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electrochemical machining,
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ELECTROCHEMICAL MICROPROCESSING ASSISTED BY DIODE PUMPED SOLID STATE ND:YAG PULSE LASER

The use of hybrid machining methods for parts and devices production become more and more attractive nowadays. The paper presents results of modelling use of DPSS (Diode Pumped Solid State) pulse laser for intensification of electrochemical processes in machine part production. Application of DPSS pulse laser enables possibility to reach high level of localization in both machining and growth processes. Laser beam energy accelerates electrochemical processing, improves process localization and prevents other than the machined surface passivation. These conditions should improve electrochemical micro part precision of manufacturing by means of shape and dimensional accuracy in both machining and growth ECM processing.

1. INTRODUCTION

The use of new engineering materials, very high technological requirements for complex micro parts induce development of new and more sophisticated production methods. High requirements limit to a certain extent the use of conventional production methods what results in development of unconventional methods and hybrid machining.

One of effective methods to overcome these problems and achieves high performance for micromachining process consists in combining various physical and chemical processes into one machining process, defined as hybrid machining.

The technological improvement of machining processes can be achieved by combining different physicochemical action on the machined material. The reasons for developing the hybrid machining process:

- to use of the combined or mutually enhanced advantages,
- to avoid or reduce some adverse effects the constituent processes produce when they are individually applied.

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2. ELECTROCHEMICAL MACHINING

Electrochemical Machining is a treatment where material removal occurs by separation of atoms from the workpiece. Looking at the principle of electro chemical machining can produce a small part because we operate on the atoms. During machining there are no forces (of cutting) and stresses.

In practice, this situation is different. Electrochemical machining accuracy is greatly limited by stray currents. In order to improve the precision and efficiency of the ECM of the stray 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 which 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 pulse processing. In order to improve the localization, we can also use a hybrid machining of the ECM. One possibility is the use of hybrid: laser beam with the electrolyte to the machining area.

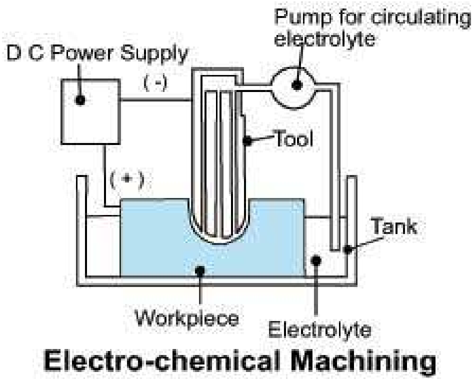

Fig. 1. Scheme of ECM process [7]

3. LASER ASSISTED ELECTROCHEMICAL MACHINING

The method combines two different sources of energy at the same time: energy of ions (ECM) and energy of photons (a laser beam). The use of laser in the process of electrochemical machining is to improve localization of the dissolution process. The main mechanism of material removal is dissolution process supported by the parallel action of the laser beam. The laser does not remove any material but assists dissolution by its thermal activation.

Laser energy increases locally the temperature of the material which is beneficial to the electrochemical reactions. Laser assisted ECM is good example of the cross processes. In normal laser machining, the precision of machining is limited by the strong evaporation or melting, re-deposition and thermal stress can hardly be avoided. While chemical processes has the advantage of burr less and stress free processing. Chemical processes under normal conditions may be inefficient. Laser irradiation can be used to accelerate such processes.

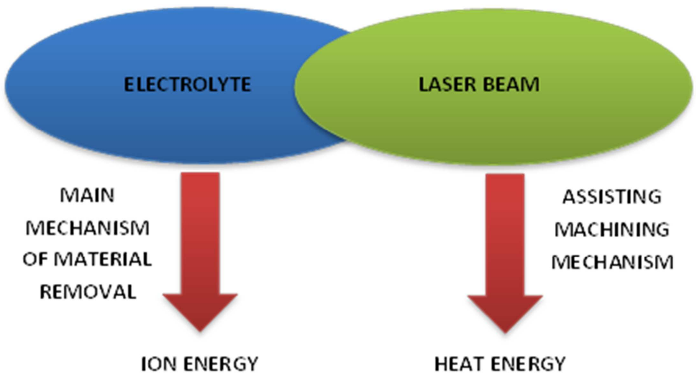

Fig. 2. LAECM idea

The role of laser treatment is introduced to improve the electrochemical dissolution, which is the main mechanism of material removal. The main tasks of the laser beam in LAECM are as follows :increasing the rate of dissolution by raising the temperature in the inter electrode in accordance with the Arrhenius law, increasing the electrolyte temperature resulting in its higher conductivity and current density, elimination of surface passivation, which increases the material removal rate intensification of the dissolution process.

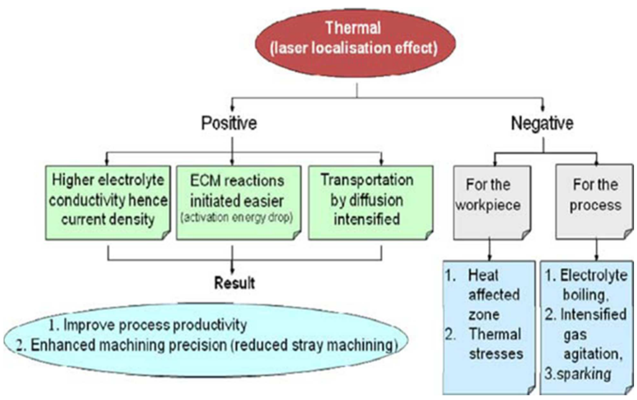

Fig. 3. Aspects of laser–electrolyte interaction in LAECM [8]

The laser beam enables the raise of the temperature in the machining zone. This effect has a positive effect on treatment by increasing electrolyte conductivity hence current density, the ECM reactions are initiated easier, transportation of the removed material and the diffusion of ions are intensified. As a result can it be expected improvement of process productivity and enhancement of the machining precision.

Some negative effect for the workpiece can be introduced such a heat affected zone and thermal stresses if the laser beam energy is too high.

Additionally it can have devastating influence on the process by the electrolyte boiling, intensified gas formation and resulting sparking.

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 is incident on the surface of a material, various phenomena that occur include reflection, refraction, absorption, scattering, and transmission.

Laser processing is one of the alternatives to traditional methods of material removing such as milling, cutting or turning in production of precision components and micro parts. It is used for a wide range of materials as metals, ceramics or composite materials.

One of the most desirable and important phenomena in the laser processing of materials is the absorption of the radiation.

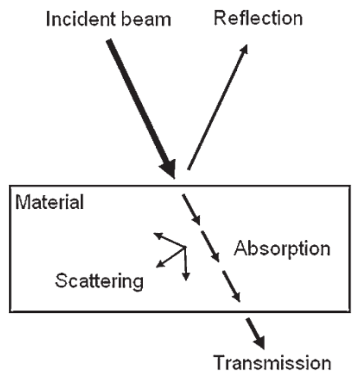

Fig. 4. Possible phenomena occurring laser beam interaction with material

Absorption of radiation in the materials results in various effects such heating, melting, 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.

The activation energy is determined by measuring the effect of temperature on the rate of the reaction. At a higher temperature there is a greater proportion of reactants with the required activation energy ($E \geq E_a$), increasing the rate of the reaction. Changing the temperature does not however change the activation energy. It 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 ($E \geq E_a$). Arrhenius proposed an equation to represent the proportion of molecules with $E \geq E_a$.

Based on the article of J. Kozak [4] one can see the increase of current density due to temperature rise. The value of current density depends on the workpiece. It is important not to increase the temperature over the value at which the electrolyte would boil.

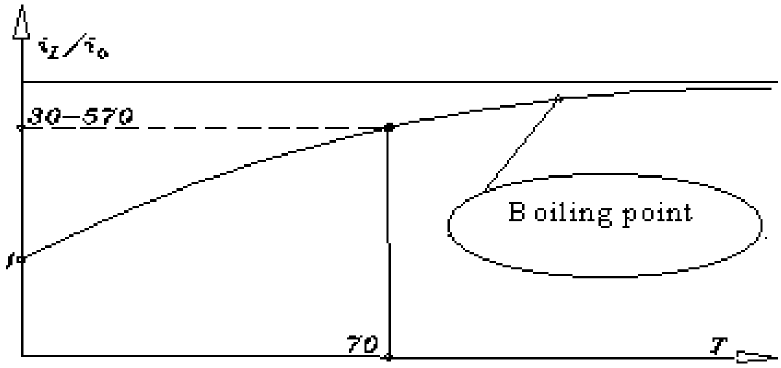

Fig. 5. Effect of temperature on the current density of electrochemical electrode processes [4]

The effect of temperature on the rate of these processes is described by following Arrhenius equation:

$$i_L = i_0 exp\left(\frac{E_0 \Delta T_s}{R T_0 (T_0 + \Delta T_s)}\right) \quad (1)$$

where:

T_0 and T_s are initial and final values of surface temperature respectively, i_o is current density without heating, E_0 is the activation energy, R stands for universal gas constant.

It is assumed that electrochemical machining efficiency and accuracy can be improved by laser assistance by means of local heating of the machined surface in selected area. Therefore it is important that the temperature rise resulting from laser heating of the machined surface should not exceed electrolyte boiling temperature. Otherwise the electrolyte would boil and interrupt ECM process.

4. MATHEMATICAL MODEL

Present mathematical model takes into account the two parts:

- the first part of the mathematical model takes into account the effect of laser beam polarization on reflection,
- the second part we take into account the temperature in the workpiece.

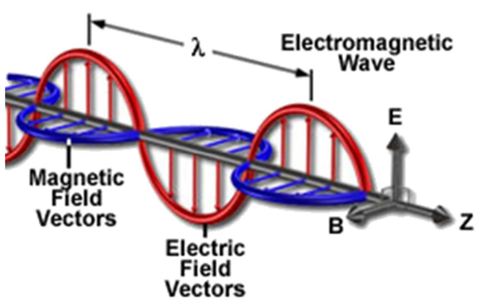

Fig. 6. Idea of electromagnetic wave [5]

Polarization control methods are used in laser cutting. In configuration perpendicular, the electric field vector is oriented perpendicular to the machining direction. The electric field vector (*E*) extends into the side walls of the cut as opposed to running along the direction of cutting. Beam polarization determines direction of electric vector during cutting.

In the mathematical model there are considered two directions of laser beam polarization in relation to the direction of cutting: parallel and perpendicular.

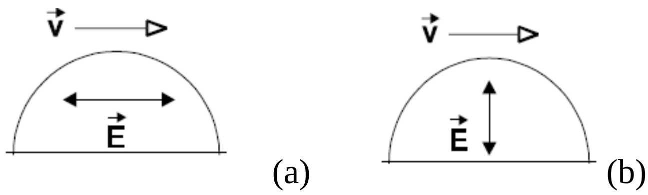

Fig. 7. Scheme of P (a) and S (b) polarization mode

The Fig. 8. demonstrates improvement in cut quality, which compares the quality of cuts through stainless steel in three different polarizations: parallel to the cutting direction, circular, and perpendicular to the cutting direction.

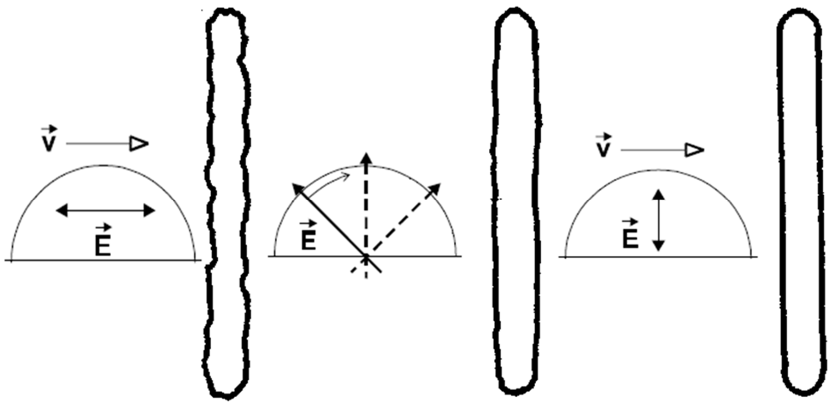

Fig. 8. Results of cutting with parallel, circular and perpendicular polarized laser beam.

The cut on the left of the figure was made with the electric field vector parallel to the direction of the cut. The cut on the right side of the figure was made with the electric field vector perpendicular to the direction of the cut. One can see that the edge of the cut quality is much better for the parallel polarization but the cutting speed is lower than when cutting perpendicular polarization. Intermediate solution is the use of circular polarization. The solution for perpendicular polarization is much more beneficial because large temperature gradient on the edges.

The data for mathematical calculations assume the parameters of the laser parameters shown in the figure below:

Laser Type	DPSS Nd:YAG
Model	PA-016-QTG
Wavelength	532 nm
Pulse Repetition Rate	4 to 15 kHz
Pulse energy	2,5mJ@9kHz
Output power	23 W@ 9 kHz
Beam Diameter @ Output Window	0,9 mm @ 9 kHz
Polarization	Linear

Fig. 9. The parameters of the laser

Mathematical modelling which takes into account polarization of the laser beam is based on Fresnel formulae. Based on these formulae, one can calculate the reflectivity for the parallel and perpendicular polarization. But it is worth to note that this equation does not include the laser beam wavelength. The purpose of the modelling is to know how it would change the reflection coefficient *r* depending on the material parameters as:

$$\frac{E_r}{E_i} = r_s = \frac{n_1 cos\alpha - \frac{\mu_1}{\mu_2}\sqrt{n_2^2 - n_1^2 sin^2\alpha}}{n_1 cos\alpha + \frac{\mu_1}{\mu_2}\sqrt{n_2^2 - n_1^2 sin^2\alpha}} \tag{2}$$

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

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:

$$R_s = |r_s|^2, R_p = |r_p|^2 \tag{4}$$

Figure above shows the relation between reflectance and angle of incidence. The graph shows that at a certain angle called Brewster's angle for the parallel polarization, the reflection of the beam is equal to zero. Theoretically, the process should be carried in this angle of laser beam incidence. In practice, the laser beam incident at that angle has instead of a circular cross section the elliptical one. This combination causes a anisotropic decrease in power density, which excludes the work this angle.

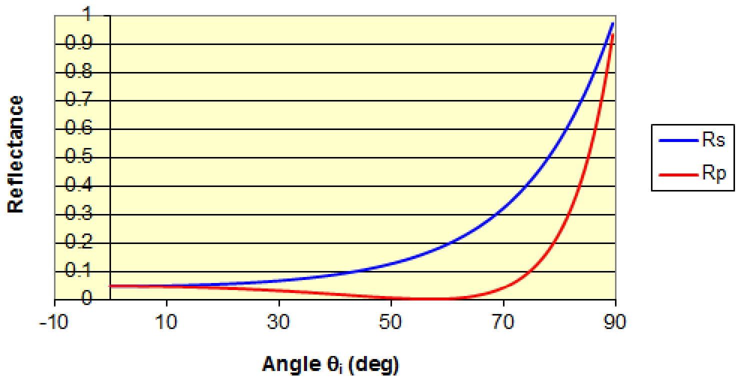

Fig. 10. Example of relation between reflectance and angle incidence

The optical properties of metals are dictated by its permittivity epsilon. The Drude model is traditionally used to determine epsilon in the considered range of light frequencies. The figure below show dependence of normal light incidence reflectivity of metal R at the wavelength λ for Fe. For. As the laser wavelength used in model is 532nm, the correction factor for reflection is 0,5.

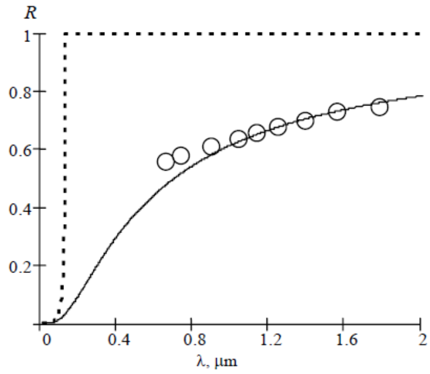

Fig. 11. The dependence of normal light incidence reflectivity of metal R at the wavelength λ for Fe [9]

5. RESULTS OF THE MODELLING

Fig. 12. shows the relation of the absorbed laser power and power density from angle of incidence. The blue line represents absorbed laser power and the green line power density. On the basis of a simulation carried of perpendicular polarization one can see that increasing angle of incidence of the laser beam, 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. 13. There is significant decrease of power density with increasing angle of incidence of the beam laser. Same as in the previous situation, the range of angle of incidence should be within the limits zero to 20 degrees.

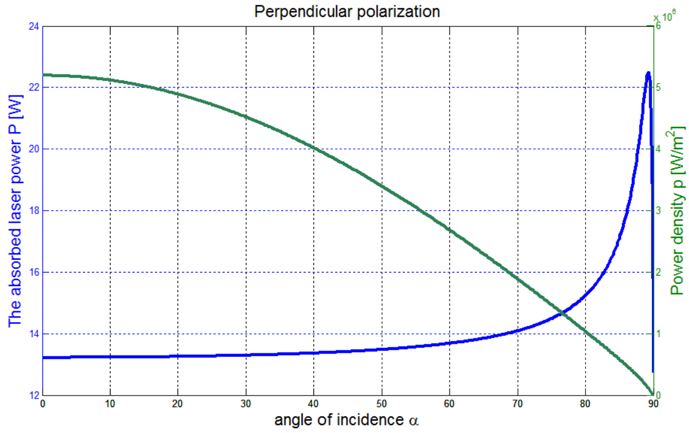

Fig. 12. Dependence of angle of incident at the absorbed laser power and power density

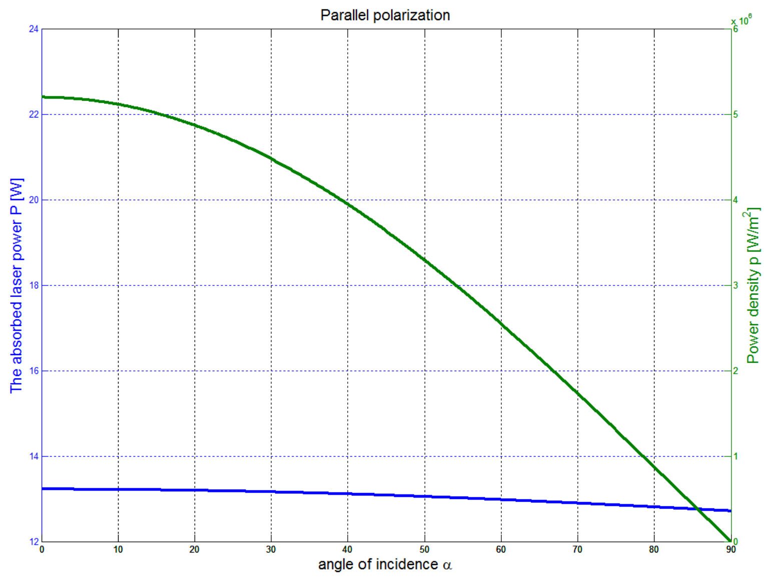

Fig. 13. The dependence of angle of incident at the absorbed laser power and power density

The next step in the calculations was to incorporate changes in temperature on the surface of the workpiece.

Boundary conditions adopted during of modelling:

- no heat exchange of by radiation, convection and electrolyte flow,

- the workpiece has limited size and there is no clamping, where the heat could be transferred to the working table.

Data to calculate the temperature change of the material: T_0 – room temperature, ρ – mass density - 7900kg/m^3, c - specific heat - 455J/(kg·K), v – machining velocity — 0,01 to 60m/s, K – heat conductivity - 58W/(m·K), P – Resulting laser power — 13W.

At distances that are large compared to the laser spot size on the surface the details of the laser intensity distribution is inessential. In that case the source can be assumed to be a point source. In our case, we cannot assume because we want to use laser to support micro-machining. Therefore assume that the temperature distribution will be conducted in accordance with Gaussian intensity distribution

Analysis performed for workpiece with a plane surface that extends into half-space.

We assume that within the beam radius 87% of the beam power is contained. The temperature distribution is given by the formula below:

$$T(x,y,z,t) - T_{-\infty} = \int_0^t \frac{2P_L}{\rho c} \times \frac{1}{\sqrt{4\pi\kappa(t-t')}} \cdot \frac{1}{4\pi\kappa(t-t')+\frac{w_0^2}{2}} \times exp\left(-\frac{\left(x-v(t-t')\right)^2+y^2}{4\pi\kappa(t-t')+\frac{w_0^2}{2}}\right) \times exp\left(-\frac{z^2}{4\kappa(t-t')}\right) dt' \quad (5)$$

Variables in this equation are: P_L - corrected laser power, w_0 – beam waist, ρ – mass density, c – specific heat capacity, κ – temperature conductivity.

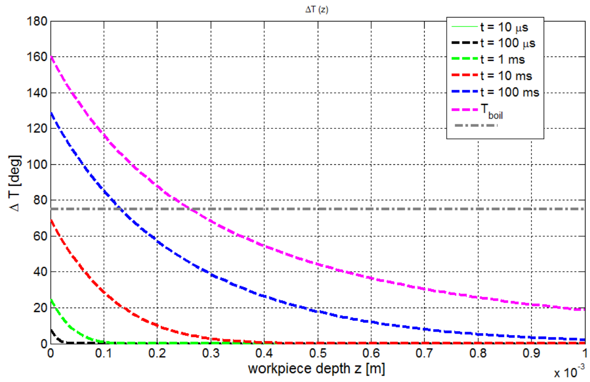

Fig. 14. Temperature rise in material, depending on processing time for v=10mm/min and laser beam w_o =0,9 mm

Presented above graph shows the temperature distribution in the workpiece during the interaction of the laser beam. One can see that after a time of one millisecond 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 ECM treatment.

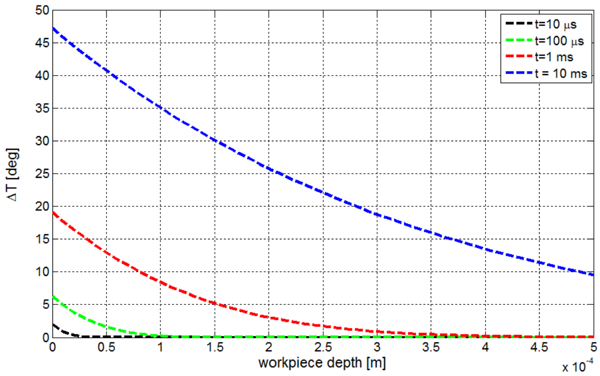

Fig. 15. Temperature rise in material depending on processing time for v=10mm/min and laser beam w_o=1,8mm

Presented above Fig. 15. shows the temperature distribution in the workpiece during the interaction of the laser. One can see that the increase of the laser beam diameter decreased the temperature of the surface.

Fig. 16. below shows the relation between power density and angle of incidence for laser beam for diameter d_0 = 0,9mm and d_0 = 1,8mm. Increasing the diameter of the laser beam has a positive effect on temperature rise.

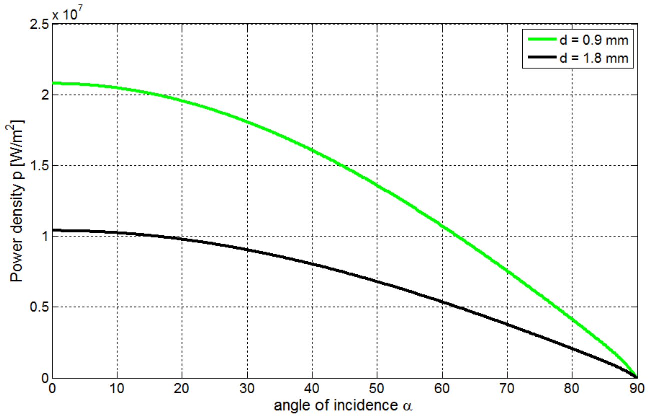

Fig. 16. Relationship between power density and angle of incidence for laser beam w_o= 0,9 mm and w_o= 1,8 mm

For processing micro elements is not a good solution because it reduces the power density and expands localization of working area. As before the angle of incidence should be in the range from zero to twenty degrees.

The test stand will be equipped with XYZ moving table, pulse ECM generator and the laser source. Laser source is diode pumped solid state laser.

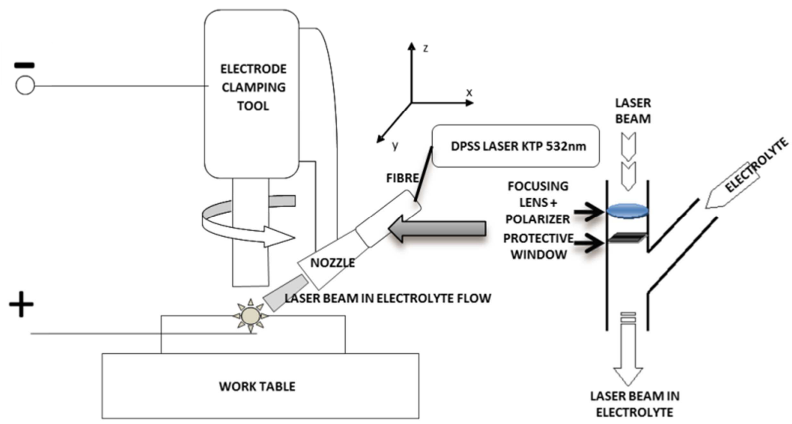

Fig. 17. Conception of research test stand

Optical fibre [6] will be applied to deliver laser beam directly to processing area. The fibre will be ended with polarizer and adjustable focusing lens in order to change the laser energy density by spot size on machining in order to check the process rate and accuracy.

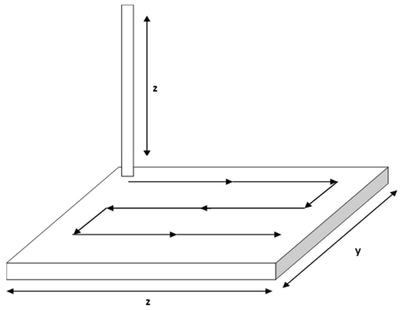

Fig. 18. Kinematics of working will be conducted in milling regime

6. SUMMARY

The analysis of the literature shows that the temperature increase in working zone a positive effect on dissolution process location.

Use of DPSS Nd:YAG pulse laser to assist the process of electrochemical micro machining requires the use of suitable sophisticated equipment.

With use of mathematical modelling one can predict the temperature rise and choose the appropriate treatment parameters.

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