can be applied as combine process, where laser is applied to modify properties of surface layer (applying mask on the workpiece surface), and as a hybrid machining process, where two following variations can be distinguished:

- laser assisted electrochemical machining (LAECM, the reason of combination is to improve accuracy of electrochemical machining) [13–15],
- electrochemically assisted laser machining (EALBM, the reason of electrochemical effect introduction is improvement the workpiece surface layer quality by minimization of, typical for laser beam machining, heat affected zone [16, 17]. The process is carried in similar way to laser drilling or cutting, but the beam is run in electrolyte jet supplied from the jet nozzle connected to negative voltage pole and the workpiece is connected to positive voltage source. In laser machining, the precision of machining is limited by

the strong evaporation or melting. Thanks to electrochemical interaction re-deposition and thermal stress can hardly be avoided. The advantage of the process burr less and stress free processing in comparison to LBM.

In case of sequential connection of laser and electrochemical machining, the laser radiation is used for positive or negative workpiece surface masking, which then is electrochemically machined. The process is carried in similar way to the lithographic one, but instead of series of chemical treatments the laser radiation is applied.

The example of excimer laser application for positive mask registration on the titanium surface has been presented in [18, 19]. Process takes place in four steps: anodizing, laser masking, electrochemical dissolution and ultrasonic cleaning (Fig. 1). As was mentioned before, steps are similar to lithographic methods, but it is worth to mention following advantages i.e. relatively inexpensive way of mask registration (masking takes place in air, no major requirement for room cleanliness), environmentally friendly processing (significantly less chemicals agents) and greater process flexibility (the process is more effective in short and prototype series). While the disadvantages includes relative (in comparison to lithography) long time of mask registration (tens of minutes). The example of this process possibility has been presented in Fig. 2.
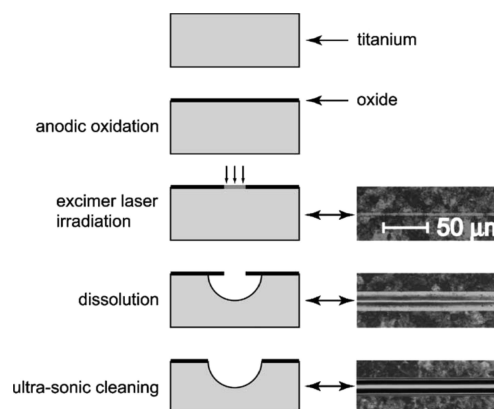

Fig. 1. Scheme of the laser – electrochemical sequence applied to structuring the titanium alloy after Ref. 19
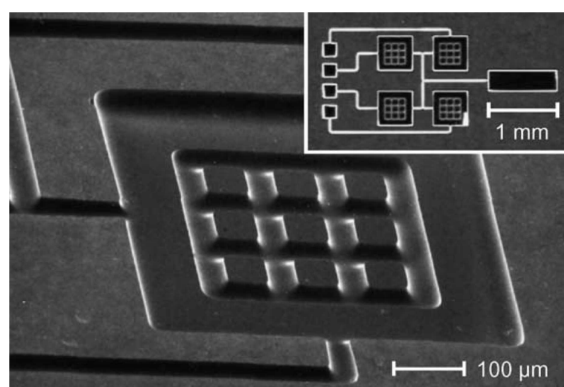

Fig. 2. Example of application laser beam masking and electrochemical dissolution sequence to structuring titanium alloy. The structure consisting of four arrays of grooves has been etched in two levels into larger cavities linked by channels after Ref. 19

A focused laser beam can be also used to apply negative mask on the workpiece surface (Fig. 3). As the result of the laser impact thin layer of nonconductive oxides Cr_2O_3, FeO and Fe_2O_3 and some structural changes on the workpiece surface occur [20–22]. These areas are characterized by significantly lower electrical conductivity and therefore, a ratio of electrochemical dissolution is smaller in comparison with a native material. Thanks to fiber optics and technological equipment positive laser masking and electrochemical dissolution can be carried out on the same machine tool. Electrochemical dissolution takes place in water solution of $NaNO_3$ with interelectrode voltage $U = 11.5$ V, pulse time $t_i = 50$ μs, pause time $t_p = 500$ μs and relative big interelectrode gap $S_o = 200$ μm. Sequence of laser masking and electrochemical dissolution can be repeated a few times, what extends capabilities of this method in comparison to other lithographic one (Fig. 4).
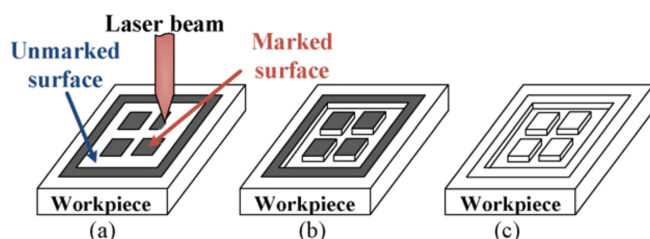

Fig. 3. Scheme presents the laser beam application for registering the negative mask on the electrochemically dissolved surface: a) registering the mask, b) electrochemical dissolution and c) ultrasonic cleaning after Ref. 22
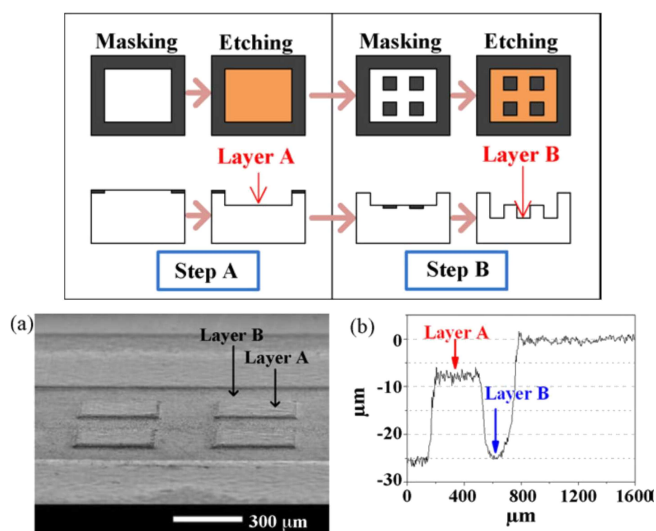

Fig. 4. Example of laser beam and electrochemical etching sequence application for multi-step microstructuring of the steel after Ref. 22

It should be mentioned that area of the laser beam and electrochemical dissolution sequence application is surface machining i.e. microstructuring for medical application. Due to problems of reliable laser beam masking such methods have limited possibility of application in 3D sculptured machining.

4. Laser assisted electrochemical machining

4.1. Physical fundamentals of the electrochemical process laser assistance.
From thermodynamic point of view the electrochemical anodic dissolution begins, when the energy of the metal ions become higher than the desired reaction activation energy E_a. In general, it can be stated that to achieve good machining effects two solutions occur: decrease of the activation energy barrier or increase of the energy of the metal ions located in an inner Helmholtz plane of electrical double layer between anode and electrolyte.

In the first case it is realized by a set of the proper positive overpotential of the workpiece surface, which results from electric field distribution and relation between diffusion, convection and migration of ions in an electrolyte layer adjacent to the workpiece. Speed of an electrochemical process is a function of current density, so according to the Buttler-Volmer equation [23] electric field and overpotential distribution over the workpiece surface defines the amount of machined material in desired areas of the workpiece. Therefore, to achieve necessary in micromachining high electrochemical process localization, the primary current density which results from uniform distribution of electric field has to be modified. The main research trends in this area is to apply the voltage pulses in range of micro to nanosecond [8–11].

The activation energy of the electrochemical reaction is determined by the electrical potential and temperature. At a higher temperature there is a greater proportion of electroactive ions with the required activation energy $E \geq E_a$. Changing the temperature does not however change the activation energy but only changes the frequency of collisions and the proportion of reactants with the kinetic energy E that is greater than or equal to the activation energy E_a necessary to disintegrate crystalline structure (break up the ionic lattice and separate the ion). The effect of temperature on the rate of these processes is described by following Arrhenius equation:

$$i_L = i_0 \exp\left(\frac{E_0 \Delta T}{RT_0\left(T_0 + \Delta T\right)}\right), \tag{1}$$

where T_0 – initial surface temperature, ΔT – temperature increase due to laser irradiation, i_0 – current density during electrochemical process without heating, i – current density during electrochemical process thermally enhanced, R – gas constant, E_a – activation energy. Presented on the Fig. 5 relations indicate, that increase of workpiece surface temperature results in several time current density increase. This effect is strongly dependent on the E_a value – the higher E_a then the temperature increase gives better results. For electrochemical anodic dissolution E_a is about 30 kJ/mol but for deposition (inverse process) is much higher, what cause that this method is more effective for the electrochemical additive process. It has to be underlined, that the current density i increase is limited by the electrolyte boiling temperature and speed of electroactive ions diffusion (limited current i_L) [23].

From the above presented discussion, it can be stated, that application of selective area workpiece heating gives a possibility to localize the electrochemical dissolution. The heat source has to be local, rapid and easy controllable, therefore

the laser radiation is preferred in this kind of application. The advantages of laser beam heating over the other heating methods are the rapid, high and local temperature rise of the heated surface (the only desired volume of material can be heated). Therefore, the heat affected zone and thermal distortion by the laser beam are small due to the controllable spot size and power density.
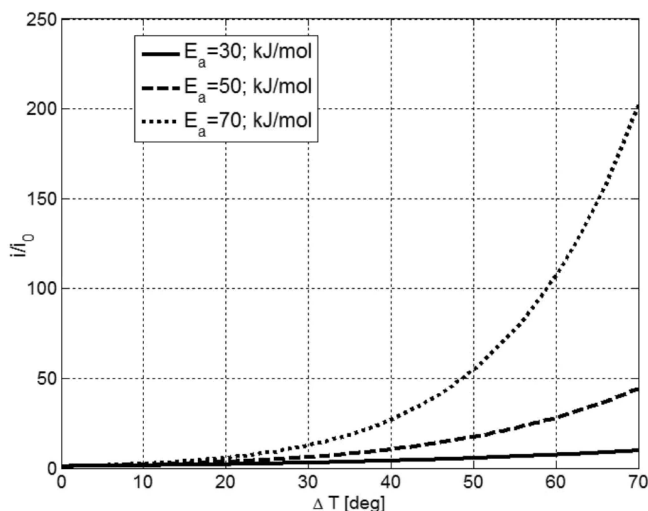

Fig. 5. Relationships between workpiece surface temperature and electrochemical process rate increase for different values of activation energy E_a (calculated from relation 1)

Research on laser enhanced chemical and electrochemical reaction has been carried out since seventies of XX century [24, 25]. Generally, according to these publications, the positive effect of laser irradiation is connected with:

- local electrolyte temperature increase, what results in additional convective movement in the fluid (electrolyte mixing and decrease of concentration overpotential) and increase of electrolyte conductivity (according to Bruggeman relation),
- increase of charge transfer rate on the workpiece – electrolyte interface resulting from workpiece temperature increase,
- decrease of workpiece equalibrum potential.

Some negative effects of laser assistance is:

- increased probability of sparking due to electrolyte boiling and intensified gas formation,
- increased chance of thermal stresses and heat affected zone in workpiece surface layer.

4.2. Mathematical modeling of laser influence in electrochemical machining. Understanding the capabilities and limitations of laser machining requires the knowledge of physical processes occurring during the laser beam interactions with materials. When the laser beam incidents the surface of a material, various phenomena occur include: reflection, refraction, absorption, scattering, and transmission. However, the most desirable phenomena in the laser processing of materials is the absorption of the radiation, which in general results

in various effects such heating, melting and vaporization. The extent of these effects primarily depends on the characteristic of laser beam and the thermo-physical properties of the material. The laser parameters include: intensity, wavelength, angle of incidence, polarization, illumination time, whereas the materials parameters include: absorptivity, thermal conductivity, specific heat, density, latent heat [26].

In the present mathematical modelling the effect of laser beam polarization on reflection and changes of workpiece temperature due to laser heating has been considered. In analogy to laser cutting process where polarization of the laser beam influences cutting quality this factor should be also taken into account during laser enhanced electrochemical process. In laser system configuration with perpendicular polarization, the electric field vector is oriented perpendicular to the machining direction and extends into the side walls of the cut as opposed to running along the direction of cutting. It results in large temperature gradient on the edges but cut quality is not satisfactory (Fig. 6a). On the other side, the edges of the cut quality is much better for the parallel polarization (Fig. 6c) but the cutting speed is significantly lower than when cutting with perpendicular polarization. Intermediate solution is the use of circular polarization (Fig. 6b) [27]. Thus analogous to laser cutting has to be also taken into account during laser assistance of electrochemical dissolution, therefore in presented analysis two directions of laser beam polarization in relation to the direction of cutting has been considered: parallel (P) and perpendicular (S).
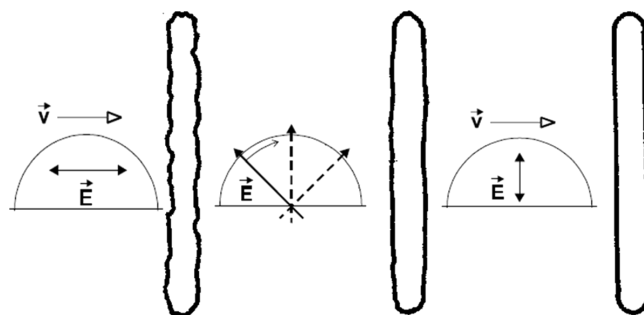

Fig. 6. Results of cutting with parallel, circular and perpendicular polarized laser beam after Ref. 27

During calculation, the following data has been assumed:

- Laser type: DPSS Nd:YaG, wavelength $\lambda = 532$ nm,
- Pulse repetition rate: $f = 9$ kHz,
- Pulse energy: 2.5 mJ,
- Output power: $P = 23$ W,
- Beam diameter: $w_0 = 0.9$ mm.

First of all, based on the Fresnel formulas the reflectivity for the parallel and perpendicular polarization has been calculated. The reflection coefficient r is depending on the material parameters according to following equations [28]:

$$\frac{E_r}{E_i} = r_s = \frac{n_1 \cos\alpha - \dfrac{\mu_1}{\mu_2}\sqrt{n_2^2 - n_1^2\sin^2\alpha}}{n_1 \cos\alpha + \dfrac{\mu_1}{\mu_2}\sqrt{n_2^2 - n_1^2\sin^2\alpha}}, \qquad (2)$$

$$\frac{E_r}{E_i} = r_p = \frac{\frac{\mu_1}{\mu_2}n_2^2\cos\alpha - n_1\sqrt{n_2^2 - n_1^2\sin^2\alpha}}{\frac{\mu_1}{\mu_2}n_2^2\cos\alpha - n_1\sqrt{n_2^2 - n_1^2\sin^2\alpha}}, \quad (3)$$

where μ_1, μ_2 – magnetic permeability of media 1 and 2, respectively, n_1 and n_2 are the indices of refraction of the two media, E_i – electric field of the incident beam; E_r – electric field of the reflected beam and α stands for the angle of beam incidence. When the phase differences between the fields are not of interest it is advisable not to use the amplitudes but the squares of the absolute values of the amplitudes. R_s and R_p thus give the ratio of the intensities of the incident waves respectively [28]:

$$R_s = |r_s|^2, \qquad R_p = |r_p|^2. \quad (4)$$

It has to be mentioned, that the relation $R_p(\alpha)$ between reflectance and angle of incidence for parallel polarization is characterized by Brewster's angle when the reflection of the beam is equal to zero. Theoretically, the process should be carried in this angle of laser beam incidence, but in practice due to elliptical cross section of the beam anisotropic decrease in power density occurs, which excludes the work in this angle.

The optical properties of metals are dictated by its permittivity ε and the Drude model is traditionally used to determine ε in the considered range of light frequencies. Assuming iron as machined material and the laser wavelength used in model ($\lambda = 532$ nm), the correction factor for reflection is equal 0.5 [29].
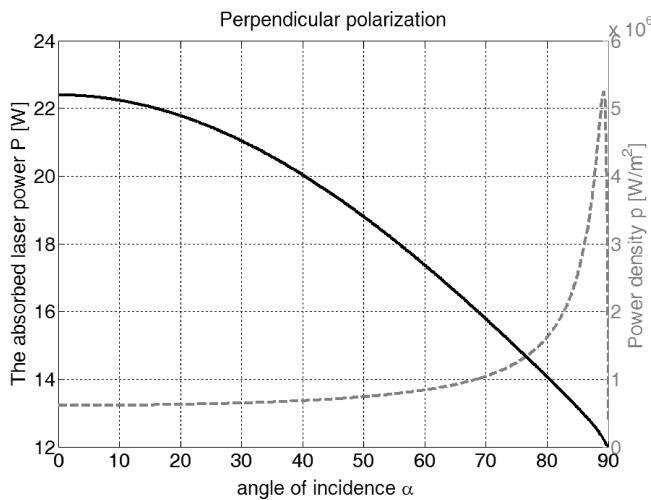

Fig. 7. The dependence of angle of incident at the absorbed laser power and power density for perpendicular polarization

In Figs. 8 and 9 the relations between of the absorbed laser power and power density from angle of incidence has been presented. On the basis of a simulation carried for perpendicular polarization one can see that angle of incidence increase, decreases the power density. To keep a high energy absorption and isotropic power distribution in the beam the angle of incidence range should be within the limits of zero to 20 degrees. The situation is similar if the parallel polarization is applied (Fig. 9). There is significant decrease of power

density with increasing laser beam angle of incidence. Same as in the previous situation, the range of angle of incidence should be within the limits zero to 20 degrees.
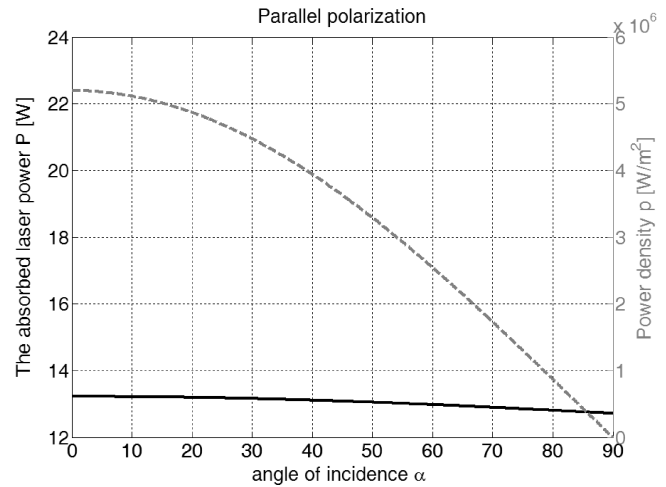

Fig. 8. The dependence of angle of incident at the absorbed laser power and power density for parallel polarization
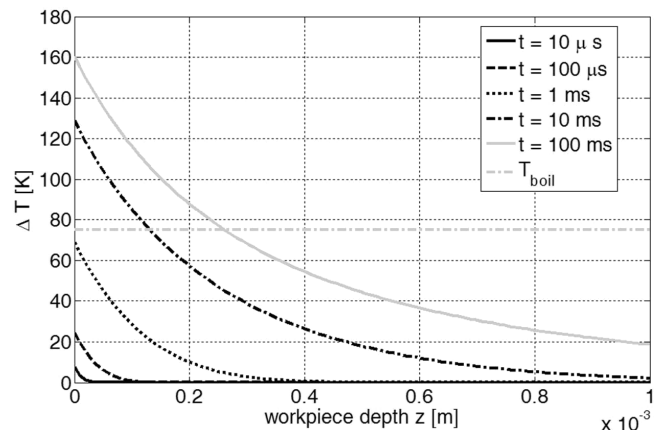

Fig. 9. Temperature rise in material, depending on processing time for $v = 10$ mm/min and laser beam waist $w_o = 0.9$ mm

The next step in the calculations was to incorporate changes in temperature on the surface of the machined workpiece. Boundary conditions and data assumed during of modeling are as follows:

- no heat exchange by radiation, convection and electrolyte flow,
- the workpiece has limited heat capacity, the clamping ensures ideal thermal insulation,
- analysis has been performed for workpiece with a plane surface that extends into half-space,
- data to calculate the temperature change of the material: T_0 – room temperature, mass density $\rho = 7900$ kg/m^3, specific heat $c = 455$ J/(kg·K), machining velocity $v = 0.01$ to 60 mm/s, heat conductivity $K = 58$ W/(m·K), resulting laser power $P = 13$ W.

At distances that are large compared to the laser spot size on the surface the details of the laser intensity distribution are inessential, therefore in that case the source can be assumed to be a point one. In the analyzed case the idea is to apply laser beam to support electrochemical micro-machining, so assumption that the temperature distribution will be conducted in accordance with Gaussian intensity distribution is correct. For modeling purpose it has been assumed that within the beam radius 87% of the beam power is contained. The temperature distribution is given by the following formula [28]:

$$T(x, y, z, t) - T_\infty = \int_0^t \frac{2P_L}{\rho c} \times \frac{1}{\sqrt{4\pi\kappa(t-t')}}$$

$$\cdot \frac{1}{4\pi\kappa(t-t') + \frac{w_0^2}{2}} \times \exp\left(-\frac{(x-v(t-t'))^2 + y^2}{4\pi\kappa(t-t') + \frac{w_0^2}{2}}\right) \quad (5)$$

$$\times \exp\left(-\frac{z^2}{4\kappa(t-t')}\right) dt',$$

where $P_L = 0.87\,P$ – corrected laser power, w_0 – beam waist, ρ – mass density, c – specific heat capacity, κ – temperature conductivity.

Figure 9 shows the temperature distribution in the workpiece during the interaction of the laser beam. One can see that after the time of one millisecond the increase in temperature is already at the limit boiling of the electrolyte. Continuation of the laser heating of surface causes boiling of the electrolyte and stops electrochemical treatment. In the Fig. 10 one can see that the increase of the laser beam diameter to $w_o = 1.8$ mm decreases the temperature of the surface which has a positive effect on the analyzed process. However, obtained results indicate that laser assistance should be carried out in a discrete way.
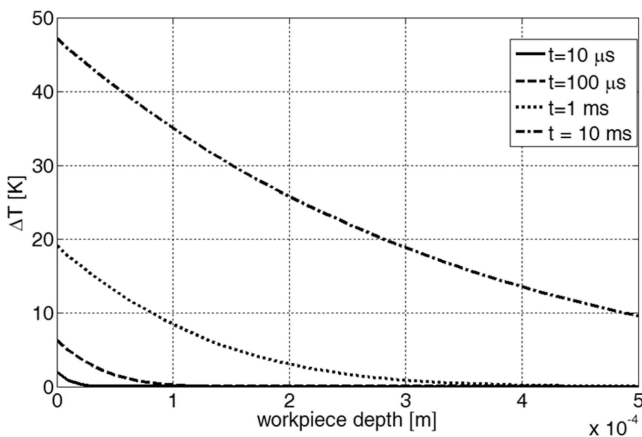

Fig. 10. Temperature rise in material depending on processing time for $v = 10$ mm/min and laser beam $w_o = 1.8$ mm

It can be assumed that the current density is related to a speed of the electrochemical process (be it dissolution or deposition). Thanks to Archenius law the relation between surface temperature and electrochemical reaction velocity can be

described with Eq. (1). The effect of workpiece surface temperature on current increase has been presented in Fig. 12. A temperature increase $\Delta T = 60$ K causes significant increase of current density (about sixty times). One can state, that it is a theoretical value, and did not take into account mass transport limitations connected with diffusion of dissolved material and thermal limitations connected with increased Joule heating. However, based on this analysis one can state about potential capabilities of electrochemical dissolution or deposition laser intensification.
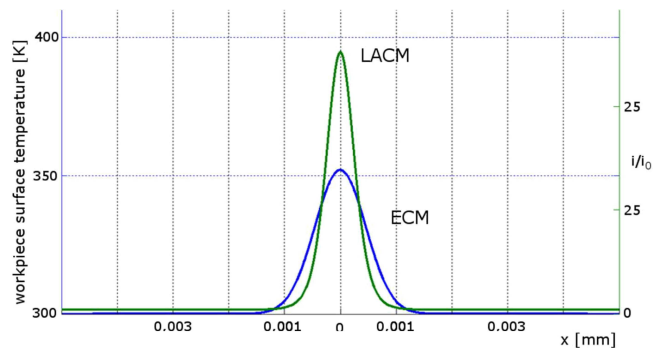

Fig. 11. The effect of workpiece surface temperature increase on current increase, $\Delta T = 60$ K, $w_0 = 1.8$ mm
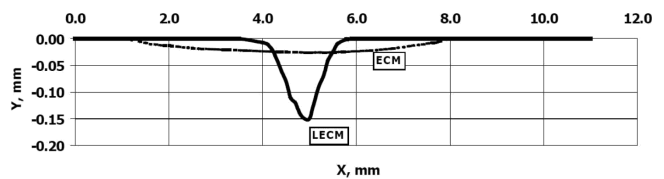

Fig. 12. Comparison of the surface profile after electrochemical (ECM) and laser assisted electrochemical machining (LECM). The current density $i = 4.4$ A/cm^2, electrolyte 15% water solution of NH$_4$NO$_3$, $U = 12$ V, machining time 90 s, electrolyte flow rate $Q = 1.14$ l/min, machined material 145CrV6 tool steel after Ref. 13

4.3. Potential application and limits of electrochemical process laser assistance. To obtain an effective thermal enhancement of electrochemical machining, the heat source should be local, rapid and controllable, what makes the laser preferable as a main choice for this application. The advantages of laser beam heating over the other heating methods are the rapid, high and local temperature rise of the heated surface (only the desired volume of material can be heated). Therefore, the heat affected zone and thermal distortion by the laser beam are small due to the controllable spot size and power density. Effective heating of a workpiece surface is dependent on the amount of radiation absorbed by electrolyte covering the surface. It has been evidenced that for the typical conditions of dissolution due to a low absorption coefficient in electrolyte the best choice is a green laser with the wavelength within the range 470–560 nm [17].

The main problems of laser application in electrochemical processing are repeatability of laser radiation conditions

and some limitations of the machining depth. Therefore, laser assistance in machining processes based on electrochemical dissolution up to now has limited industrial application. Investigations which confirmed positive effect of laser beam on electrochemical dissolution rate have been presented in [13]. The research was carried on the specially designed test stand, which enabled to dissolve material by application of ring electrode tool with parallel CO_2 laser assistance. One of the important conclusions from this research is, that laser irradiation is especially helpful when the anodic dissolution is carried out on the border between passive and transpassive state. One can conclude that the barrier of electrochemical dissolution laser assistance are: mass transport limitations (mainly speed limits of electroactive particles diffusion from and towards the anode) and heat dissipation limitations (heat connected with laser radiation and increased speed of electrochemical process).

The introduction of the laser beam in the electrochemical deposition process provides more application possibilities. Because of much higher activation energy of this process, the laser assistance results in almost a thousand times increase of deposition velocity [24, 30]. Typical example of such effective laser application has been described in [31]. The scheme of this process has been presented in Fig. 13. The copper anode has been immersed in mixture of $CuSO_4$, H_2SO_4 and HCl, the interelectrode distance has been adjusted to 5 mm and connected to the external current source. The interelectrode voltage value has been set slightly below the copper deposition border ($U = 20$–22 mV). Then, the workpiece surface has been selectively heated with application of DPSS green laser ($\lambda = 532$ nm) with pulse frequency 25 kHz and pulse

time within the range 20–70 ns. In these areas the copper deposition occurs. The width of the copper layer has been related to applied laser power and laser beam scanning velocity and has been in range 450–650 μm – this parameters define local workpiece temperature increase. The thickness of deposited copper layer is about 10 μm (Fig. 14).
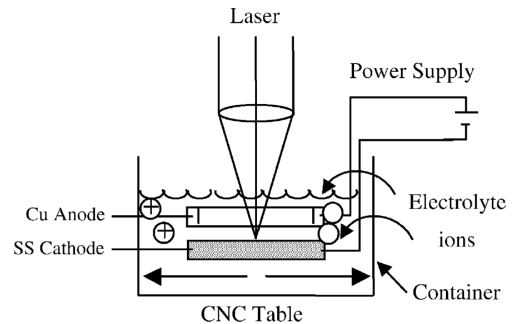

Fig. 13. Laser-controlled selectively electroplating configuration, Ref. 31

Generally one can state that the potential application of laser enhanced electrochemical machining is workpiece surface structuring, especially for biomedical and bearing applications. In such applications surface topography plays an important role i.e. in cell attachment and differentiation or lubrication improvement. Application of laser enhanced ECM gives possibility to fabricate series of micrometer sized cavities of different size and separation distance, what can be useful for the changes of such surfaces' functional properties.
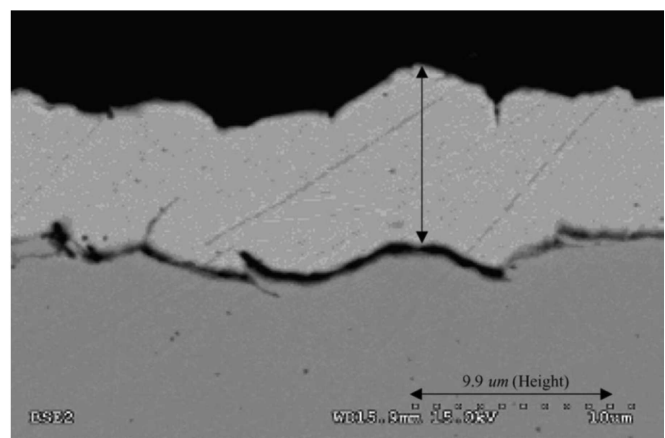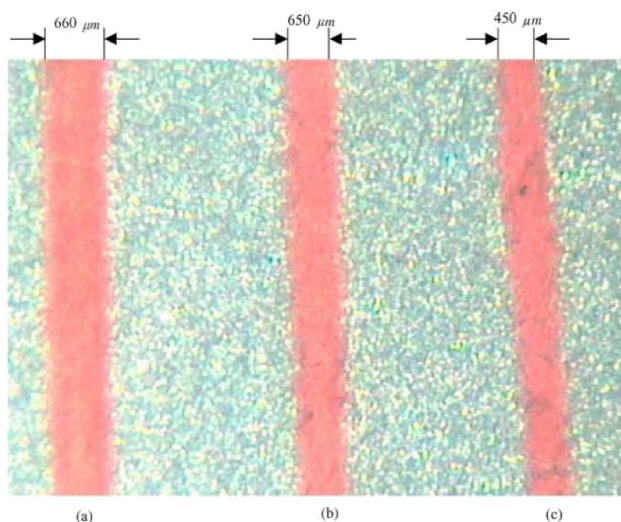

Fig. 14. Copper deposition distributed across each line after 20 scans with different scanning speeds: a) 100 mm/s, b) 200 mm/s, c) 300 mm/s, with the laser power of 3.3 W; SEM micrograph cross-section of the copper track illustrating the copper plating in the electrode–electrolyte interface (b), Ref. 31

Based on the literature analysis and the author's experience, the main barrier of laser radiation application during electrochemical treatment is the technical aspect related to precise supply of the beam to machining zone. In case of material removal (dissolution) laser beam supply could be solved in two ways:

- by supplying the beam in the micro electrochemical milling (Fig. 15), but in this case numerous problems occur with providing constant laser radiation density power (it strongly depends on beam angle of coincidence α, as presented in Fig. 16). Such test stand has been designed on in the Institute of Production Engineering of Cracow University of Technology. The test stand has been equipped with XYZ moving table, pulse ECM generator and the laser source – DPSS Nd:YaG, wavelength 532 nm. Optical fibre has been applied to deliver laser beam directly to processing area. The fibre has been ended with a polarizer and an adjustable focusing lens in order to change the laser energy density by changing the laser beam spot size on machining area. Such a solution enables the control of laser assistance parameters in order to control the electrochemical process rate and accuracy,
- by application of electrolyte jet – guided laser beam (the use of a total internal reflection phenomenon), in this case the workpiece is machined with application of electrolyte jet (Fig. 17).
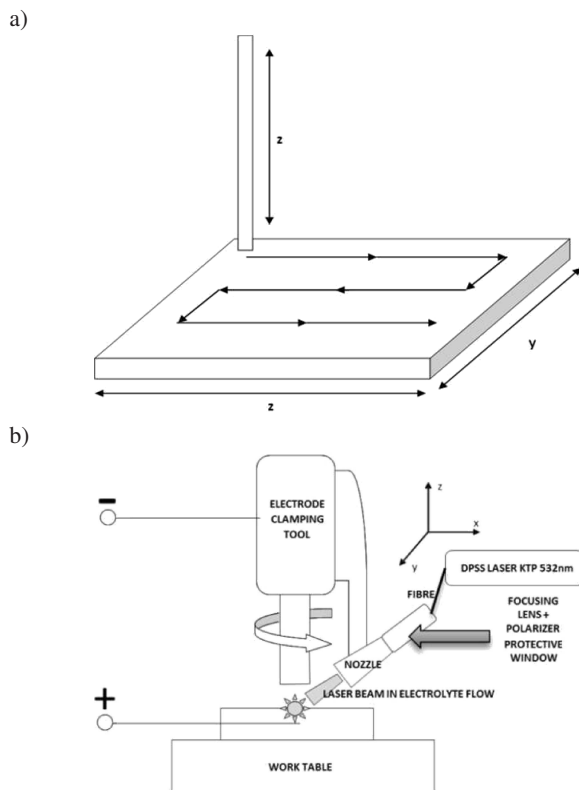
a)

b)

Fig. 15. Scheme of kinematics in electrochemical milling regime (a) and a conception of a research test stand for such an application, Ref. 32
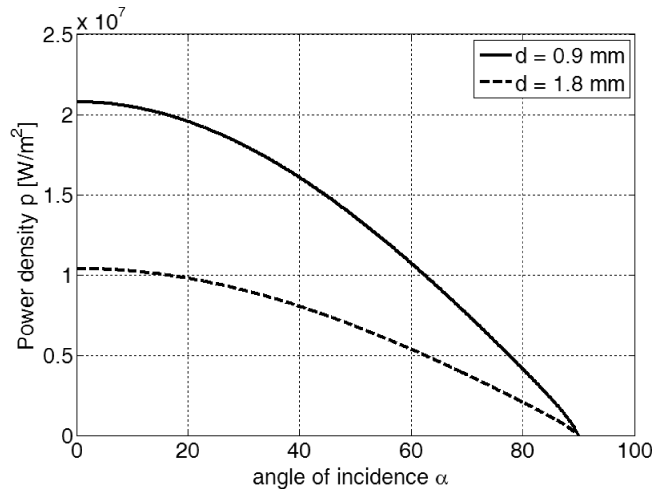
Fig. 16. Relation between power density and angle of incidence for laser beam $w_o = 0.9$ mm and $w_o = 1.8$ mm
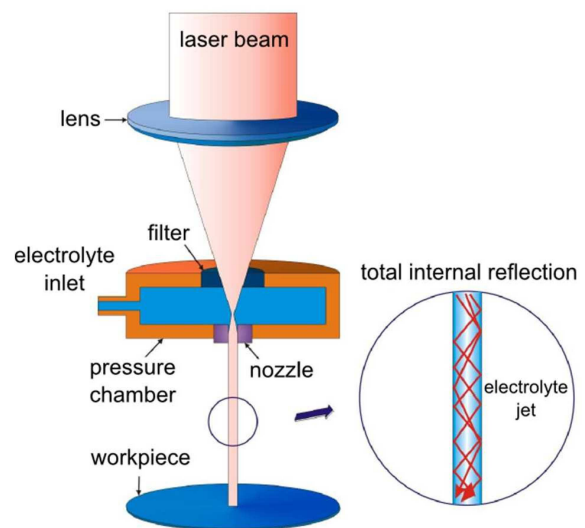
Fig. 17. Scheme of application of laser assistance during electrochemical jet machining with the use of a total internal reflection phenomenon (conception based on Laser MicroJet solution by Synova S.A. company)

5. Summary

Combination of thermal and electrochemical interaction on the machined material gives a possibility to obtain advanced technological solutions. Thermal and electrochemical energy sources integrated in a single machine tool can be combined into the sequence or hybrid machining process. In the first case, the potential benefits are: decreased machining time, shortening of the production chain, reduction of machining costs and increase of a product quality.

An application of the thermal energy source in a hybrid electrochemical machining process gives a possibility to local increase of dissolution or deposition velocity, which results in a machining accuracy increase. Taking into account that during analyzed connection a heat source should be local, rapid and controllable one can state that a laser beam is preferred

for this application. Due to the controllable spot size and power density such a solution gives a possibility to heat only a desired volume of material and minimalize the heat affected zone and thermal distortion. The analysis of the literature has shown that due to a low absorption coefficient in electrolyte, preferred for such an application is a green laser with the wavelength within the range 470–560 nm (especially DPSS Nd:YAG). Additionally, the power density of the laser beam has to be chosen carefully with the condition for electrolyte $T < T_{boil}$ (T_{boil} – electrolyte boiling temperature).

Therefore, in order to properly select laser radiation intensity the mathematical model has been developed. The model considers the effect of laser beam polarization on reflection and changes of workpiece temperature due to laser heating. One can state, that the described mathematical modeling procedure can be utilized to check condition connected with an electrolyte temperature increase.

Generally, one can state that the potential application of laser enhanced electrochemical machining is workpiece surface structuring, especially for biomedical and bearing applications. Laser assistance may have application in electrochemical dissolution and deposition operations, however, the main barrier of laser radiation application during electrochemical treatement is a technical aspect connected with a precise supplying the beam to the machining zone. Laser beam supplying into the machining area could be implemented in electrochemical milling or by application of the electrolyte jet – guided laser beam. In both cases application of a pulse laser to assist the process of electrochemical treatment requires the use of suitable sophisticated equipment.

The test stand for research on laser enhanced electrochemical machining has been designed in the Institute of Production Engineering of Cracow University of Technology, which gives a possibility to carry out the research in this area and probe the presented assumption correctness.

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