NON-TRADITIONAL MACHINING PROCESSES BY MEANS OF VELOCITY SHEAR INSTABILITY IN PLASMA

R.K. Tyagi*, K.K. Srivastava*, R.S. Pandey**

**Department of Mechanical Engineering,*
Birla Institute of Technology Mesra Ranchi, Jharkhand, India, tyagi_rk1@rediffmail.com
***Department of Applied Physics,*
Amity School of Engineering and Technology, Amity University Utter Pradesh, Noida, India

The material removal within different machining process can be performed in distinct modalities. One of the modality is based on the effect of impact phenomenon. In this paper theoretical model of non-traditional machining process based on impact phenomenon is discussed. The material is removed from the surface due to the impact of ions. The velocity of ions is equal to the velocity at which the electrostatic ion-cyclotron instability driven by parallel flow velocity shear generated by massive ions takes place. The main ways for the material removal as consequence of the impact phenomenon are the microcracking, microcutting, melting and vaporizing of small quantities from the work-piece surface layer.

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INTRODUCTION

Machining concerns the modification of the workpiece on the shape, on the dimensions, on the outward view and eventually on the material constitution, to obtain the product with certain qualities. There are two machining processes, one is the traditional machining process and second is the non-traditional machining process. In traditional machining process we can find two modalities, which are the big pressure exerted between the tool and the workpiece, or the chemical reaction into the work medium [1].

In non-traditional machining process there is one modality, which is the impact phenomenon. This impact phenomenon can be classified into two ways [1].

When there is a temporary contact of some particle with workpiece material. The dimension of macroparticles being some tenths of millimeter; such particles are used with abrasive jet machining, water jet machining, ultrasonic machining [2–4].

When impact phenomenon is occurs due to subatomic particle with the workpiece surface layer. Subatomic particles include ions, electrons, the photons, and sometimes, just the concrete atoms. Such particles are used within the electrical discharge machining, the plasma beam machining, the ion beam machining, the electron beam machining [2, 3].

If the impact is generated by subatomic microparticles, the main effect derives from the change of the kinetic energy into thermal energy. The kinetic energy of the microparticles directed to the workpiece surface. It is clear that not all this energy is transformed in thermal energy, a part of the kinetic energy being necessary for the afterward motion of the particles. Due to their small dimensions, the electrons could initially penetrate a thin surface layer, without to obtain significant effect from the point of view of the machining method. If the electrons energy is high enough to continue their trajectories at depths higher than the dimension defined by the Shenland's relation, the electrons are able to transfer their kinetic energy to the atomic structures (atoms, molecules) of the workpiece material. This means that the amplitude of the atomic structures oscillations round to their equilibrium positions increase and this fact is materialized by the increasing of the temperature. If the temperature is high enough, a so-called thermal source appears and the workpiece solid material is transformed in melted material or even in vapors [5].

The micro-scale movable mechanical pin joints, springs, gears, sliders, sealed cavities, and many other mechanical and optical components have been fabricated using surface micromachining of polysilicon. The analog devices have commercialized such as ADXL-50, a 50 g accelerometer that was developed using surface micromachining for activating air-bag deployment. Texas Instruments' Digital Micromirror Device is also based on surface micromachining [6].

In particular, a micro-manufacturing refers to the fabrication of products or components where the dimensions of at least one feature are in the micrometer range. Similarly, nano-manufacturing refers to the production of devices where some of the dimensions are in the nanometer range. A broad range of technologies exists for micro- and nano-manufacturing, and the physical principles implemented in them are very diverse. Several researchers have proposed classification schemes to categories' these technologies. For example, Masuzawa [7] focused on micromachining processes and classified them according to the implemented machining phenomena. Madou [8] categorized the micro-fabrication techniques as traditional or non-traditional methods and lithographic and non-lithographic methods. Perhaps the most widespread classification is that by Brinksmeter et al. [9].

OBJECTIVE

The objective of this study is to find out the effect of magnetic field, electric field and its inhomogeneity on the metal removal from surface due to the impact of subatomic particles such as ions by using theoretical calculations. Note that the main consequences of the impact phenomena are the generation of craters on the workpiece surface, as consequence of the energy dissipation and development of heat, small quantities of the workpiece material are melted, vaporized and ejected out of the workpiece.

GENERATION OF VELOCITY SHEAR INSTABILITY

We consider plasma in which the massive heavy positive ions are produced due to ionization of K^+ and light electrons are produced from SF_6^-. Fully ionized and collisionless potassium plasma is produced by contact ionization of potassium atoms (K) sprayed onto a tungsten (W) plate. The machine is equipped to produce or to control magnetic field-aligned K^+ flow and its velocity shear including the following features [10].

The plate W for K^+ production (positive ion source) is concentrically segmented.

Another W plate to supply thermionic electrons (the electron source) is mounted at the opposite end of chamber column.

A mesh grid (stainless steel) negatively biased with respect to grounded vacuum chamber is situated in front of the positive ion source.

The generation and control of the parallel velocity shear are achieved by individually biasing each segment of the segmented ion source i.e. a difference between voltages applied between two conjunctive segments. The generation of parallel velocity shear instability can be ensured by the electrostatic energy analyzer and with the laser induced florescence diagnostic technique [11]. The negative ions are produced by introducing sulphur hexafluoride (SF_6) gas into the potassium plasma [12, 13]. An SF_6 molecule has a great electron attachment cross-section for the electron energies less than 1 eV [14]. Due to this production of negative and positive ions in different layers which have shear of velocity and density gradient in respective layer. The velocity shear instability is generated as it is shown in fig. 1.

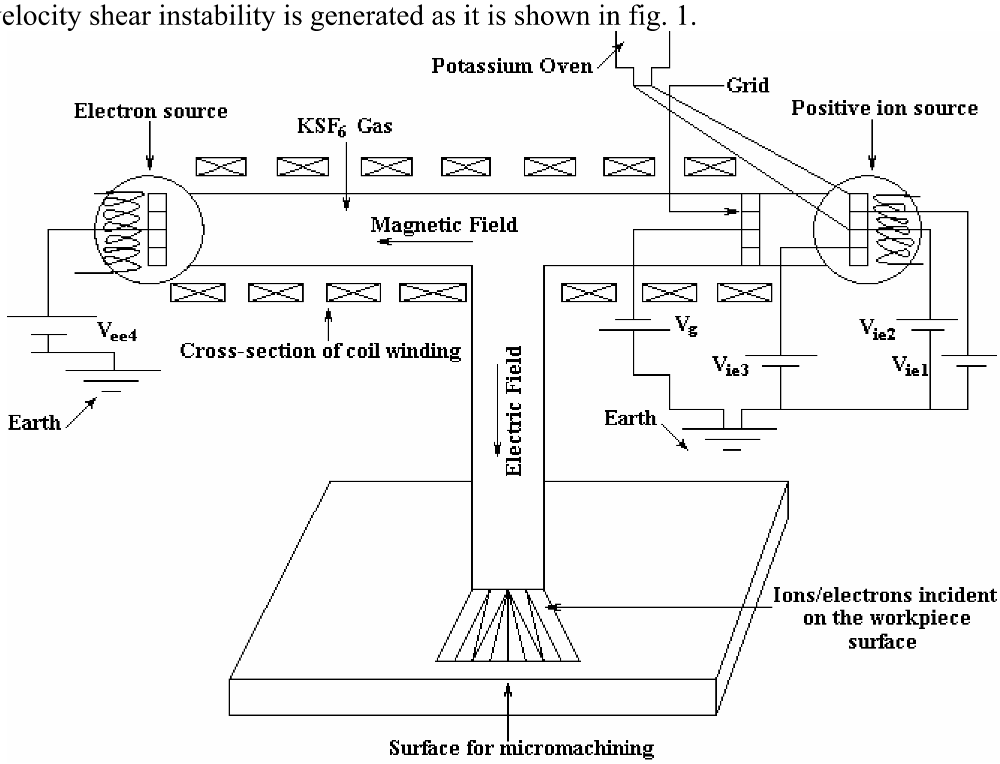


Fig.1. The model of micromachining process (V_{ie} and V_{ee} are the bias voltages applied to the positive ion source and electron source, respectively. V_g is the grid bias voltage.)

MACHINING PROCESSES BY USING IONS

A kinetic energy of the moving particles is transmitted to workpiece material: really, the substantial part of the kinetic energy transforms in thermal energy. Thus, the oscillation amplitude of atomic structure increases. The insignificant increase of this amplitude means that a temperature will increase. If the increase of the oscillation amplitude is larger, then some structural changes occur in the workpiece material. Hereafter, if the oscillation amplitude exceeds a certain value then there is possibility for some structures to leave the place, so that process of melting or vaporizing occurs. The material from the work surface can be removed by circulation of the work liquid [1].

MATHEMATICAL MODEL

The ions/electrons must have enough energy to go through the distance up to the workpiece and to penetrate into the workpiece surface layer. Since the ions are the electrical charges, their trajectories and velocities are influenced by electric and magnetic field**.** Using the results by Tyagi et al. [15], it is easy obtained the expression for the group velocity of electrostatic ion-cyclotron wave in the laboratory reference system assuming small perturbations of the electric field E_1, magnetic field B_1 and distribution function f_{s1}. For the perturbed values of the electric and magnetic fields the harmonic dependence as exp i(kr-ωt) are assumed.

Now the ion's velocity *v* (assuming it to be equal the group velocity of wave, i.e. as $\partial\omega_r/\partial k$, and using the expression for the real frequency ω_r of the wave incident on the workpiece surface according to equation (15) from Tyagi et al. [15]) can be written as:

$$\frac{\overline{\omega'}}{\Omega_i} = -\frac{b_1}{2a_1}\left[1 \pm \sqrt{\left(1-\frac{4a_1c_1}{b_1^2}\right)}\right] \tag{1}$$

where:

$$a_1 = a_2\left(\frac{\Omega_i}{k_{||}\alpha_{||}}\right)^2, \quad b_1 = \frac{\Omega_i}{k_{||}\alpha_{||i}}b_2 - \frac{2k_\perp\Delta'}{k_{||}^2\alpha_{||i}^2}a_2\Omega_i,$$

$$a_2 = \frac{\eta_e}{\eta_i}\frac{T_{\perp i}}{T_{||i}} + \frac{T_{\perp i}}{T_{||i}} - \Gamma_n(\mu_i)\frac{T_{\perp i}}{T_{||i}}, \quad b_2 = \frac{\Gamma_n(\mu_i)k_\perp}{2k_{||}}\varepsilon_n\rho_i\frac{\alpha_{\perp i}}{\alpha_{||i}} - \frac{\Gamma_n(\mu_i)k_\perp}{2k_{||}} - \frac{\Gamma_n(\mu_i)k_\perp n\Omega_i}{2k_{||}^2\alpha_{||i}},$$

$$c_1 = \frac{\Gamma_n(\mu_i)T_{\perp i}}{2T_{||i}}\left(1-\frac{k_\perp}{k_{||}}A_i\right) - \frac{b_2k_\perp\Delta'}{k_{||}\alpha_{||i}} + \frac{k_\perp^2\Delta'^2}{k_{||}^2\alpha_{||i}^2},$$

$$\eta_i = 1-\frac{\overline{E_i'}(x)}{4\Omega_i^2}, \quad \eta_e = 1-\frac{\overline{E'_e}(x)}{4\Omega_e^2}, \quad \overline{\omega}' = \overline{\omega} - n\Omega_i,$$

$$\overline{E}(x) = \frac{e_sE(x)}{m_s}, \quad E(x) = E_0\left(1-\frac{x^2}{a^2}\right),$$

$$\Omega_s = \frac{e_sB_0}{m_s}, \quad \alpha_{\perp s} = \left(\frac{2k_BT_{\perp s}}{m_s}\right)^{1/2}, \quad \alpha_{||s} = \left(\frac{2k_BT_{||s}}{m_s}\right)^{1/2},$$

$$\xi = \frac{\overline{\omega} - (n+p)\Omega_s - k_\perp\Delta'}{k_{||}\alpha_{||s}}, \quad \Delta' = \frac{\partial\Delta}{\partial t}, \quad \Delta = \frac{\overline{E}(x)\ t}{\Omega_s}\left[1+\frac{E''(x)}{E(x)}\cdot\frac{1}{4}\left(\frac{v_\perp}{\Omega_s}\right)^2 \ldots\ldots\ldots\ldots\right],$$

$$A_s = \frac{1}{\Omega_s}\frac{\delta v_{oz}(x)}{\delta x},\ \varepsilon_n = \frac{\delta \ln n_0(x)}{\delta x},\ A_T = \frac{\alpha^2_{\perp s}}{\alpha^2_{\|s}} - 1,\ \overline{\omega} = \omega - k_{\|} v_{oz}(x),$$

$$\Gamma_n(\mu_s) = \exp(-\mu_s) I_n(\mu_s),\ \mu_s = \frac{k_\perp^2 \rho_i^2}{2},\ (s = i, e).$$

Here $\mathbf{E}(x)$ is the inhomogeneous DC electric field, and it is perpendicular to the external magnetic field $\mathbf{B_0}$, which is parallel to ion flow. The detailed description of all variables, which used in the given model, is considered in [15].

The dimensionless real frequency and ion's velocity have been calculated by computer technique with the help of equation (1) for inhomogeneous DC electric field. For inhomogeneous DC electric field the condition $\frac{x}{a} \le 1$ has been taken.

The kinetic energy of the charged particle under action of voltage U determines as:

$$eU = \frac{mv^2}{2} \tag{2}$$

Evidently, the metal removal rate is dependent versus generated voltage U, which defines the depth of ion penetration in the workpiece material. The thickness of this surface layer is defined by the Shenland's relation [5]:

$$\delta = 2.2 \cdot 10^{-12} \cdot \frac{U^2}{\rho} \ \text{[cm]} \tag{3}$$

where ρ is the workpiece material density, in g/cm^3 and U is the acceleration voltage, in V.

RESULTS AND DISCUSSION

In this mathematical model of machining processes the experimental data [16, 17] are used. We show the solution of the equation (1), (2) and (3) using parameters may be representative of laboratory by Kim, Merlino [18] and Rosenberg, Merlino [19]. We consider the plasma in which the heavy positive ions are produced due to ionization of K^+ and light electrons are produced from SF_6^-. We have assumed that electron-ion temperature ratio $\frac{T_e}{T_i}$ is 2. It is further assumed that the plasma is immersed in a magnetic field whose strength varies from 0.11 T to 0.17 T and inhomogeneous DC electric field with strength from 12 V/m to 20 V/m, so that the given fields are perpendicular. In this case for the positive ions the gyro-radius is ρ ~ 0.095 cm and the temperature anisotropy is $A_T = \frac{T_{\perp i}}{T_{\| i}} - 1$ = 1.5 with density gradient $\varepsilon_n \rho_i$ = 0.2. In this case we would accept that for the heavy positive ions the electrostatic ion-cyclotron instability could become excited by the parallel velocity shear with scale length from $A_i = 0.5$ to $A_i = 0.55$.

Fig. 2 shows the variation of ion penetration in the metallic surface (μm) versus $k_\perp \rho_i$ for different values of the magnetic field strength B_0 with other fixed parameters listed in figure caption. The ion penetration decreases with increasing of the magnetic field strength. Due to the change of the magnetic field the gyro-frequency changes, therefore the magnetic field strength is a useful parameter for the machining processes. The maximum value of ion penetration is 41 μm when the value of magnetic field is 0.11 T and the minimum value is 0.137 μm for 0.17 T with other fixed parameters listed in the figure caption.

Fig. 3 shows the variation of ion penetration versus $k_\perp \rho_i$ for various values of inhomogeneous DC electric field. The real frequency increases with increasing the value of electric field. In general, this has a stabilizing effect owing to resonant and non-resonant interactions affecting the real frequency. The maximum ion penetration is 14 μm, when the value of inhomogeneous DC electric field is 20 V/m and the minimum value is 2 μm for 12 V/m with other fixed parameters listed in the figure caption.

Fig. 4 shows the variation of ion penetration versus $k_\perp \rho_i$ for various values of inhomogeneity (x/a) in DC electric field and other parameters being fixed. The ion penetration decreases at increasing the value *x/a*. For inhomogeneity of the DC electric field the condition x/a<1 is taken. Herewith x/a shows the destabilizing effect on the wave incident on the workpiece surface.

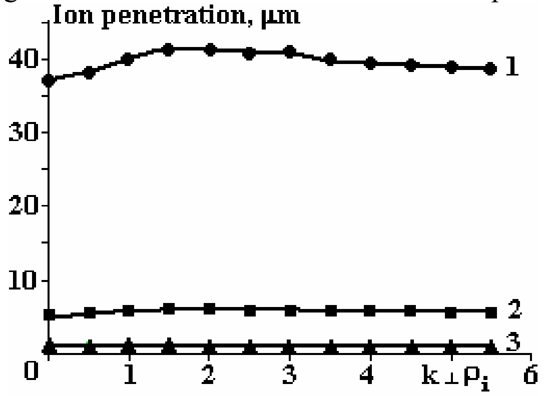
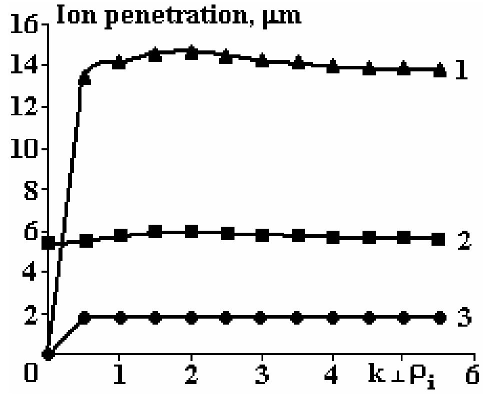


Fig. 2. The variation of ion penetration versus $k_\perp\rho_i$ *with other fixed parameters:* A_i*=0.5,* T_e/T_i*=2,* E_0*=16 V/m, x/a = 0,2,* θ *= 88,5°,* A_T*=1.5,* $\varepsilon_n\rho_i$*=0.2,* $k_\perp/k_\parallel$ *= tan(θ), the density of metal = 3000 kg/m*^{3}*. 1 – Series 1,* B_0 *= 0,11 T; 2 – Series 2,* B_0 *= 0,14 T; 3 – Series 3,* B_0 *= 0,17 T*



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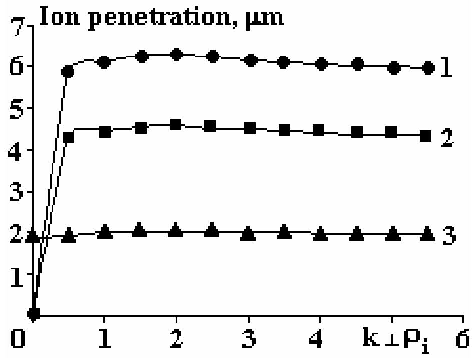

Fig. 4. The variation of ion penetration versus $k_\perp\rho_i$ *with other fixed parameters:* A_i *=0.5,* T_e/T_i*=2,* B_0*=0.14 T,* E_0*=16 V/m,* θ *= 88,5°,* A_T*=1.5,* $\varepsilon_n\rho_i$ *= 0.2,* $k_\perp/k_\parallel$*=tan(θ), the density of metal=3000 kg/m*^{3}*. 1 – x/a = 0,1; 2 – x/a = 0,4; x/a = 0,7*

If the potential difference *U* has a value corresponding to voltage applied usually within the electrical discharge machining (for example, *U* = 70 V), one can notice that the depth of electron's penetration is insignificantly small ($\delta = 1.381\times10^{-9}$ cm). But if the potential difference is *U* = 5000÷200000 V, then the depth of electron's penetration in the surface layer of the metallic workpiece is much more ($\delta = 7.05\times10^{-8}\div1.128\times10^{-2}$ cm). After the penetration of the electrons through the layer of depth δ, the electron's energy is dissipated and as a consequence the temperature of workpiece material increases up to the vaporizing and melting temperatures, so that the micro-explosions are produced and the small quantities of the workpiece material are ejected and the small craters are generated [20].

The theoretical results obtained from the given mathematical model are found out within the range of experimental result [20].

CONCLUSION

This paper describes the mathematical model for the micromachining process. This shows the flexibility of using the magnetic field, electric field and its inhomogeneity for control of ion penetration into metallic surface. It has been shown that under the parameters considered, the maximum value of ion penetration is 41 µm (at value of the magnetic field 0.11 T, voltage 16 V and inhomogeneity 0.2). Moreover, the theoretical results show that the ion penetration increases with corresponding decrease of the magnetic field value and inhomogeneity in the DC electric field and by increasing of the DC electric field value.

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Реферат

Удаление материала при разных процессах обработки может быть выполнено различными способами воздействия, в том числе способом, основанном на эффекте ударного явления. В работе обсуждается теоретическая модель процесса нетрадиционной обработки, основанная на ударном явлении. Материал удаляется с поверхности благодаря ударам ионов. Скорость ионов равна скорости, при которой имеет место электростатическая ион-циклотронная неустойчивость, обусловленная параллельным сдвигом скорости потока, порожденного массивными ионами. Основными путями для удаления материала, вследствие ударного эффекта, являются микротрещины, микроразрывы, плавление и испарение небольших количеств вещества из поверхностного слоя заготовки.