# A Review on Plasma Welding/Cutting with and without Velocity Shear Instability in Plasma

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***Abstract*-Engineering applications of plasma welding technology hold a marked significance in manufacturing industry. The effect of variation of electric field, magnetic field and other parameters on plasma heat flux, Debye length, temperature of ions etc. has been demonstrated in selected lead range for plasma welding/cutting for metallurgical and non metallurgical use. This review article analyses the experimental and theoretical effect of different plasma factors namely magnetic field , homogenous DC electric field, shear scale length, temperature anisotropy, heterogeneity in DC electric field and density gradient on the heat flux, Debye length, temperature and the number of ions. In this process, effectiveness of heat transfer from plasma to work-piece/electrode depends upon parameters such as temperature of ions, Debye length, number of ions striking the work surface etc. which can be controlled according to specific need by adjusting magnetic, electric field and aforementioned plasma factors without making any dimensional change to the machine. Through plasma welding, defects such as gas porosity, formation of oxide films, tungsten and other inclusions, hot and cold cracks, lack of fusion defects and cavities are reduced. Plasma welding/ cutting process is applicable to a broad range of samples from very small to large sized components by restricting to a set of parameters suited to them.**

***Keyword- Plasma; Velocity Shear Instability; Plasma Welding; Plasma Metal Cutting; Heat Flux***

## I. INTRODUCTION

Theoretical and experimental discussion of some industrial applications of plasma welding/cutting with/without velocity shear instability in plasma will be reviewed in this article. Plasma welding and metal cutting are the industrial applications that have been discussed.

The plasma welding/metal cutting parameters are temperature of ions/electrons, Debye length, number of ions/electrons hitting the target, heat flux etc., the values of which can be controlled by adjusting plasma parameters. The objective of this review article is to study the effect of magnetic field, electric field, heterogeneity in DC field and other plasma parameters on the metal cutting/welding. The key consequence of the process is based on development of heat and energy dissipation wherein some quantities of the work-piece material are melted, vaporized and ejected out of the work-piece. This technology is very useful for intricate and small components. In existing plasma welding/metal cutting machines, plasma welding parameters are controlled by adjusting the current. The maximum temperature generated in plasma welding varies from $10000^0$C to $20000^0$C. Shielding effect in plasma welding is controlled by side jet of helium. In this review article, theoretical and experimental plasma welding/cutting parameters such as heat flux, Debye length, temperature of ions etc. are analyzed by controlling magnetic field, electric field, temperature anisotropy, heterogeneity in DC electric field and other plasma parameters.

Plasma is often referred to as the fourth state of matter. The high energy content of plasma represents one of its outstanding features which may open new avenues in the field of high temperature chemistry and material processing. A thorough understanding of the heat transfer process from plasma to a solid or a liquid is needed to fully exploit the enormous opportunity plasma state offers. This process is much more complicated than in the case of an ordinary gas [1]. Heat transfer from plasma to work piece depends upon many parameters like heat flux, temperature of ions, Debye length and numbers of ions striking the probe [2].

In 1964, the plasma welding process was introduced to the welding industry and was acknowledged to bring better control to the arc welding processes in lower current ranges. Plasma, besides this, provides an advance level of control and accuracy to produce high quality weld in both miniature and precision applications and long electrode life for high production requirements at all levels of amperage. Due to these advantages, nowadays plasma is used in a variety of joining operations ranging from welding of miniature components to seam welding, high volume production welding and many others [3].

Plasma welding is quite similar to Gas Tungsten Arc Welding, the only significant difference being the constriction of arc plasma by a nozzle to produce a high-energy, high temperature plasma stream (10000 to $20000^0$C). The plasma jet does not provide adequate protection for the weld pool because it is extremely narrow, so a large diameter annular stream of shielding gas is added [4].

In the machine manufacturing industry, the plasma is used as an instrument specially in cutting operations, coating, welding, melting and support of the mechanical processing operations such as turning, threading, drilling, grooving etc., in order to improve the machinability of various materials and alloys [5].

The laser produced plasma significantly affects the efficiency of deep penetration laser welding due to its shielding effect. A lot of research efforts have been made on the control of plasma. Liu and Tse tried to use the effect of magnetic field to reduce the shielding effect of the plasma [6].

The application of plasma with Aluminum alloys in diverse areas of manufacturing is being explored incessantly. The fabrication and patch up of these structures/frames has been approved by a number of welding technologies, in particular, argon-shielded consumable and non-consumable electrode welding. The function of arc welding technologies is accompanied by a number of troubles posed by either some particular features of welding materials or by some deviation in the expected results of the process. They comprise a reduced productivity in welding metals of enlarged thickness, shortcoming of welded joints, the heterogeneity of the welded joints and parent's metal and troubles in the fabrication of bulky structures with dissimilar spatial allocation of the welded joints. Characteristic deficiencies in arc welding Aluminum alloys are gas porosity, the creation of oxide films, tungsten and other insertions, hot and cold cracks, lack of fusion defects, cavities, etc. most of which can be resolved along with an improvement in efficiency by plasma welding [7].

The heat and mass transport in the electrode, arc plasma and molten pool are regarded in one integrated form. Using the capacity of liquefied technique, the transportation phenomena are dynamically considered in the following processes: droplet creation and indifference, droplet flight in arc plasma, intrusion of beads on the molten puddle and solidification after the arc extinguishes. The simulation of heat and mass transfer in the arc plasma considers the growing surface profile of the electrode and molten puddle and also the effect of the fluttering droplet within the arc plasma [8].

The processes based on thermal effect of plasma began to play an increasingly significant role in the great family of unconventional machining processes. In the present times, the plasma arc cutting machining (PAC) represents one of the major machining technologies used in the industrial domains such as machines manufacturing, electronics, aeronautics, fine mechanics etc. Its success is mainly attributable to the fact that it allows machining of the high-alloy refractory and stainless steels with highest of productivity, to the optimum capacity, to the low down expenses against traditional techniques and also due to the merit obtained of the surface material. The plasma/ion beam machining is based on thermal or chemical effects generated in the contact zones between ions or plasma and the accessible surfaces of the work-piece [9].

The electric energy is used to form the jet of plasma in the presence of a plasmogen gas. The primary gas ought to ensure protection to the incandescent electrode against the oxidation process and to be neutral towards the material of the work-piece. The mono atomic inert gases which are today mostly used to produce thermal plasma (Argon, Helium, air etc.), accomplish these conditions. Since in the process the thermal energy is released, the material in solid state is heated, melted and then boiled. The inter-atomic material bond-breaking is realized by thermal phenomenon. Plasma is a state of matter similar to a gas but it is characterized by a high level of dissociation and ionization although on the whole it behaves as a neutral medium. Plasma includes a mix of free electrons, cations, ionized molecules or atoms, neutral molecules and photons [10].

In plasma, if number density and velocity of each layer in plasma species is different, instability is generated in plasma which is called as velocity shear instability in plasma. The plasma can be generated by an inert gas or by $KSF_6$, $SF_6$ or by some other gas [11].

Production of metal compositions in gap will entail exercise of a variety of metal joining methods. The plasma arc welding (PAW) technique is one of numerous methods being considered for this reason. Plasma arc welding is an arc welding process in which coalescence, or the joining of metals, is created by heating with a squeezed arc between a non-consumable electrode and the work-piece (transferred arc) or the electrode and the constricting nozzle (non-transferred arc). The PAW process is the same as the gas tungsten arc welding (GTAW) process as in both processes, the arc is utilized as a heat resource to fuse the joint and filler metal is filled in the grooves. In contrast to the GTAW process, because the electrode is recessed inside the constricting nozzle, the PAW method has numerous singular in service characteristics [12].

The purpose of this review article is to summarize the works of various scientists in the field of plasma welding/cutting based on the theory of velocity shear instability in plasma, which will be valuable for developing new plasma welding/cutting for various sophisticated and precision applications.

## II. REVIEW OF LITERATURE

Review of literature of plasma welding/cutting has been discussed in tabular form.

| Plasma Welding/Cutting literature review | | | | |
|---|---|---|---|---|
| 1 | Bychenkov V Y., et al [2]. | Heat transfer in a turbulent laser plasma | American Institute of Physics | This paper describes the relation between plasma density, heat flux, debye length, temperature of ions/electrons. Also, formulation of basics equations for turbulent flow of collisionless plasma is discussed. |
| 2 | Tse H C., et al [6]. | Effect of electric field on plasma control during CO2 laser welding | Optics and Laser in Engineering | Experiment was performed to find out effect of electric field on plasma factors such as debye length, temperature of ions and number of ions/electrons striking the workpiece. |
| 3 | Tse H C., et al [4]. | Effect of magnetic field on plasma control during CO2 laser welding | Optics and Laser in Engineering | Experiment was performed to find out effect of magnetic field on plasma factors such as debye length, temperature of ions and number of ions/electrons striking the workpiece. |
| 4 | Turichin G A., et al [13]. | Special features of formation of plasma torch under condition of hybrid laser arc welding | High temperature | Various equations were derived for hybrid discharge plasma under conditions of laser arc welding. |
| 5 | Chamarthai, et al [14]. | Cut quantity analysis at plasma arc cutting | Procedia Engineering | Cut quality at plasma arc cutting is analyzed. In order to determine how the cutting data influence the quality obtained at plasma arc cutting some experimental tests were made in an industrial enterprise on a CNC plasma arc cutting equipment. |
| 6 | Tyagi, et al [15]. | Effect of Electric and Magnetic field on metal cutting by Velocity Shear Instability | Journal of Emerging Trends in Engineering and Applied Science | Effect of electric and magnetic field on metal removal rate is studied. |
| 7 | Tyagi, et al [16]. | Effect of Electric and Magnetic field on Welding parameters | Journal of Engineering, Science and Technology | This paper presents effect of electric and magnetic field on plasma parameters, such as debye length, temperature of plasma species, plasma density etc. |
| 8 | Tyagi, et al [11]. | Heat Flux and Plasma Parameters in Plasma Welding By Means of Velocity Shear Instability | Journal of Engineering and Technological Research | This article shows effect of different plasma parameters on heat flux |
| 9 | Tyagi, et al [17,18]. | Analysis of Electrostatic ion cyclotron instability driven by Parallel flow velocity Shear Instability, Analytical and experimental study of velocity Shear Instability in the presence of inhomogeneous perpendicular D.C electric field | Surface Engineering and Applied Electrochemistry, Journal of Engineering and Technological Research | Theoretical value of real frequency and growth in wave has been calculated by taking Marlino et al data, when considering homogeneous/heterogeneous DC electric field. |
| 10 | Paradkar et al., [19] | Numerical modeling of fast electron generation in the presence of preformed plasma in laser-matter interaction at relativistic intensities | Physical Review | In this article experimental value of Debye length is calculated when plasma density varies from $10^{18}/cm^3$ to $10^{26}/cm^3$. |

| | | | | |
|---|---|---|---|---|
| 11 | Bourham and Gilligan [20] | Heat transfer in a turbulent laser plasma | JETP Lett | In this article experimental value of Temperature is calculated when plasma density was $10^{23}/m^3$ |
| 12 | Pfender [21] | Heat transfer from thermal plasmas to neighboring walls or electrodes | Pure Applied Chemistry | This article expresses the correlation between current densities and heat fluxes follows from an anode energy balance. |
| 13 | Begic et al [22] | Some Experimental Studies on Plasma Cutting Quality of Low Alloy Steel | Annals of DAAAM for 2012 & Proceedings of the 23rd International DAAAM Symposium | This article presents an experimental study to evaluate the effect of the cutting parameters on the cut quality during plasma cutting |
| 14 | Marta et al [23] | Comparison of different Material Cutting Technologies in Terms of their Impact on the Cutting Quality of Structural Steel. | Technical Gazette | This article deals with a comparison of the most frequently used thermal cutting technologies applied to the structural, low carbon steel EN S355J0 |
| 15 | Dasgupta et al [24] | Optimization of Weld Bead Parameters of Nickel Based Overlay Deposited By Plasma Transferred Arc Surfacing. | International Journal of Modern Engineering Research | This article shows weld bead penetration (P) increases significantly when welding current increases. |
| 16 | Prasad et al [25] | Effect of pulsed current micro plasma arc welding process parameters on fusion zone grain size and ultimate tensile strength of Inconel 625 sheets. | Acta Metall. Sin | This article relates input parameters have greater influence on the mechanical properties of the weld joints. |
| 17 | Siva et al 26] | Analysis and optimization of weld bead parameters of nickel based overlay deposited by plasma transferred arc surfacing. Engineering | Archives of Computational Materials Science and Surface. | This article shows wear, corrosion and heat resistance and weld bead geometry |
| 18 | Tyagi R.K [27] | A review of few unconventional machining processes based on the concept of velocity shear instability in plasma | Production and Manufacturing Research | This article summarizes micro/nano machining based on the concept of velocity shear instability in plasma. The working environment for micro/nano machining should be vacuum. |

## III. THEORETICAL FORMULATION OF PLASMA WELDING/CUTTING

The velocity and energy of plasma can be found out by the relation derived by [17, 18].

The effect of different plasma parameters on plasma energy has been elaborated by [28]. The result obtained by Tyagi 2012 indicates that magnetic field, electric field, temperature anisotropy, temperature ratio and density gradient effect plasma energy. With the help of equation (1) energy of plasma has been calculated.

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

Number of ions striking the work piece per second can be found out by relation [6].

$$n_i = n_p \times c/4 \tag{2}$$

$n_i$ = no of ions striking the work piece, $n_p$ = plasma density, $c$ = group velocity of waves which is found out by equation (1). Plasma density is $10^{15\text{-}16}/\mathrm{m}^3$ [29].

$$eV_a = m_i v_i^2/2 \tag{3}$$

$$eV_a = K_b T_i = \frac{m_i v_i^2}{2} \tag{4}$$

$v_i$ is the group velocity of waves/ions, m is the mass of ions, Kb is the Boltzmann constant, Ti is the temperature of ions.

$$\lambda_{De} = \sqrt{\frac{\varepsilon_0 T_i}{e n_p}} \tag{5}$$

$\lambda_{De}$ is the Debye length of ion, $n_p$ is the plasma density

$$n_{probe} = \frac{n_i c}{4}\exp\left(\frac{eV_a}{K_b T_i}\right) \tag{6}$$

$n_{probe}$ is the number of ions striking the probe per unit area per second.

The correlation between current densities and heat fluxes follows an anode energy balance. Local heat fluxes to the anode may be expressed by [21].

$$q_a = q_c + q_r + j_i\left(\frac{5}{2}K_b t_i/e + V_a + \phi_a\right) \tag{7}$$

In most cases of practical importance heat transfer to the anode is governed by the electron flow (last term in eqn (7) i.e.

$$q_a = j_i\left(\frac{5}{2}K_b T_i/e + V_a + \phi_a\right) \tag{8}$$

For known values of $q_a$ heat flux U can be found out by relation $q_a/j_i$.

Random current density, $j_i$ and $\phi_a$ can be found out by relation

$$j_i = e n_i v_d/4\exp(e\phi_a/K_b T_i) \tag{9}$$

$v_d$, $v_i$ are the drift velocity and velocity of ions respectively

Potential drop across shield

$$(\phi) = K_b T_i / e \ln(e n_i v_i / 4 j_i) \tag{10}$$

The relation between number of ion-acoustic waves, temperature of ions, Debye length, and electron heat flux is given by [2] as:

$$N(k) = \frac{26q_e}{kT_i} \frac{(m_e m_i)^{1/2}}{k^4} ln(\frac{1}{k\lambda_{De}})\delta\delta(cos - cos\theta_0) \tag{11}$$

The relation between heat flux and number of ions striking the target, temperature of ions/electron, ion acoustic wave velocity is given by [2] as:

$$q_e \geq 6.5 n_e k T_e v_s \tag{12}$$

## IV. RESULT AND DISCUSSION

Plasma welding is one of the influential techniques for joining process for a range of manufacturing applications. In this article, effect of different plasma parameters on heat flux, Debye length and temperature of ions in plasma for wide range of materials and for varying shapes has been studied. This article emphasizes upon heat flux, Debye length and temperature of ions in plasma welding/ cutting. It was found in various articles that the effect of electric field, magnetic field, temperature anisotropy, shear scale length, density gradient etc. influences significantly the heat flux, Debye length and temperature of ions/particles. The outcome from [30] also indicates that the heat flux, Debye length and temperature of ions are enhanced by escalating the value of temperature ratio and intensity of electric field and reduced by raising the intensity of magnetic field, heterogeneity in DC electric field, density gradient and temperature anisotropy.

(Tyagi et al 2012) studied the influence of the magnetic field on ion temperature and mass of metal removed from aluminum surface by fixing the value of DC homogenous electric field. In it, magnetic field varies from 0.20T to 0.28T.The maximum value of metal cutting is $1.04 \times 10^{-3}$ Kg/sec at 0.20T [30].

Maximum value of ion temperature, Debye length and number of ions striking the probe are $2.4 \times 10^4$K, $3.65 \times 10^{-6}$ mm and $4.75 \times 10^{25}$m$^3$ respectively at 24V, when $k_\perp \rho_i = 2$.

The plasma Debye length is experimentally found out by [19] in which Debye length are in micron range when density of plasma varies from 1018 per cm3 to 1026 per cm3. The value of Debye length calculated by [18] is also in the same range.

Figure 1 and 2 shows the effect of electric and magnetic field on Debye length. The value of debye length increases upon increasing the value of electric field and decreases upon increasing the value of magnetic field [16].

Figure 3 and 4 shows the effect of electric and magnetic field on Heat flux. The value of heat flux length increases upon increasing the value of electric field and decreases upon increasing the value of magnetic field [18].

The plasma temperature experimentally found by [20] in which temperature of plasma species varies from $8.8 \times 10^3 K$ to $1.4 \times 10^4 K$ density of plasma is 1023/m$^3$. The value of temperature of plasma species calculated by [31] conforms to the same.

Begic et al, [22] presented an experimental study to assess the consequences of the cutting parameters on the cut quality during plasma cutting of 5 mm thick low alloy steel sheets. The cutting parameters considered include cutting speed and plasma gas pressure. Results show that good quality cuts can be produced in plasma cutting of low alloy steel, at the cutting speed from 400 to 700 mm/min and at the plasma gas pressure from 4 to 5 bars.

Marta et al [23] conducted an assessment of the most frequently used thermal cutting technologies applied to the structural, low carbon steel EN S355J0 in engineering enterprises with a spotlight on experimental quantity and assessment of characteristics of the heat affected zone. It gave a mutual comparison of these technologies in terms of the achieved heat affected zone. The goal of this paper was to use the property changes in the used material (affected by laser, plasma arc and oxygen cutting) as the quality indicator of the cutting process.

Dasgupta et al., [24] studied the effect of welding current on penetration (P). This is attributed to the fact that heat input to the base metal increases when current is increased. Penetration decreases as Oscillation width increases. This is due to spreading of heat resulting from more melting of base metal. Penetration decreases steadily with the increase of Travel speed as less amount of powder is deposited per unit length of bead. Penetration decreases to a lower value when pre heat temperature increases but afterwards penetration increases with further increase of preheat temperature. This may be the reason

why at lower preheat temperature the heat received from plasma arc will not spread in the stainless steel substrate due to lower thermal conductivity resulting in cushioning of arc. Penetration decreases with increase of powder feed rate.
In welding processes, the input parameters have greater influence on the mechanical properties of the weld joints. By varying the input process parameters, the output could be changed with significant variation in their mechanical properties. Accordingly, welding is usually selected to get a welded joint with excellent mechanical properties [25].

Plasma Transferred Arc surfacing is increasingly used in applications where enhancement of wear, corrosion and heat resistance of materials surface is required. The shape of weld bead geometry affected by the PTA Welding process parameters is an indication of the quality of the weld. The modeling, analysis and optimization of weld bead parameters of nickel based overlay deposited by plasma transferred arc surfacing were done by [26].

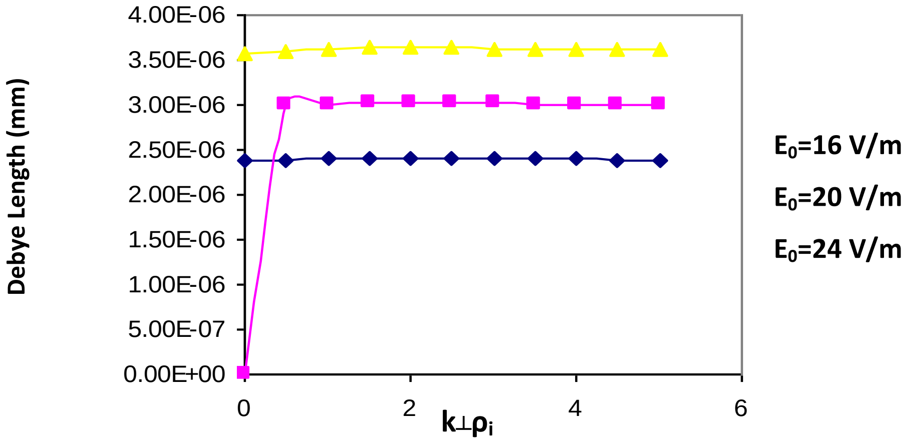


Fig.1.Variation of Debye Length verses $k_{\perp}\rho_i$ of ions for different values of Voltage and other parameters are $A_i$ =0.5, $T_e/T_i$ =1, $\theta_1 = 88.5^0$ , $A_T$ =1.5, $\varepsilon_n\rho_i$=0.2, $B_0$=0.24T.

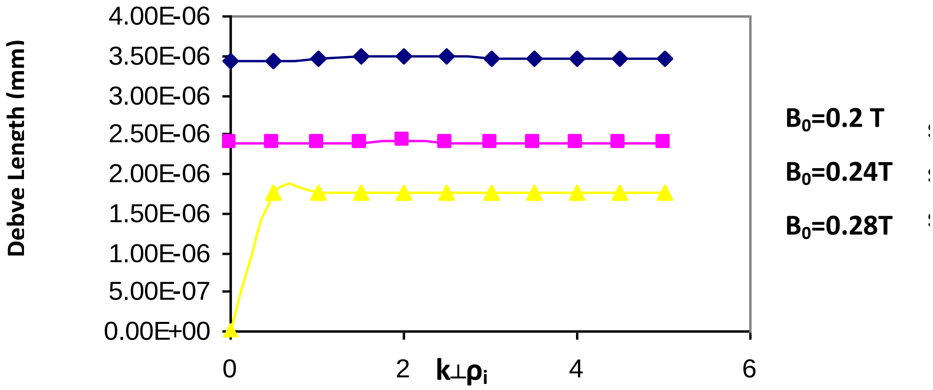


Fig. 2 Variation of Debye Length verses $k_{\perp}\rho_i$ of ions for different values of magnetic field and other parameters are $A_i$ =0.5, $T_e/T_i$ =1, $\theta_1 = 88.5^0$ , $A_T$ =1.5, $\varepsilon_n\rho_i$=0.2, V=16V.

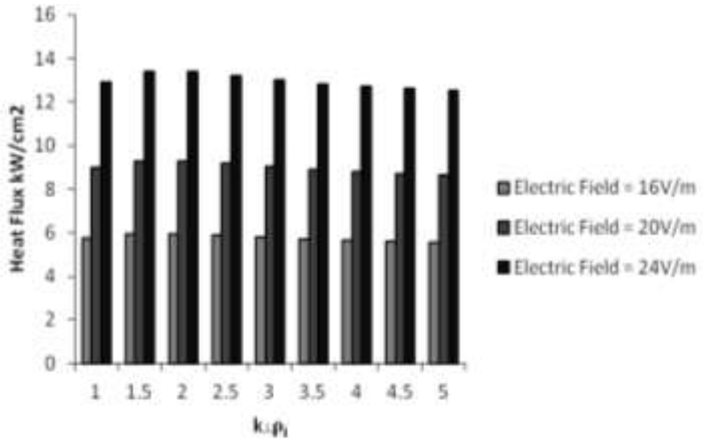


Fig. 3 Variation of heat flux verses $k_{\perp}\rho_i$ for different values of DC electric field ($E_0$) x and other parameters are $A_i$ =0.5, $T_e/T_i$ =2, $\theta_1 = 88.5^0$ , $A_T$ =1.5, $\varepsilon_n\rho_i$=0, $B_0$=0.20T

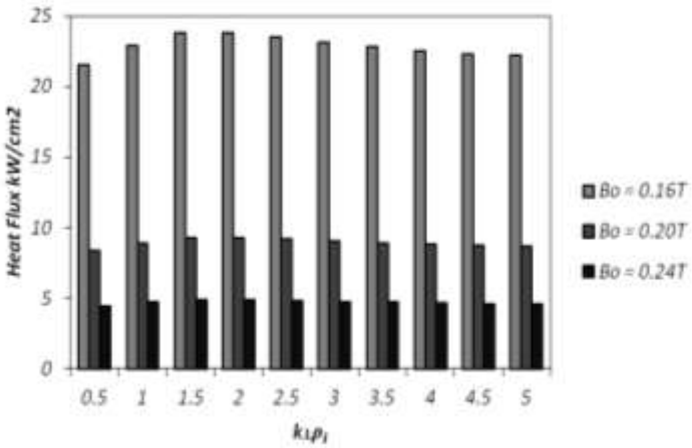


Fig. 4 Variation of heat flux verses $k_{\perp}\rho_i$ for different values of magnetic field and other parameters are $A_i$ =0.5, $T_e/T_i$ =2, $\theta_1 = 88.5^0$ , $A_T$ =1.5, $\varepsilon_n\rho_i$=0, V=20V

## V. AREA FOR FUTURE RESEARCH

This review article summarized various articles on plasma welding/cutting and presents the flexibility of using magnetic field and electric field to control Debye length, temperature of ions, and number of ions striking the work-piece. It furthermore presents the effect of different plasma parameters on heat flux, Debye length. The results presented in this review article have been a useful impression for designing machine for plasma welding/cutting. The deduction of this work is experimental/theoretical results presented in this review article would be useful to design a new plasma welding machine or to increase efficiency of existing welding/cutting machines. With the help of above study, one can utilize a single plasma welding/cutting machine for different sizes/materials components by selecting appropriate plasma parameters.

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