A review of few unconventional machining processes based on the concept of velocity shear instability in plasma

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In this article, published work on unconventional machining process, plasma spray process, plasma etching and abrasive jet machining has been summarized. In unconventional machining process, based on the concept of velocity shear instability in plasma, the material is removed from metallic surface by the impact of ions. Single-crystal silicon surface roughness (up to nanometer sizes) induced by gas plasma in plasma etching based on the concept of velocity shear instability in plasma has been achieved. The material removal from metallic surface can be explained on the basis of erosion phenomena. Momentum transfer from ions to abrasive particles accelerates micron-sized abrasive particles. In this process, material removal from metallic surfaces varies from a few milligrams to a few grams per second. Plasma spray process is based on the concept of velocity shear instability in plasma. In this process, heat generated in plasma and velocity of ions is used to develop high quality surface. Actually, the velocity of ions depend upon different parameters like magnetic field, homogenous D.C electric field, shear scale length, temperature anisotropy, heterogeneity in D.C electric field, density gradient, etc. Therefore, a combination of aforementioned parameters is selected to suit the requirement.

Keywords: velocity shear instability; group velocity of waves; micro-machining process; plasma etching; abrasive jet machining; plasma spray technology

1. Introduction

The purpose of researching the information available in this area is that after analysis of the properties that influence metal removal as well as different processes that are used to serve the purpose, a single machine could be devised for different metal removal requirements, i.e. for range varying from micrometer to nanometer as well as for different applications. The required value of parameters for a particular application can be chosen with the help of theoretical and experimental models suggested earlier. Introduction of this review article has been divided into velocity shear instability, unconventional machining process, plasma spray, etc.

Shanbhag et al. (2003) developed ion-beam micro-contouring process by using ionized argon ions on small optical components. This process is very useful when the dimensions of components are less than mm dimensions. The depth of ion penetration is a function of ion-beam shape and an ion-beam dwell function. Silicon surface can be polished up to nanometer sizes (see Table 1).

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The machining processes can be classified into three categories on the basis of accuracy achieved: conventional machining, precision machining and ultra-precision machining. Ultra-precision machining is the process by which the highest possible dimensional accuracy is or has been achieved at a given point of time. This is a relative definition which varies with time. It has been predicted that by 2010 AD, machining accuracies in conventional processes would reach 1 \( \mu \text{m} \), while precision and ultra-precision processes would attain accuracies of the order of 0.01 \( \mu \text{m} \) (10 nm) and 0.001 \( \mu \text{m} \) (1 nm), respectively (Jha & Jain, 2006).

In laboratory plasma, if the number density and velocity of different layers in plasma are different, then in any two adjacent layers, disturbance is created in terms of waves, which is called as velocity shear instability. The instability is generated by plasma species which are in majority, i.e. ions (positive and negative) or electrons.

Ichiki, Kaneko, Hayashi, Tamura, and Hatakeyama (2009) realized velocity shear instability in laboratory by using SF\(_6\) gas and potassium plasma. The electrostatic ion cyclotron instability generated by Ichi et al. is based on non-traditional magnetic field.

However, due to parametric constraints in fusion studies, assumption is made in case of shear-driven phenomena that the shear scale length is much larger than the ion Larmor radius. Although this assumption is in conformity with the experimental observations, it fixes the time scale of variation of the radiant shear-driven phenomenon as much larger than the ion-gyro period (provided that the maximum drift speed is not much larger than the electron thermal speed (Ganguli, Lee, & Palmadesso, 1985).

First time, collisionless drift wave instability has been realized by using segmented tungsten plate and SF\(_6\) gas and potassium plasma. This type of machine is called as Q-machine (Ichiki et al., 2009).

Laboratory study related to energetic ions in ionosphere–magnetosphere system is described with the help of cesium Q machine with a region of non-uniform magnetic field. Electrostatic ion cyclotron waves were generated by above machine (Cartier, Angelo, & Merlino, 2012).

Theoretical value of real frequency and growth in wave has been calculated by taking Marlino et al. data, when considering homogeneous and inhomogeneous DC electric field (Tyagi, Srivastava, & Pandey, 2012).

Machining process can be divided into two parts: one is traditional machining process and second is unconventional machining process. The examples of traditional machining process are turning, boring, milling, shaping, grinding, etc. and unconventional machining processes are abrasive jet machining, ultrasonic machining, water jet machining, electro-discharge machining, electro-chemical machining, etc.
The material removal in different machining process can be performed in different modalities. One of the modalities is based upon impact phenomenon, i.e., micro-cracking, micro-cutting, melting and vaporizing of small quantity of metal from workpiece surface layer by ions impact (Slătineanu, Coteață, Dodun, Iosub, & Apetrei, 2008).

If the temperature is high enough, a so-called thermal source appears and the workpiece solid material is transformed in molten material or even in vapor (Slătineanu et al., 2009).

In particular, 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.

Slătineanu et al. (2008) develop some mathematical equation to describe non-traditional machining process based on impact phenomenon for ions/electrons, impact of ions (negative and positive)/electrons on metallic surface with the help of electrical discharge machining process and finding out ion penetration.

Several micro-mechanical manufacturing technologies were studied to characterize geometries such as micro-channel. The technologies used were electro-discharge machining, sand blasting and abrasive jet machining, and performance is compared with lithography capabilities (Jáuregui, Siller, Rodríguez, & Elías-Zúñiga, 2010).

The pulse electro-chemical micro-machining close the gap between the normal ECM with gap width in the middle micrometer range and EC nano-machining (Burkert, Schutzle, Gmelin, & Leone, 2009).

Comparison of different micro/nano-manufacturing technologies namely micro-electro-discharge machining, laser ablation, micro-milling, focused ion beam machining, micro-injection molding, hot embossing and electroforming had been studied by Brousseau, Dimov, and Pham (2010).

Garvin, Garmire, Somekh, Stoll, and Yariv (1973) describe sputtering process by plasma ions. The plasma is usually created in an inert gas by DC or RF discharge. Ion beam sputtering is performed by bombarding the target surface with a collimated ion beam in high vacuum.

Plasma etching is a process in which metallic or non-metallic surface roughness can be increased or decreased according to requirement by using plasma species. Plasma etching depends upon various factors, such as true contact area, molecular strength, density, conductivity, etc. Generally surface roughness is calculated in terms of rms value (Greenwood & Williamson, 1966).

Plasma etching is a chemical etching process and chemical reaction occurs between a solid atom and a gas atom to form a molecule (Verdonck, 2006).

Actually plasma etching consists of formation of reactant particle, adsorption of the reactant particle, formation of product molecule, etc. Tyagi (2013a) derived an expression and found out the theoretical value of plasma etching when phenomenological power law for the heights of surface roughness was taken into consideration.

The central goal of sputtering by plasma processing is to obtain any high rate, while preserving anisotropy, uniformity and selectivity at the obtained rate. Important advances in basic understanding of plasma-assisted processes have been reported in the recent past, although engineering development of new system continues to rely heavily upon trial and error procedures (Economou & Alkire, 1988).

Using a one-dimensional radial dispersion model, the role of physical factors such as etchant convection and diffusion has been examined, which are determined by the concentration of the etchant. In particular, in (Economou & Alkire, 1988), a detailed
study of the etch rate of polymer in an oxygen plasma as a function of pressure, power and flow rate is presented (Economou & Alkire, 1988).

Theoretical value of ion penetration on metallic surface by computerization had been found out when utilizing the parameters of Statineu et al. Surface roughness also has been calculated, when metal is removed by ion beam machining process (Tyagi, 2012a; Tyagi, 2013a; Tyagi, Srivastava, et al., 2012).

Non-traditional machining process by macro-particle impact is known as abrasive jet machining. Generally, macro-abrasive particle are accelerated by compressed air and directed to the contact surface by a nozzle. It has been studied that due to plastic deformation, material removal mechanism causes crack and spalling of ductile material (Bitter, 1963; Finne, 1972).

The material is removed from surface by mechanical erosion process due to impact of high-velocity abrasive particles. The erosion phenomenon in an AJM may be considered to constitute two phases. The first phase consists of transportation phase, i.e. the quantity of abrasive particles flown, and the direction and velocity of impinging particles as determined by the fluid flow condition of solid-gas suspension. The second phase is the determination of the material removal rate or the erosion rate (Roy & Paul, 1987).

The complete mechanism of erosion is complex and involves mechanical, chemical and material properties. The erosion depends upon various factors, such as speed, angle of impact, ductility or brittleness of impinging particles and elasticity of the material. Neema and Pandey proposed an equation for material removal rate by equating the kinetic energy of the impacting particle to the work of deformation during indentation (Neema & Pandey, 1977).

\[ Q = kn_a d^3 v^{3/2} (\rho_a/12\sigma_y) \]

In abrasive jet machining, there is large wear and tear in nozzle. (Tyagi, 2012a) suggested a nozzle-free model of abrasive jet machining, the abrasive particles being accelerated by momentum and high velocity of ions. KSF₆ gas was chosen for the study because it has high electron affinity and higher molecular weight. Wensink and Elwenspoek (Schlautmann, Wensink, Schasfoort, Elwenspoek, & Berg, 2001) studied effect of impact angle and abrasion size. The results obtained reflect that smaller abrasion size and less impact angle improves the machinability. Investigation of the effect of abrasive grit size and mixing ratio on machinability was also done (Balasubramaniam, Krishnan, & Ramakrishnan, 1998).

Plasma spray is a process which includes metallic melting, quenching and solidification in a single operation. The complete plasma spraying consists of injection of metallic powder particles into plasma, melting of powder particles and formation of an adherent coating, i.e. high quality coating. The coating is built up by impact of successive particles by process of flatttering, cooling and solidification. The generated surface is fine-grained and homogeneous because cooling rate is high (Herman, 1988).

Plasma spray deposition is one of the most important technologies available for producing the high-performance surfaces required by modern industry. Over the past 25 years, there have been significant advances in the understanding of plasma physics and in the development of spraying equipment and techniques. This has enabled a range of materials including metals, alloys, ceramics and cermets to be plasma-sprayed on to a great variety of substrate types and geometries. During this period, the uniquely aggressive environment within the gas turbine engine has provided not only some of the
greatest challenges to plasma spraying technology, but also some of its most successful applications (Gill & Tucker, 1986).

Plasma spraying has undergone a rapid expansion in the past 30 years due to a couple of important advantages. Firstly, it can conveniently treat specimens with a complex geometry. Secondly, the wide spectrum of materials that can be handled by this technique has spurred applications in the area of corrosion-resistant, high-temperature, and ablation-resistant coatings as well as biocompatible films. One of the disadvantages of plasma spraying is the poor adhesion between the substrate and coating, but several measures can be used to improve it. For instance, the thermal gradient at the substrate–coating interface caused by the rapid quenching of the molten particle splats that leads to deposition of an amorphous coating can be reduced. In addition, one can prevent a steep gradient in the coefficients of thermal expansion between the substrate and coating to avoid the formation of strong tensile forces that give rise to crack generation, chipping and/or delamination (Kurzweg, Heimann, Troczynski, & Wayman, 1998).

In cold spray technology, micro-size metallic particles are accelerated with the help of nozzle and air momentum. Tyagi et al. accelerated micro-size metallic particles by momentum transfer of ions to metallic particles. But the main condition of momentum transfer is that energy of plasma ions should not be transferred to micro-size metallic particles. This can be achieved when vacuum is maintained throughout the process. The velocity of micro-sized metallic particles is calculated when density gradient is zero in plasma (Tyagi, 2013b; see Table 2).

The effect of processing parameters for coating was assessed in terms of adhesion, density (micro-hardness), roughness, composition, thickness and continuity in tabular form which presents the range of these characteristics and those of the best coating (Meletis, Nie, Wang, & Jiang, 2002).

Fauchais (2004) wrote a topical review paper, which consists of plasma spraying for metallic and non-metallic particles. Metallic particles size is of micron size. In this work, a model of a plasma gun is also discussed with its dimensions.

Titanium coating on surface is developed by cold spray process with the help of helium and nitrogen gas under different temperature and pressure. The effect of the gas type and temperature on deposition behavior was examined (Cheng & Weng, 2003).

Schmidt, Gaertner, and Kreye (2006) discuss the effect of particle size and temperature of particle on material properties.

Tyagi, Kumar, and Pandey (2012) and Tyagi (2013b) develop a model of machine for plasma coating process, actually this technology is the combination of cold spray and hot spray technology.

Table 2. Surface properties in plasma spray process.

| Parameter             | Zn coating-I | Zn coating-II | Zn-Al coating |
|-----------------------|--------------|---------------|---------------|
| Thickness, μm         | 12           | 15            | 18            |
| Deposition rate (μm/s)| 0.37         | 0.47          | 0.56          |
| Roughness (Ra), μm    | 3.5          | 2.5           | 2.3           |
| Element contents      | Zn           | Zn            | 3.0 at. % Al, Zn bal |
| Adhesion strength (MPa)| >70       | >70           | >70           |
| Hardness (Gpa)        | 0.97         | 1.06          | 1.3           |
2. Decision-making problems

As described in introduction, there are various manufacturing applications based on velocity shear instability in plasma. Some of these applications are non-traditional machining process, surface coating, surface etching, etc. In this review article, all these processes are summarized and suggested that by a single machine, all operation can be performed by using various combination of plasma parameters.

3. Methodology adopted

In mathematical modeling, magnetic and electric field are considered to remain constant w.r.t time though, the value of electric field may or may not be constant w.r.t distance. Vlasov equation is used to find the relation between number of particles which participate in energy transfer from plasma species to waves and those which do not. Lagrange force equation was applied to calculate displacement, velocity and acceleration of plasma species with the help of electric and magnetic field. This method is known as method of characteristic solution. Number of particles which are present at a particular location and time is described by perturbed distribution function. With the help of perturbed distribution function, dispersion relation and subsequently velocity of ions has been calculated.

Tyagi et al. considered plasma of K⁺ and SF₆⁻ gas. The potassium ions are produced by spraying potassium atoms onto a tungsten plate and SF₆ ions are produced from the electrons which are released from another tungsten plate. The generation and control of the parallel velocity shear are accomplished by independently biasing each segment of ion source, i.e. a variable voltage applied between two conjunctive sections. The generation of parallel velocity shear instability canister is guaranteed by the electrostatic energy analyzer and the laser-induced florescence diagnostic technique. The negative ions are produced by introducing sulfur hexafluoride (SF₆) gas into the potassium plasma. An SF₆ molecule has a great electron attachment cross-section for the electron energies less than 1 eV. Due to this production of negative and positive ions, different layers have velocity shear and density gradient in adjacent layer. The detailed description of generation of velocity shear instability is described by Tyagi et al. (2011a, 2011b).

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

where:

\[ a_1 = a_2 \left( \frac{\Omega_i}{k_i |E_i|} \right)^2, \quad b_1 = \frac{\Omega_i}{k_i |E_i|} b_2 - \frac{2k_i \Delta'}{k_i^2 |E_i|} a_2 \Omega_i, \]

\[ a_2 = \frac{\eta_e T_{\perp i}}{\eta_i T_{|| i}} + \frac{T_{\perp i}}{T_{|| i}} \Gamma_n (\mu_i) \frac{T_{\perp i}}{T_{|| i}}, \quad b_2 = \frac{\Gamma_n (\mu_i) k_i}{2k_i} \frac{\eta_i T_{|| i}}{\eta_i T_{|| i}} \Gamma_n (\mu_i) k_i \frac{\eta_i T_{|| i}}{\eta_i T_{|| i}} - \frac{\Gamma_n (\mu_i) k_i}{2k_i} - \frac{\Gamma_n (\mu_i) k_i}{2k_i} n \Omega_i, \]

\[ c_1 = \frac{\Gamma_n (\mu_i) T_{\perp i}}{2T_{|| i}} \left( 1 - \frac{k_i}{k_i} A_i \right) - \frac{b_2 k_i \Delta'}{k_i |E_i|} + \frac{k_i^2 \Delta'^2}{k_i^2 |E_i|}, \]

\[ \eta_i = 1 - \frac{E_i}{4 \Omega_i^2}, \quad \eta_e = 1 - \frac{E_e}{4 \Omega_e^2}, \quad \bar{\omega}' = \bar{\omega} - n \Omega_i, \]
\[
E(x) = E_0 \left(1 - \frac{x^2}{a^2}\right), \quad \bar{E}(x) = \frac{e_s E(x)}{m_s}
\]

\[
\Omega_s = \frac{e_s B_0}{m_s}, \quad \alpha_{\perp s} = \left(\frac{2k_B T_{\perp s}}{m_s}\right)^{1/2}, \quad \alpha_{||s} = \left(\frac{2k_B T_{||s}}{m_s}\right)^{1/2},
\]

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

\[
A_s = \frac{1}{\Omega_s} \frac{\partial \nu_{voc}(x)}{\partial x}, \quad \nu_w = \frac{\delta \ln n_0(x)}{\delta x}, \quad A_T = \frac{x_{||s}^2}{x_{||s}^2} - 1, \quad \bar{\omega} = \omega - k_{||s} \nu_{voc}(x),
\]

\[
\Gamma_n(\mu_s) = \exp(-\mu_s) I_n(\mu_s), \quad \mu_s = \frac{k_s^2 \rho^2}{2}, \quad (s = i, e).
\]

where, \(E(x)\) is the inhomogeneous DC electric field, perpendicular to external magnetic field \(B_0\) and parallel to ion flow. The detailed description of all variables, which used in the given expression, is well thought-out in (Tyagi et al., 2011b).

The dimensionless real frequency and ion’s velocity have been calculated by mathematical model and computerization technique for Equation (1) for heterogeneous DC electric field. For heterogeneous DC electric field, the condition \(\frac{x}{a} \leq 1\) has been taken.

The kinetic energy of the ions under the action of equivalent voltage \(U\) is determined by Tyagi (2012b).

\[
E = eU = \frac{mv^2}{2}
\]

Clearly, the metal removal rate is dependent on generated voltage \(U\), which defines the depth of ion penetration in the workpiece material. The thickness of this surface layer for the free penetration of the electrons has been distinct by the Shenland’s relation:

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

where, \(\rho\) is the workpiece material density (in g/cm³) and \(U\) is the acceleration voltage (in V).

The complete depiction of ion penetration with effect of plasma factors on ions penetration is presented by (Tyagi, Srivatava, et al., 2012).

By using an atomic force microscope, the topographical charts of the surface have been documented. The root mean square value of the roughness altitude was calculated from power law. The pragmatic law for surface roughness (\(rms\)) was found to obey the following phenomenological power law, in which \(\beta = 1\) and \(\eta = 0.45\) (Pétri et al., 1994):

\[
rms \propto \frac{1}{\sqrt{E}} (J^+/J_F)^{\eta} t^{\beta}
\]

where, \(J^+\) is the ion flux impinging on the substrate, \(E\) is the kinetic energy of the ion, \(J_F\) is the SF₆ atom flux and \(t\) is the exposure time.

\[
n_0 = n_p \times v/4
\]
\( n_0 \) = No of ions striking the workpiece, \( n_p \) = plasma density and \( v \) = velocity of ions which is found out by Equation (1).

Plasma density is \( 10^{22-23}/m^3 \) (Tyagi, 2012a).

\[
Q = kn_d d^{3/2}(\rho_a/12\sigma_v)
\]

where, \( d \) is the size or diameter of an abrasive particle; \( \rho_a \) is the density of the abrasive material; \( v \) is the velocity of the abrasive particle and \( \sigma_v \) is the yield stress of the work material.

4. Results and discussions

4.1. Result and discussion of unconventional machining process

Tyagi, Srivastava, et al. (2012) found out ion penetration vs. \( k_p \rho_i \) for different combinations of plasma factors, such as magnetic field, magnetic field and heterogeneity in DC electric field. The value of ion penetration varies from 0.137 to 2.0 \( \mu m \) when plasma parameters are temperature anisotropy 1.5, temperature ratio 2; DC electric field varies from 12 to 20 V/m; and shear scale length from \( A_i = 0.5 \) to \( A_i = 0.55 \).

Shanland et al. in Romania experimentally penetrated the ions on metallic surface when value of applied voltage varies from 5000 to 200,000 V. The value of ions penetration varies from \( \delta = 7.05 \times 10^{-8} \) to \( 1.128 \times 10^{-2} \) cm. When ions penetrate the metallic surface, due to momentum of ions, adjacent particles oscillate. Due to oscillations, upper surface of metal melts and is removed from surface by circulation of fluid.

In electron-beam machining, material from surface is removed by the impact of high velocity electrons. The electrons are generated in electron gun. Jets of electrons are accelerated up to speed of light by applying voltage up to 50 kV between anode and cathode. Magnetic lens are used to focus the accelerated electron beam on workpiece. The energy density of electron beam is of the order of 108 W/cm. The kinetic energy of the electrons is converted into heat which is sufficient to cause rapid melting and vaporization of the workpiece material. To eliminate scattering of the beam of electrons, the work is done in a high vacuum chamber. Electron-beam machining can be applied to a wide range of materials. As a result of extremely high energy density of the beam and the short duration of beam–workpiece interaction, thermal effects on the workpiece material are limited to a heat affected zone that seldom exceeds 0.025 mm in depth. The high beam power density also enables high aspect ratio holes to be drilled, often as large as 15–1 (Velayudham, 2007).

4.2. Results and discussion of plasma etching process

Tyagi (2013a) theoretically found out surface roughness for different combinations of plasma parameters. These plasma parameters are ratio of ion flux to the neutral reactant flux \( (J^P/J_F) \), heterogeneous DC electric field, exposure time, magnetic field, heterogeneity \( (x/a) \) in DC electric field etc. The maximum value of surface roughness was 3.24 nm and minimum value of surface roughness was 1.32 nm.

Pétri et al. (1994) in calculated experimental value of surface roughness on silicon surface by considering following parameters: ratio of ion flux to the neutral reactant flux \( (J^P/J_F) \) varies from 20 to 80, the exposure time varies from 2 to 12 min, the magnetic field is 0.10 T, the homogeneous DC electric field is 15 V and other parameters also described in [5]. The value of silicon surface roughness varies from 2 to 20 nm.
4.3. Results and discussion of abrasive jet machining process

Matthew, Chastagner, and Albert (2007) found out the effect of three parameters on edge erosion. These two parameters are distance between nozzle and edge, and angle of impingement varies from 0 to 30°. Input air pressure was fixed at 552 kPa. In the first experiment, the author maintained \( l = 0 \text{ mm} \) and \( \alpha = 0^\circ \), while \( t \) was varied from 0 to 15 in 1 s increments. Another test was conducted under the same conditions with \( t = 30 \text{ s} \). This experiment studies the effect of time of blasting. In yet another experiment, the effect of distance between nozzle and edge tip was investigated. The value of \( l \) was varied from 0 to 5 in 1 mm steps, while \( t = 7 \text{ s} \) and \( \alpha = 0^\circ \). Also, the effect of angle \( \alpha \), which was varied from 0° to 30° in 5° increments (with \( l = 0 \text{ mm} \) and \( t = 7 \text{ s} \)) was studied. Three repeated tests were conducted for every test condition. All tests eroded a spot on the edge. In production, the nozzle is expected to move along the edge to generate the desired edge radius. The spot test in this study is the first step in understanding the magnitude of the edge radius and collateral damage in AJM.

Tyagi (2012a) presented a new technique of abrasive jet machining based on the concept of velocity shear instability in plasma. The effect of different plasma parameters on metal removal from metallic surface was studied. The plasma parameters were different values of electric field \( (V_0) \), heterogeneity in D.C electric field, magnetic field, heterogeneity in electric field, shear scale length, etc. The maximum value of metal removal is 2.2 gm/s and minimum value is 0.2 gm/s.

Figure 1 shows the variation of metal removal (gm/s) vs. magnetic field \( (B_0) \) for different values of electric field \( (V_0) \) by fixing other parameters. The value of metal removal (gm/s) decreases by increasing the value of magnetic field (Tyagi, 2012a). The maximum value of metal removal is 0.2 gm/s when the value of magnetic field is 0.2 T and the value of homogeneous DC electric field is 24 V/m with other fixed parameters listed in the figure caption. Heterogeneity in D. C. electric field is a useful parameter to control ion penetration into metallic surfaces. It has been shown that under the parameters considered, the maximum value of ion penetration is 41 \( \mu \text{m} \) (at value of the magnetic field 0.11 T, voltage 16 V and inhomogeneity 0.2). Moreover, the theoretical

![Figure 1. Variation of metal removal rate vs. magnetic field for different values of \( E_0 \) and other parameters are \( A_i = 0.5, T_e/T_i = 2, \theta_1 = 88.5^\circ, A_T = 1.5, \epsilon_0 \rho_i = 0.2, \chi/\alpha = 0 \), plasma density = \( 10^{22}/\text{m}^3 \), abrasive particle = \( 10^4/\text{min} \), size of abrasive particles = 0.45 mm, density of abrasive = 2.3 gm/cm\(^3\) and density of workpiece = 2.8gm/cm\(^3\).]
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 (Tyagi, Srivastava, et al., 2012).

5. Conclusion

In this review article, theory and model of non-tradition machining process, plasma spray technology, Plasma etching and abrasive jet machining have been discussed. The outline of this review article is divided into some industrial applications based on velocity shear instability in plasma. The computational/experimental results of this review article will be useful to fabricate a new plasma spray machine, unconventional machining process, plasma etching and abrasive jet machining or to increase the effectiveness of existing plasma spray machine and non-tradition machining process. This article shows the flexibility of using the plasma parameters for controlling/achieving some unconventional machining operations.

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