Plasma Control in Deep Penetration Laser Welding

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ABSTRACT

Abstract of thesis entitled "Plasma Control in Deep Penetration Laser welding"
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During high power CO_2 laser beam welding, the plasma above the keyhole has a shielding effect that it not only absorbs part of the laser energy but also defocuses the laser beam. As a result, the welding efficiency and the aspect ratio of the welds are influenced. In order to reduce the effect of plasma, Helium as a plasma control gas has been used successfully and effectively. However, the cost of Helium in South East Asia is extremely high and therefore the production cost is significantly increased when Helium is used as a continuous bleeding plasma control gas. Furthermore, due to the directional property of the side jet, profile welding is not possible by laser welding with a gas jet.

To search for an alternative plasma control technique, feasibility in using magnetic and electric field effects for plasma control was explored in this project. The individual and synergistic influences of magnetic field, electric field and both electric and magnetic fields on the penetration depth and the width of bead on stainless steel were studied. In addition, the effect of electric and magnetic field strengths, field direction, laser power, welding speed, shielding gases on the penetration depth and the width of bead were also investigated. Experimental results indicated that the fields can influence the shielding effect of the plasma. It was found that at suitable magnetic field strength, the magnetic field can increase the penetration depth by about 3%. On the other hand, using electric field can enhance the penetration depth by 8%. Using the effect of both electric and magnetic fields can not only increase the penetration depth by 13%, but also reduce the bead width significantly. In addition, the results were explained in terms of directional flow of ionic species in the laser plasma.

These new plasma control methods, especially both electric and magnetic fields, are found applicable to profile welding. Moreover, the cost of production of laser welding can be reduced.

ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

1.1 BACKGROUND INFORMATION

Laser welding is one of the many fusion welding techniques. It does offer a number of advantages when compared to the other conventional welding techniques such as electric arc, ultrasonic and resistance welding processes. For example [1, 2]:

- Deep, narrow and high-strength welds can be produced.
- Very low thermal distortion of the workpiece and small heat-affected zone (HAZ) can be achieved due to minimum heat inputs.
- High production rates and process flexibility.
- Able to weld some metals difficult to weld by other techniques, especially dissimilar metals.
- No filler or electrode is used so that it minimizes contamination.

Therefore, laser welding machines are widely accepted in industry as reliable and flexible welding tools. However, due to the shielding effect of plasma during deep penetration laser welding, the efficiency of welding is affected. Under proper conditions the plasma is responsible for the major and rapid heat input to the workpiece [3]. However, in some conditions, the laser-produced plasma acts on the negative way. When the density of the ionized species in the plasma is above a critical value, defocusing and reflection of the laser beam will occur [1, 4]. In other words, it affects the efficiency of the coupling of the laser energy to the workpiece. This will cause a change in the weld shape [5], and even total collapse of the keyhole. Therefore, in order to achieve the advantages of rapid heat transfer and reduce the negative effect of the plasma simultaneously, the plasma must be carefully controlled.

A lot of research effort has been spent on the control of the plasma above the work surface or inside a vapor filled cavity in order to increase the weld penetration depth. For example, welding in vacuum or reduced atmosphere is one of the successful methods [6, 7]. However, because of the long cycle time, these methods are not applicable in industry. Another technique is the Laser Spike Seam Welding (LSSW) technique [8] in which the beam is moved forward and backward for avoiding the plasma formation during welding. Yet, it has attracted little industrial interest. Using high repetition rate pulsed laser [7, 9] and shorter wavelength laser [10] are other techniques which interfere the growth of the plasma. Previous studies have shown that the use of shorter wavelength lasers, e.g., Nd:YAG Laser 1.06μm, can strongly decrease the perturbing effects of the inverse Bremsstrahlung absorption and refraction of the laser plasma. The most popular technique to reduce the shielding effect of the plasma is the use of a gas jet. In fact, laser welding with a gas jet is the most commonly used and successful method for suppressing the plasma above the keyhole. It has been well documented that the penetration depth and the weld bead profiles can be improved by using a Helium side-jet [11-14]. However, there are a number of disadvantages associated with this method. Firstly, in some regions of the world, such as South East Asia, Helium is expensive so that the production cost is largely increased. Although a new plasma blowing method has been developed [15, 16] to reduce the helium consumption, this technique is still under investigation. Secondly, it has been shown that the shape and behavior of the keyhole are significantly affected by the blowing velocity of the gas jet [8]. In other words, the location of the side-jet and its jet/weld pool interaction is critical and this makes the process and quality control difficult. Furthermore, the energy of the plasma is wasted. Last but not least, due to the directional property of the side-jet, profile welding is not possible by laser welding with a side gas jet.

In conclusion, most of the available techniques for plasma control have limitations. Therefore, it is necessary to search for an alternative plasma control technique so as to improve the welding efficiency, the weld profile, the process quality control and to reduce the production cost. In fact, many researchers [17-21] have shown that electric or magnetic fields does affect the laser-produced plasma. However, no continuos wave laser welding data associated with this plasma control method was reported. In this project, feasibility of using magnetic and electric effects as a control tool will be explored.

1.2 OBJECTIVES OF THIS PROJECT

The main objectives of this research study can be summarized as shown below:

- To study the effect of magnetic field on weld bead profile during laser welding.
- To study the effect of electric field on weld bead profile during laser welding.
- To study the effect of both electric and magnetic fields on weld bead profile during laser welding.
- To examine the welding efficiency of these new techniques as compared with the side-jet inert gas control technique.
- To study the possible application areas of using electric and magnetic fields for plasma control.

2.0 LITERATURE REVIEW

2.1 OVERVIEW OF LASER APPLICATIONS

2.1.1 General applications of Lasers

Lasers have become valuable tools in industry, communication, medicine, military as well as scientific research. Lasers can be used to not only drill holes in very hard and brittle materials, but also measure distances from micros to thousands of kilometers with extremely high accuracy. Lasers can also be used to perform eye treatment, cosmetic surgery as well as surgery on many parts of human body. Table 2.1 summaries some main application areas of lasers. In fact, laser technology continues to replace many conventional processes or techniques in many different industries. In the past decade, the overall worldwide commercial lasers (including diode and non-diode lasers) sales have been dramatically increased. In 1989, the sales figure was only 25.1 millions, but the figure in 1998 was increased eleven times (Figure 2.1). According to expert's forecast, it will be continued growth in coming millenium.

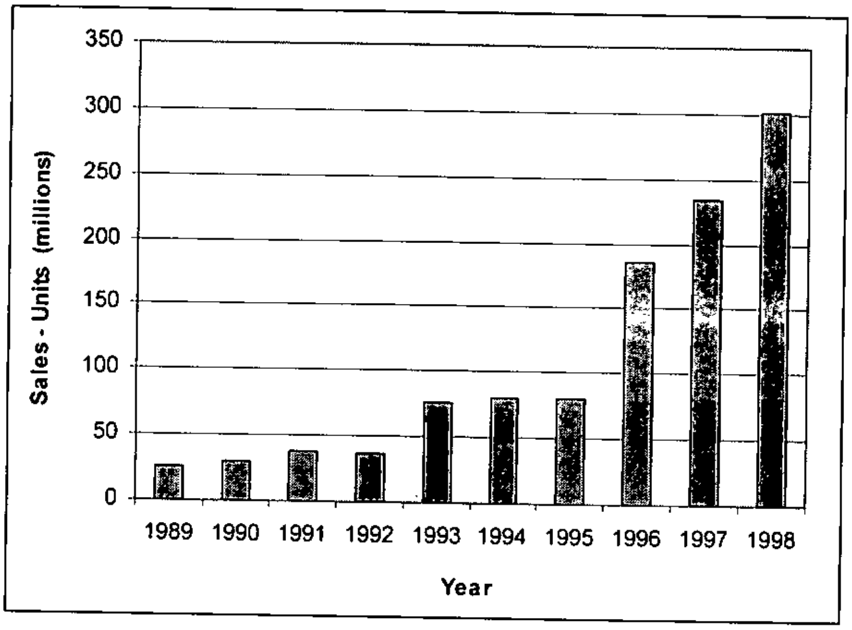


Figure 2. 1: Worldwide commercial laser sales (1989-1999) units [22-35]

Application areas	Examples
Industrial	Laser welding (Spot, deep penetration welding) Laser cutting Laser drilling Laser marking Micro-machining Surface modification (Hardening, Laser physical vapor deposition, Laser chemical vapor deposition, Alloying, Cladding)
Communication, optical information transmission and storage	Fibre-optical communication Laser printing Recording and reading discs (CD, VCD, CDR, CD-ROMs) Supermarket scanning Hand-held bar-code readers
Medical	Laser eye treatment Laser cancer treatment Laser dentistry Laser surgery Laser dermatology (e.g. skin treatment)
Military	Anti-satellite weapons Range-finding to targets War games and battle simulation
Metallurgical and scientific	Spectroscopic measurements (Fluorescence , absorption) Pollution measurement Lasers beam for alignment Measuring distance by counting waves Laser pointing Time measurement
Others	Basic research Holography Art & entertainment Producing nuclear fusion

Table 2. 1: General application areas of lasers [36-39]

2.1.2 Laser applications in industry [2, 4, 36, 39-42]

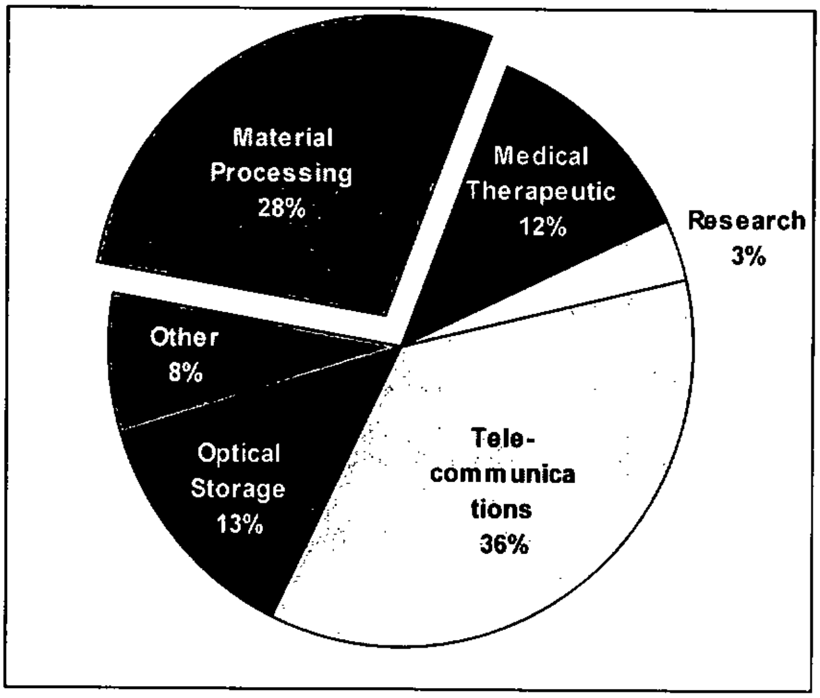


Figure 2. 2: Market division for laser applications, 1998. [22, 23]

Lasers for industrial applications do provide flexible and effective solutions for advanced manufacturing applications. Therefore, they are widely used in industry for material processing. In fact, the market share for material processing in 1998 was still very high or about 28% of total commercial laser sales (Figure 2.2).

Generally, laser produces light of a single frequency and intensity. When the laser light is focussed on the surface of materials, it can generate extremely high power density that can melt and vaporize the materials. By proper control of the laser parameters such as power level, focal point and time of exposure, a variety of materials processing operations can be carried out. Followings are some examples.

2.1.2.1 Laser cutting

Laser cutting is a process that is used to vaporize material in a well-defined area with the assistance of a coaxial gas jet (e.g. air, oxygen or nitrogen). When the high intensity laser beam moves continuously, a small cut width less than 0.1mm can be formed. The laser cutting can cut materials that are very hard, abrasive or low machinability. Moreover, the cutting profile is almost unlimited. The cutting point can be moved in any direction unlike conventional cutting processes. Last but not least, compared with the traditional cutting processes, the processing speed is very high. The advantages of cutting with a laser make it a preferred choice over conventional cutting methods. In fact, laser cutting remained the major application for industrial laser in 1998 (Figure 2.3).

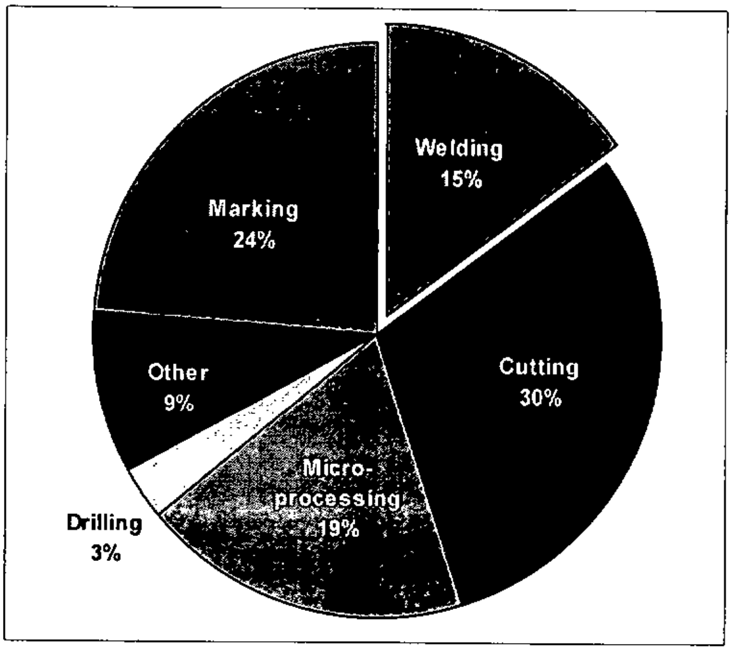


Figure 2. 3: World shares- industrial laser applications (Units of all types –1998). [43]

2.1.2.2 Laser welding

Laser welding is a non-contract process that is similar to the cutting process except the difference in size of the coaxial nozzle. The gas nozzle used in welding is large and is mainly for protecting the molten pool from oxidation. The commonly used gases for shielding are inert gases. When the laser beam focuses on the edges of metal plates, the high intensity spot causes the metal to melt and fuse together. And then, a weld will be formed. The laser welding does offer a number of advantages. These will be discussed in the next chapter.

2.1.2.3 Laser marking

Laser marking is a process of vaporizing a small amount of material with a pulsed CO_2 or Nd:YAG laser. By using this process, serial numbers, bar codes, logos and any graphics can be readily placed on many materials such as plastics, glass, wood, leather as well as metals. In fact, not only the laser mark is permanent, but also the depth of the mark is deeper than the mark's produced by other non-stamping methods. Therefore, marking application has been expanded worldwide (Figure 2.3).

2.1.2.4 Laser Drilling

Laser drilling is the process of removing material layer by layer by a series of short laser pulses with high power intensity. Holes down to 0.1 mm can be easily drilled. In fact, mechanical drills for drilling holes less than 1mm diameter are very expensive and they wear out easily after drilling a few thousand holes. Laser drilling gives benefits. Using a programmable laser machine, hole in different size and shape (e.g. round, oval or rectangular) can be easily controlled. Moreover, it not only hasn't the problem of tool wear, but also eliminates downtime due to tool changes.

2.1.2.5 Laser surface treatment

At lower power density, laser can be used to change or modify the surface properties of a material. Modifications can be made to a number of surface properties including hardness, abrasion, corrosion or oxidation resistance and fatigue life. Compared with the conventional heat treatment processes, laser has the advantages of high processing speed and low distortion. Furthermore, it heat-treats precise areas of materials without involving the entire workpiece. The principle application for laser surface treatment is producing tools particularly tools used for forging, die casting and extrusion.

2.1.3 Types of Industrial lasers [4, 39, 44-45]

There are several types of lasers and each has particular application. Based on the laser medium used, laser types are generally classified as gas, solid state, liquid and semiconductor. The most frequently used lasers for industrial applications are CO_2 laser, Nd:YAG laser and Excimer laser.

2.1.3.1 Carbon Dioxide Laser

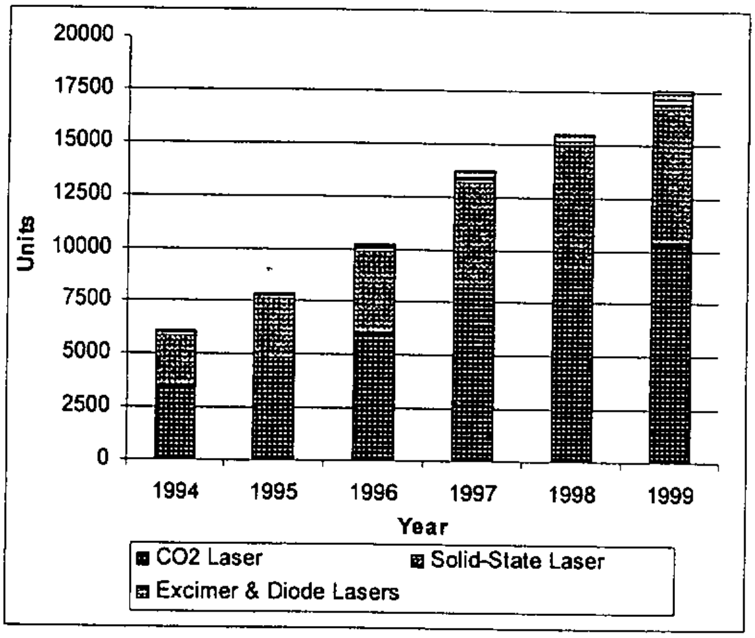


Figure 2. 4: Worldwide industrial laser production. [43, 46-49]

Due to the high efficient and high power density level, carbon dioxide (CO_2) laser is still the most widely used industrial gas laser (Figure 2.4). The lasing mechanism of CO_2 laser is provided by a set of vibrational-rotational transitions. A mixture of carbon dioxide, nitrogen and helium in an optimum ratio and under an optimum pressure is pumped through the laser cavity and excited by an electric discharge. The radiation oscillates within the cavity provided with a pair of mirrors at opposite ends and then emerges as a beam from the partially mirrored end. Its output wavelength is long and is in infrared region of 10.6μm. The wall plug efficiency (the ratio of optical energy output to total electrical energy input) is very high and can reach up to 20% (as shown in table 2.2).

Type	Wavelength (μm)	Wall plug Efficiency (%)*
Carbon dioxide	10.6	10-20
Lamp pumped Nd:YAG laser	1.06	0.4
Diode pumped Nd:YAG laser	1.06	10
Excimer (KrF)	0.249	2

Table 2. 2: Efficiency of main types of industrial lasers. [4, 39] (Wall plug efficiency* =Optical energy output / Total electrical energy input to the system)

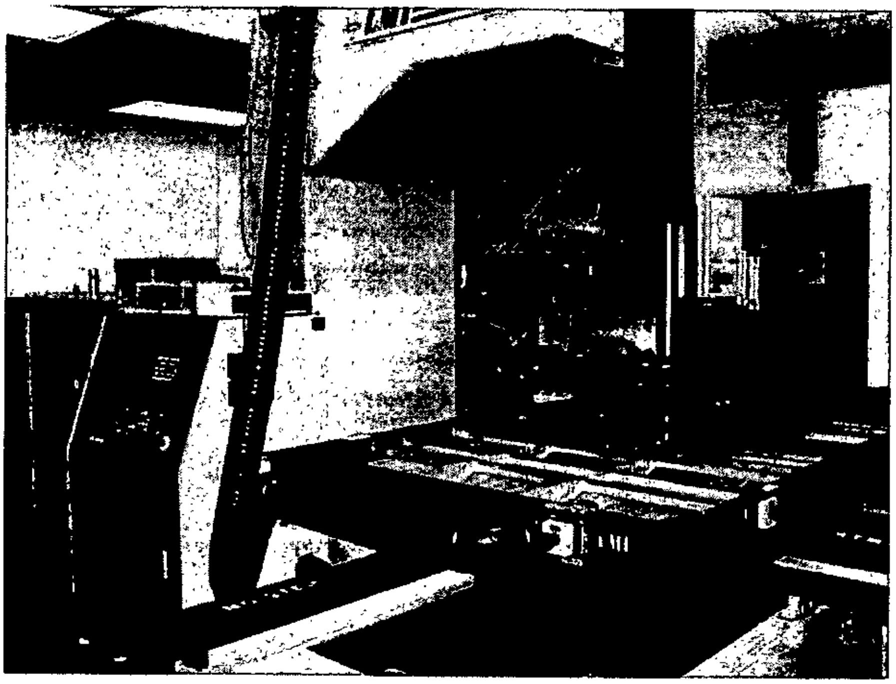


Figure 2. 5: 3500W Carbon dioxide laser (PRC, USA)

CO_2 laser can be operated in either pulsed mode or continuous mode (Figure 2.5). The laser power up to several tens of kilowatts is commercially available. Moreover, it can be used to machine many types of materials, such as wood, plastics, paper and metals. Therefore, it has been widely used in industry. Some examples are cutting, drilling, welding and marking.

2.1.3.2 Nd:YAG Laser

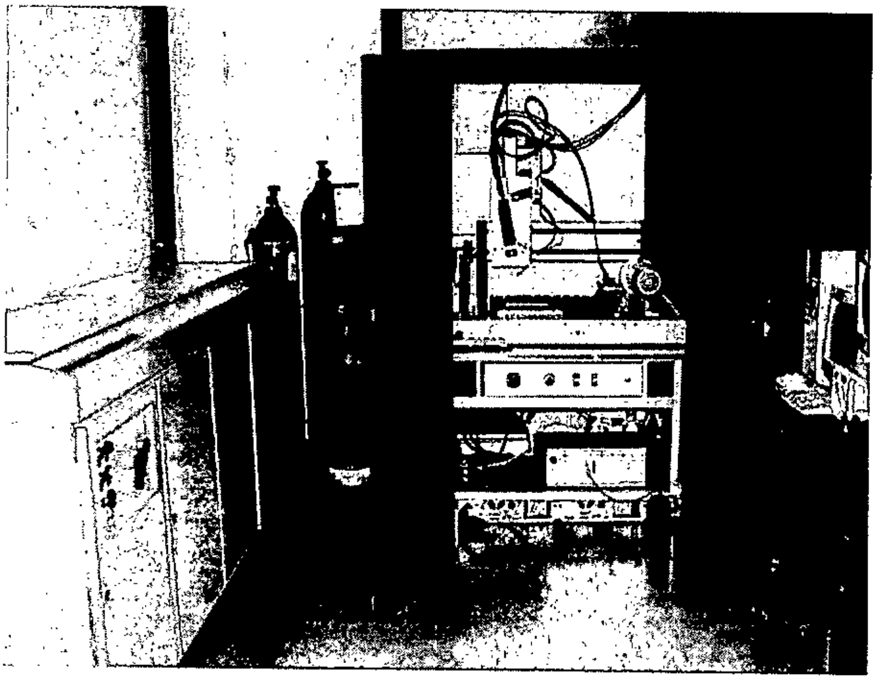


Figure 2. 6: A 2000W Nd:YAG laser (Lumonics, UK)

The Nd:YAG (Neodymium Doped Yttrium Aluminum Garnet) laser is a solid-state laser in which the light-emitting atoms (Nd ions) are fixed in YAG crystal and excited by light from an external source. The output wavelength of YAG laser is 1.06μm which is in the region of infrared. Flash lamps and arc lamps are the conventional light sources for pumping, but the wall plug efficiency is low. The efficiency of lamp-pumped Nd:YAG is about 1%. On the other hand, pumping the

YAG laser with diode laser is also common and gives many advantages. In addition to the compact size of diode, the wall plug efficiency can exceed 10% because the diode-pumped can pump energy directly into the excitation bands required.

Nd:YAG lasers can operate either continuous wave or pulsed (Figure 2.6). Due to their high peak power and short wavelength characteristics, they are suitable for drilling, spot welding, and marking, particularly materials that cannot absorb the 10.6μm wavelength of CO_2 laser. Furthermore, the laser can be transmitted through optical fibers and it makes production processes very flexible. Moreover, the laser light can also be focused precisely to a very small spot and therefore they are also widely used in electronics fabrication (e.g. resistor trimming, mask or memory repair).

2.1.3.3 <u>Excimer Laser</u>

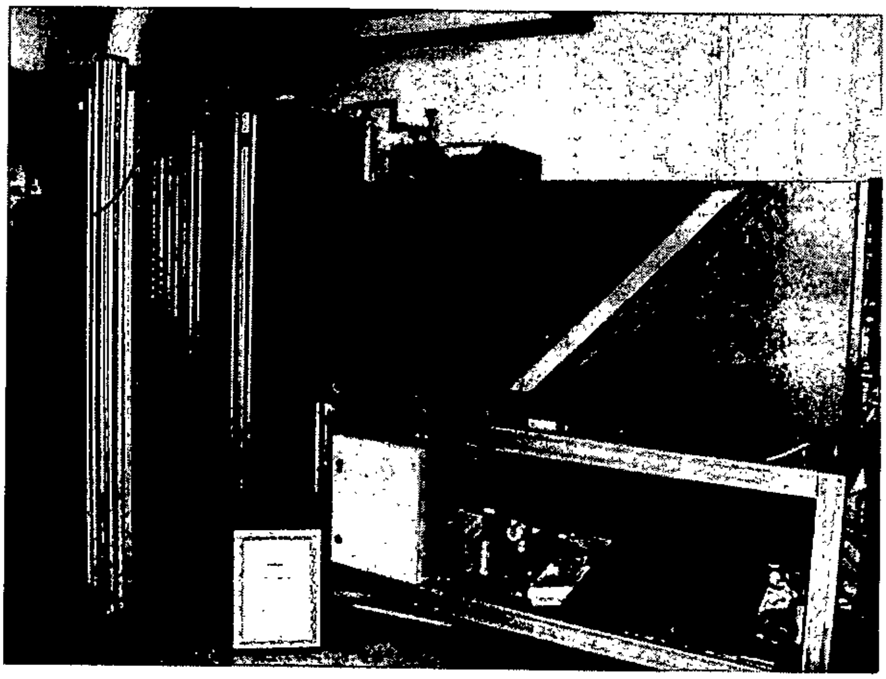


Figure 2. 7: A 800mJ excimer laser (Lambda Physik, Germany)

Excimer laser is the most powerful ultraviolet laser and has been a common industrial processing tool (Figure 2.7). The laser action is achieved by electronic transitions within short-lived molecules. The molecules containing the desired rare gas (such as argon, krypton or xeon) and halogen (such as fluorine, chlorine, or bromine) are excited by passing a short, intense electrical pulse. In fact, varying the gas mixtures can emit different wavelength lights in the ultraviolet region (Table 2.3). Compared with the lamp pumped Nd:YAG laser, the wall-plug efficiency is high and up to 2%.

Excimer laser is mainly operated in pulsed mode and the pulse is very short, typically in the order of tens of nanoseconds. Moreover, due to the ultraviolet output, the absorption coefficient for most materials is high. Therefore, excimer laser is good for micro-machining, surface treatment and microstructure modification. Some other possible applications are thin film deposition, annealing, doping of semiconductors and chemical vapor deposition. However, compared with CO_2 and Nd:YAG lasers, the capital and operating costs are still very high.

Type	Wavelength
F_2	157nm
ArF	193nm
KrCl	222nm
KrF	249nm
XeCl	308nm
XeF	350nm

Table 2. 3: Major excimer lasers [39]

2.1.3.4 **Future Trends** [50-52]

Industry has accepted high power CO_2 and Nd:YAG lasers are useful machine tools. However, small companies still find it difficult to use these laser machines because of the complexity, costs, and size of laser systems. The high power diode lasers do give massive benefits to them. In fact, high power diode lasers with a power up to 2.5 kilowatts have been commercially available for past few years. Due to their high wall plug efficiency (about 35%), short & tunable wavelength (800nm-950nm), compact size, maintenance–free, long-life and low cost, they have been a useful and common tool for materials processing. Some main applications of applying high power diode lasers are surface treatment, hardening, cladding and heat conduction welding.

However, at this moment the high power diode laser is not suitable for deep penetration laser welding. The main problem of high power diode laser is the insufficient beam quality that leads to a big focal point. As a result, the power density is limited or not enough for deep penetration welding. Therefore, further investigations and developments have to be carried out in order to solve the above problem.

Compared to well-known high power industrial lasers like CO_2 or Nd:YAG lasers, the high power diode lasers do offer a number of advantages. Moreover, the application potential of this in industry is very high. It is believed that high power diode lasers will become the most efficient and common tools. Even small manufacturing companies will be able to use this low-cost but high-power technology.

2.2 OVERVIEW OF WELDING PROCESSES

Welding is a process of joining materials [53]. In modern industry, many materials need to be welded in order to fulfill the specified function. Therefore, there are a number of welding processes in use. Tungsten inert gas, resistance, ultrasonic, electron beam and laser welding processes are some main welding processes that are commonly used.

2.2.1 Tungsten Inert Gas welding [54, 55]

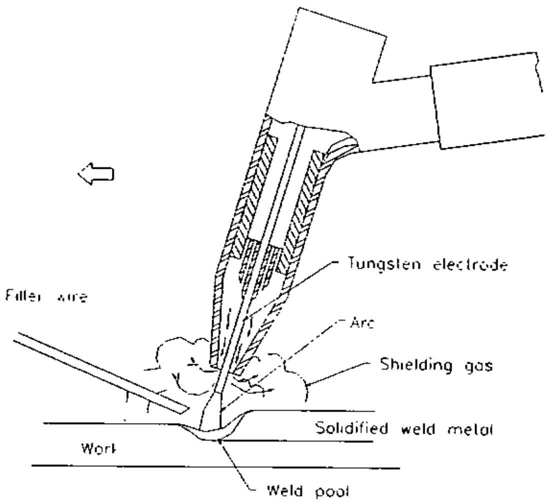


Figure 2. 8: Principle of TIG welding. [54]

Tungsten inert gas welding (Figure 2.8) is an electric arc process in which the electric arc struck from a non-consumable electrode (or tungsten) to the workpiece. The arc melts the edges of the metal parts to be joined together. Inert gas is used to shield the electron, arc and molten pool. In other words, the molten weld metal has a maximum protection from atmospheric contamination. As a result, the weld quality is high and surface finish is very good. However, compared with the oxyfuel gas welding, it is relatively expensive because of the inert gas used. It can be used to weld refractory materials such as aluminum, magnesium and titanium.

2.2.2 Resistance welding [56]

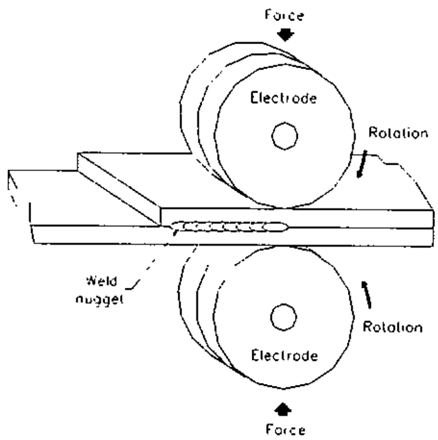


Figure 2. 9: Resistance seam welding

Resistance seam welding is the most commonly used resistance welding process in industry (Figure 2.9). This resistance welding process can produce a linear weld. Force is applied to the workpiece continuously through the current-carrying electrode wheels during the making of the weld. This resistance welding process is comparatively fast Material from 0.5mm to 3mm thickness can be welded. Moreover, it is applied to mild and alloy steels, stainless and heat-resisting alloy as well as refractory materials.

2.2.3 Ultrasonic welding [57]

Ultrasonic welding is another fusion welding technique. The source of heat is mainly by fiction (Figure 2.10). Ultrasonic vibrations are applied to lap joints pressed between the transducer and an anvil. These vibrations produce localized slip and plastic deformation between the parts and thus create a solid phase weld. By using this process, many materials in dissimilar thickness can be joined. Moreover, due to the little deformation and the local temperature rise, heat sensitive materials can also be welded.

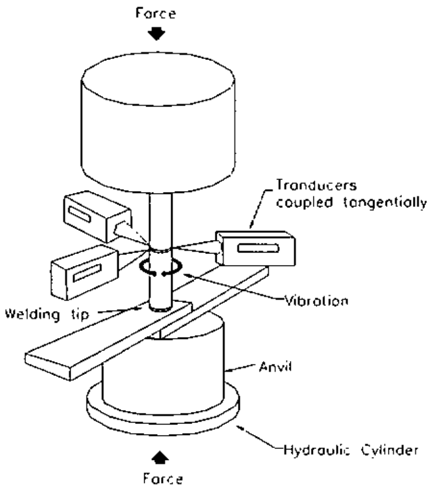


Figure 2. 10: Ultrasonic welding [57]

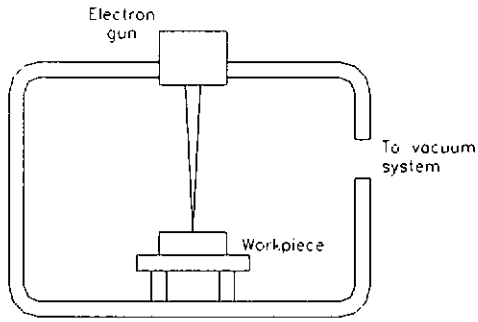


Figure 2. 11: Electron beam welding

2.2.4 Electron beam welding [56, 57]

Electron beam welding is a fusion welding and allows deep narrow welds with minimum heat affected zones (Figure 2.11). This powerful electron beam is generated by an electron gun and focused electro-magnetically on the workpiece. Heat is generated across the edges of the two parts to be joined together. In fact, only small amount of metal necessary for fusion is melted. As a result, it produces maximum joint strength with virtually no distortion. The capacity of electron beam for welding thickness from fractions of a millimeter to 200mm. In addition, the welding process requires a vacuum chamber and the weld quality is excellent.

2.2.5 Laser welding [1, 58]

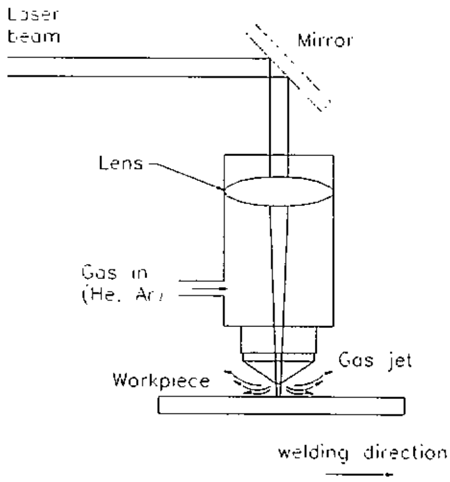


Figure 2. 12: Laser beam welding

Laser beam welding (Figure 2.12) has been widely used in industry for more than several decades. It does offer not only deep narrow welds but also little or no thermal distortion. Furthermore, no filler is used so that it minimizes contamination and produces high quality weld. The principle of laser welding is simple. Firstly, a powerful laser beam is focused optically on the metals. The beam heats the edges of the metal parts to their melting points and causes them to fuse together where they are in contact. In fact, the beam penetrates the depth of the weld completely and thus makes a proper weld joint. The welding process can be carried out in air, but shielding gas such as helium and argon must be used to protect the molten pool against oxidation. Commercially, several tens of kilowatts laser is available. It can be used to weld metals up to 200mm thickness. All materials commonly welded can be easily lasers welded. Moreover, many dissimilar and difficult to weld materials, such as carbon steel, stainless steel, quartz nickel, titanium and aluminum can also be welded.

In addition, the major advantages and disadvantages of laser welding are summarized in table 2.4.

Advantages	1. *Deep narrow weld* ✓ It eliminates the need for a V-joint preparation and the addition if a filler material.
	2. *Low heat input in material* ✓ It enables workpiece to be welded without the need for further post-weld machining. ✓ Welds can be made very close to heat sensitive components (electronic circuits and glass-to-metal seals). ✓ It reduces metallurgical damage (e.g. severe gain growth and extended HAZ)
	3. *High production rates and process flexibility* ✓ Welding speeds are high. ✓ Several workstations can time share one laser. ✓ Laser welding machines are suited to automation
	4. *Welds can be made when access is limited and from one side only* ✓ Welds can usually be positioned exactly at the abutting joint interfaces, thus improving fatigue and tensile strength when compared with alternative arc fillet welds. ✓ Mutlipe layers of material can be lap welded.
	5. *Component design opportunities are enhanced* ✓ A wide range of different joint configurations and dissimilar material thicknesses can be welded. ✓ Material allowances for post-weld machining are often unnecessary and weld land sizes can be reduced, promoting material savings.
Disadvantages	1. *Close fitting and well-clamped joints are required* × The small focused spot size of a laser beam will pass through narrow gaps especially between thin sheets. × Poorly fitting parts produce undercut welds, if not filler wire is used.
	2. *Accurate beam/ joint alignment is necessary* × The narrow weld can easily miss the joint line if not accurately positioned. × The depth of beam focus is small and its position about the work surface has to be accurately maintained to achieve the required power density.
	3. *Precision workpiece or beam manipulation equipment is necessary to control input* × The performance or beam manipulation equipment is also directly related to 2 above.
	4. *Machines are workshop based* × Safety screening around the operating envelope of the laser gun is essential for operator safety. × The optical stability of the laser resonator and system which transmits the laser beam to the work is paramount for reliable welding performance. Therefore, the equipment need to be maintained on a stable base. × The electrical and cooled water services required to operate a laser, especially a high power CO2 laser, are not readily portable.
	5. *Total equipment and operating costs are high* × Compared with arc welding machines, lasers together with the necessary work handling and ancillary equipment are expensive to purchase and operate. They require high utilization to be cost effective. × Careful adherence to maintenance schedules is necessary to ensure high equipment up-times.

Table 2. 4: Advantages and disadvantages of laser welding. [1]

2.2.6 Comparison of different welding processes

Table 2.5 shows the comparisons of different welding processes. It is obviously shown that using laser for welding has many superior qualities. Therefore, laser welding machines has been widely accepted in industry as reliable and flexible welding tools.

Quality	TIG	Resistance	Ultrasonic	Electron Beam	Laser Beam
Rate	✗	✓	✗	✓	✓
Low heat input	✗	✓	✓	✓	✓
Narrow HAZ	✗		✓	✓	✓
Weld bead appearance	✗		✓	✓	✓
Simple fixturing	✗			✗	✓
Equipment reliability	✓	✓			✓
Deep penetration		✗		✓	✗
Welding in air		✓		✗	✓
Weld magnetic materials	✓	✓	✓	✗	✓
Weld reflective material	✓	✓	✓	✓	✗
Weld heat sensitive	✗	✗	✓	✓	✓
Joint access		✗	✗		✓
Environment, noise, fume	✗	✗	✗	✓	✓
Equipment cost	✓			✗	✓
✓ Point of merit; ✗ Point of disadvantage					

Table 2. 5: Comparison of welding process [4]

2.3 High power laser welding

As mentioned before, laser welding does offer a number of advantages. Therefore, laser welding machines are widely accepted in industry as reliable and flexible welding tools. However, due to the shielding effect of plasma during deep penetration laser welding, the efficiency of welding is affected. Before discussing the effect of plasma during laser welding and common plasma control techniques, the laser welding mechanism will be introduced first.

2.3.1 Laser welding mechanism [1, 4, 59]

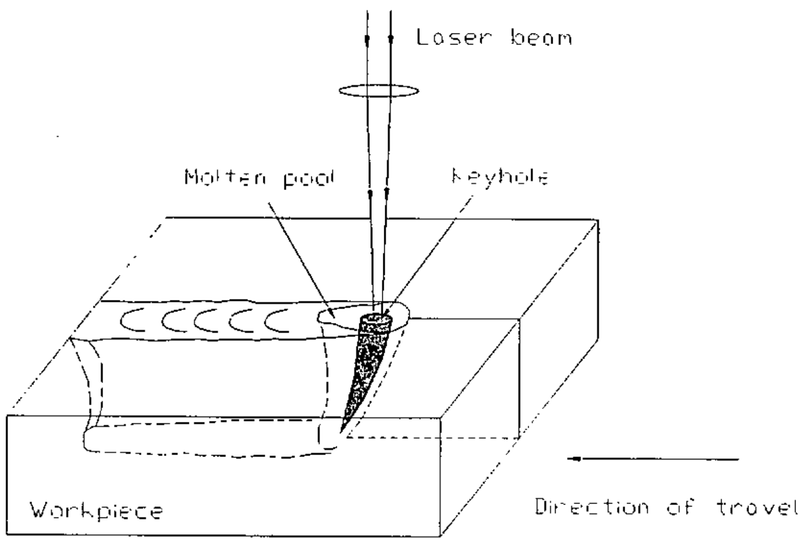


Figure 2.13: Laser welding mechanism

Figure 2.13 shows the mechanism of laser welding. To form a laser weld, the light beam is brought to focus on or very near the surface of the workpiece first. At the initial stage, a large percentage of the laser light is reflected from the cold workpiece surface and only small amount of laser energy absorbed by the work quickly which heats a thin layer of the material surface. The reflectivity of the workpiece is decreased with increasing the temperature that causes the workpiece to absorb much energy and form a molten pool. Due to the high absorption of the molten pool, vaporization starts and it produces vapor which couple the beam and the material. The rapid removal of material by vaporization and the ionized vapor exert pressure on the thin molten pool to form a depression. In other words, a small keyhole is initiated. When the laser beam moves forward, the molten layer is dragged backward due to surface tension and then the next layer of fresh metal is exposed and heated by the ionized vapor, or namely plasma. This process repeats rapidly and within microseconds a steady state is reached. On the other hand, the keyhole is kept open by plasma that prevents the molten walls from collapsing and this allows laser energy deposited deep into the workpiece. As the laser beam moves forward, the molten metal flows backward and fills in behind the hole. Lastly, it solidifies to form a weld.

2.3.2 Effect of plasma on laser welding

The efficiency of deep penetration laser welding is mostly affected by the existence of a plasma above the keyhole. As mentioned before, the positive function of plasma is used to prevent the molten walls from collapsing during welding. Furthermore, it was proved that under proper conditions the plasma is responsible for the major heat input to the workpiece [3]. It transfers the laser energy to the materials and enhances the energy coupling. The main reason is that the radiation of the plasma is in short wavelength range which is more efficiently absorbed by metallic surfaces. In addition, Michaelis [9] stated that for effective energy transfer the laser-produced plasma should be close to the metal surface.

However, the laser induced plasma can act on the negative way. When the density of the ionized species in the plasma is above a critical value, $N_e=10^{21}/\lambda^2=9\times10^{31}m^{-3}$ (where λ is the CO_2 laser wavelength, 10.6μm), defocusing and reflection of the laser beam will occur [60, 61]. In other words, it affects the efficiency of the coupling of the laser energy to the workpiece. This will cause a change in weld shape, e.g. decrease in weld depth and an increase in weld width [5], and even total collapse of the keyhole. Moreover, the plasma tends to cover the molten pool and prevent the escape of metal vapor. As a result, it is easy for porosity formation [13, 14].

Therefore, in order to achieve the advantage and reduce the negative effect of the plasma simultaneously, the plasma must be carefully controlled.

2.3.3 Current plasma control techniques

The shape and the quality of the welds are significantly influenced by laser-produced plasma in high power laser welding. A lot of research effort has been spent on the control of the plasma above the work surface or inside a vapor filled cavity. Some plasma control techniques are discussed below.

2.3.3.1 Vacuum laser welding

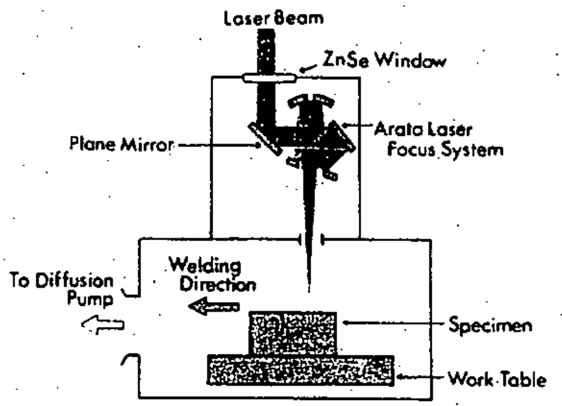


Figure 2. 14: Vacuum Laser welding [6].

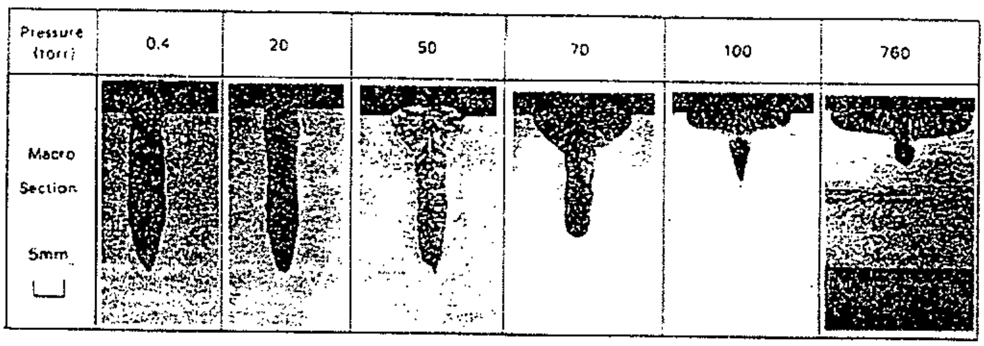
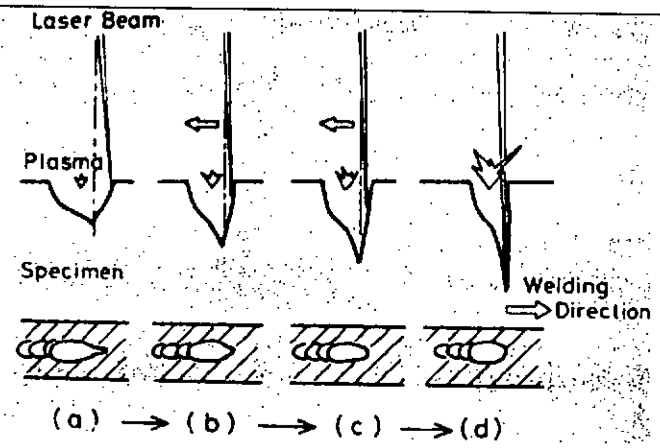


Figure 2.15: Effect of pressure on bead shape [7]

It was shown that laser welding in vacuum atmosphere (Figure 2.14) can not only reduce or almost completely suppress plasma but also allow deep penetration at a very slow welding speeds [6, 7, 62, 63]. It can penetrate about three times as deep as laser welding in atmospheric pressure at the same power and same speed (Figure 2.15). Moreover, it has been proved that it can prevent the porosity formation [7]. However, because of its long cycling time, it is not applicable in industry.

2.3.3.2 Arata welding technique

Arata et al [8, 64] developed a method, Laser Spike Seam Welding or LSSW, for avoiding plasma formation (Figure 2.16). It suppresses the plasma by moving the laser beam forward just before the plasma formation. Previous results showed that the penetration depth obtained by using LSSW was deep as two times those obtained by conventional laser welding. Unfortunately, because of its complex welding mechanism, it has little industrial interest.



a) When the laser beam is in its original position, the laser beam easily drills the specimen, because there is only a small amount of plasma
b) The laser beam moves backwards along the specimen with the same speed as the worktable. It stops relative to the specimen, and quickly melts down the front wall.
c) As the laser beam drills the specimen, the amount of plasma produced gradually increases.
d) Just before a large amount of plasma is produced, the laser drills the specimen deeply.
e) Then the laser beam is quickly shifted forwards to its original position to avoid the plasma, and it again starts to drill the specimen.

Figure 2.16: Welding mechanism of LSSW. [8]

2.3.3.3 Laser beam pulsation

Another solution interfering the growth of the laser plasma is to use high repetition rate pulsed laser [7, 65]. It was found that the penetration depth can be increased with increasing pulse frequency (Figure 2.17). Moreover, it has been reported that high repetition rate pulsed laser can penetrate 1.5 times as deep as continuos-wave laser welding. In addition, previous studies [9] also revealed that the laser pulse shape can be changed in a wide range for effective laser welding. However, this method is only applicable to welding at low speed range. Moreover, this possibility is still under study.

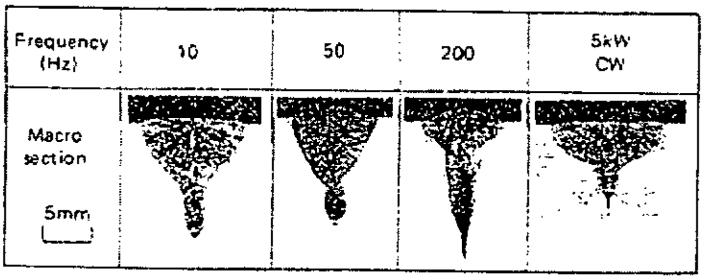


Figure 2.17: Effect of pulse frequency on bead shape [7]

2.3.3.4 Shorter laser wavelength lasers

Using shorter laser wavelength laser is another possibility to reduce plasma. Previous studies have shown that the use of shorter laser wavelength lasers, e.g., Nd:YAG laser (1.06μm), can strongly decrease the perturbing effects of inverse bremsstrahlung absorption and refraction in the laser plasma [10, 66]. In other words, much energy can be absorbed by the workpiece. As a result, deeper penetration depth can be obtained.

Nevertheless, the efficiency of the commercial available YAG lasers is very low. On the other hand, at this moment the high power diode laser is not suitable for deep penetration laser welding due to its limited power density.

2.3.3.5 Plasma control by adding magnetic field

Plasma control by using magnetic field is one of the most fundamental problems in plasma physics, but the effect of magnetic field on the penetration depth of laser welding was investigated in recent years [20]. It was shown that a suitable magnetic field placed under the workpiece, the magnetic field lines vertically passing through the workpiece surface and plasma, can increase the penetration depth of welding. Moreover, the ratio of energy absorbed by workpiece to laser energy can be increased to 1.75 times. However, the application of this plasma control method is constrained by the size of the workpiece and the mechanical design of the machine table. It cannot find industrial applications. Furthermore, this method is still under study.

2.3.3.6 Laser welding with a side-jet

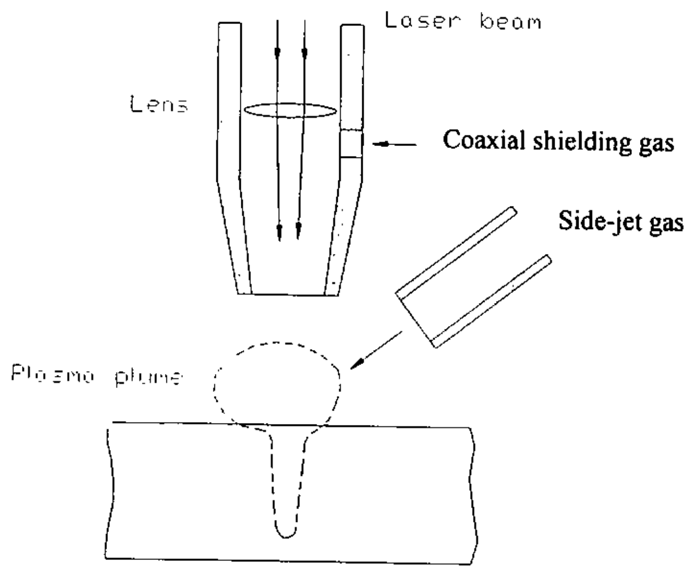


Figure 2. 18: A simple side tube shielding device

Laser welding with a side-jet (Figure 2.18) is the most commonly used and successful method for suppressing the plasma above the keyhole. With suitable gas jet parameters such as position and velocity, the plasma can be blown away efficiently, which results in a reduction in the shielding effect of the plasma. It was revealed that the penetration depth and the weld bead profiles can be improved by using this method [11, 12, 67-70] (Figure 2.19). In fact, the weld produced is uniform in terms of form and solidification structure [11]. Previous investigations showed that the optimum penetration depth obtained with plasma control was 1.3 times that obtained without plasma control. Moreover, the efficient removal of plasma made metal vapor escape easily from the molten weld pool. Therefore, less porosity welds can be achieved with plasma control [13, 14].

Helium, argon, nitrogen, carbon dioxide and oxygen are the common shielding gases. The choice of the proper gas used for laser welding depends on the laser intensity, the material thickness and the quality of weld required. In fact, Helium and argon are widely used by industry because of their inert property. They do not easily react with the weld metal. Conversely, nitrogen, carbon dioxide and oxygen are reactive gases that can easily cause metallurgical effects [71].

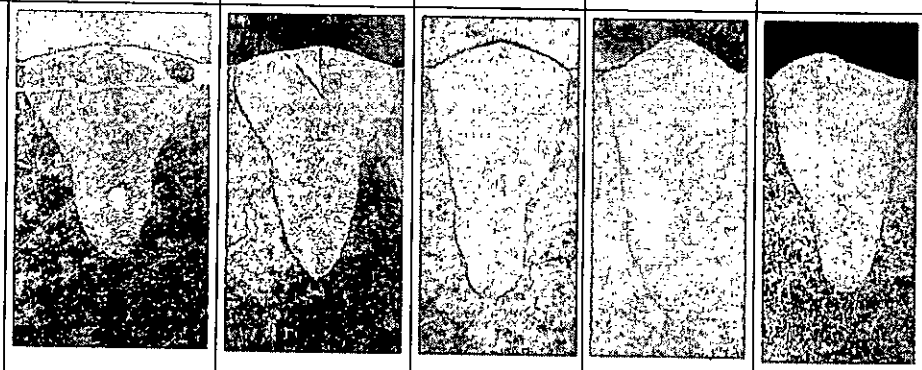
Side jet gas flow rate	a.0 L/min	b.15 L/min	c.30 L/min	d.45 L/min	e. 60 L/min
Cross-section 1mm					

Figure 2.19: Effect of side-jet gas flow rate on bead shape.

Gas	Ionization potential (eV)
Helium	24.46
Argon	15.68
Oxygen	12.50
Carbon dioxide	14.41
Nitrogen	14.53

Table 2. 6: Ionization potential of common welding gases

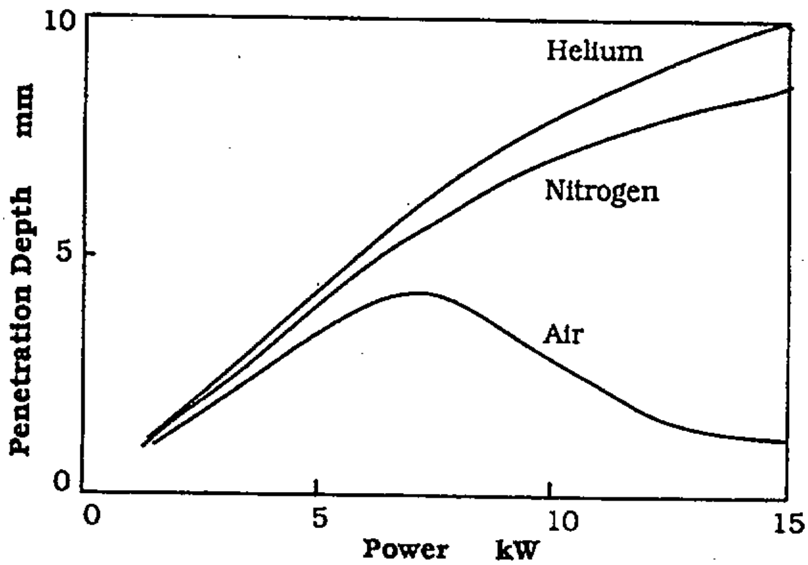


Figure 2. 20: Effect of type of shielding gas on penetration depth [4]

Helium is the common and more efficient gas for plasma control due to its high ionization potential (Table 2.6). Compared with other shielding gases, using Helium can produce deeper penetration depth (Figure 2.20)[72]. However, there are a number of disadvantages of using this method for plasma control. First of all, in South East Asia the inert gas is expensive (as shown in Table 2.7) so that the production cost is largely increased. In order to reduce the helium consumption, a new plasma blowing method was developed [16]. It was shown that helium mixed with non-inert gas, e.g. 10% of helium mixed with nitrogen or 75% of helium mixed with oxygen, with higher blowing velocity can suppress the plasma and prevent the occurrence of porosity. However, this solution is still under study.

Gas	Unit Price (in HK$)	
	in HK	in USA
Helium	$260/m³	$195/m³
Argon	$100/m³	$50/m³
Oxygen	$30/m³	$15/m³
Carbon dioxide	$24/kg	$16/kg
Nitrogen	$23/m³	$18/m³
* Price (not including delivery charges) quoted by Martin K. H. Luk, Hong Kong Oxygen & Acetylene Co. Ltd. on 1st July 1998.		

Table 2. 7: Unit prices of gases in HK & USA.

Second, it has been shown that the shape and behavior of the weld bead are significantly affected by blowing velocity [8]. Too high a flow rate of plasma control gas may push away the molten metal and enlarge the upper part of the weld bead. It reduces the "Wall Focusing Effect" for the laser beam. In other words, the location of the side jet and its jet/weld pool interaction is critical and this makes the process and quality control difficult. Furthermore, the energy of plasma is wasted.

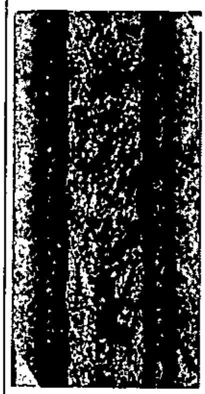
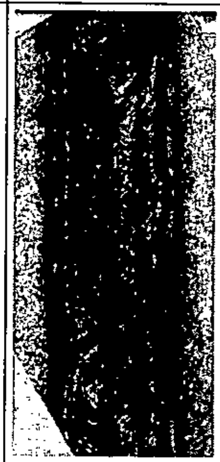
Shielding condition (Coaxial shielding: Ar)	no side-jet	Side-jet gas flow rate > optimum value
Weld track [1 mm		

Figure 2. 21: Weld defect encountered if flow rate is above critical value.

Last but not least, due to the directional property of the side jet, profile welding is not possible by laser welding with a gas jet.

In conclusion, all of the available techniques for plasma control have limitations. Therefore, it is necessary to develop a new plasma control technique so as to improve the efficiency of laser welding, ease the quality control and reduce the production cost.

2.4 LASER-PRODUCED PLASMA CHARACTERISTICS

Plasma formation takes an important part during laser processing and it requires the vaporization of the material at the first step. The vaporization depends on not only materials properties such as reflectance, thermal conductivity and diffusivity, specific heat, latent heats of melting and vaporization, melting and vaporization temperatures but also laser processing parameters such as laser intensity and interaction time. In addition, it has been reported that the type of shielding gas [5] and welding condition, e.g. under different atmosphere [73], also affect the plasma formation.

It has been known that the laser-produced plasma is a partially ionized plasma containing charged particles such as electrons and ions. Based on its "charged" characteristic, many researchers [17-21] have used electric or magnetic field to control the plasma or affect the plasma behaviors. For example, for diagnostic purpose, Mott-Smith [74] used an electric probe to determine plasma density and temperature. For thin film deposition, Tsiu et al [75] used an axial magnetic field to confine and guide a significant fraction of an expanding laser-produced plasma along a 15cm trajectory to a target surface. For laser drilling, Hamoudi et al. [21] used the effect of electric field to increase the hole depth.

As shown above, using electric and magnetic fields for plasma control do offer a number of advantages. However, no continuous wave laser welding data associated with this plasma control method was reported. In this project, feasibility in using electric and magnetic field effects for plasma control during laser welding was explored.

3.0 THEORY OF PLASMA CONTROL

The theoretical possibility of using electric and magnetic effects will be introduced in the following section. First of all, the effect of the level of electron density in plasma plume on beam absorption & defocusing will be discussed. In fact, the electron density is a main parameter deciding the level of perturbing effect of the laser-produced plasma.

3.1 EFFECT OF THE LEVEL OF ELECTRON DENSITY IN PLASMA PLUME

3.1.1 Relation between electron density & beam absorption

It has been known that the ionization of the plasma is increased by absorption of the incoming laser radiation [76]. The free electrons absorb the beam by inverse Bremsstrahlung (IB). According to [10], the IB phenomena is described by the absorption coefficient α,

$$\alpha \approx \frac{v\omega_p^2}{c(v^2+\omega^2)} \qquad \text{......(3.1)}$$

where v is the electron collision frequency, ω is the laser radiation frequency, ω_p is the plasma frequency and c is the speed of light in a vacuum (2.998×10^8 ms^{-1}). Equation 3.1 shows that the absorption coefficient of the plasma is directly proportional to the plasma frequency, ω_p. On the other hand, Lieberman [77] stated that if the difference between the masses of ion and electron in the plasma is very large ($M >> m$, where M is the mass of ion), the relation between the plasma and the electron plasma frequency can be written as equation 3.2.

$$\omega_p \approx \omega_{pe} \qquad \text{......(3.2)}$$

In addition, the electron plasma frequency can be calculated from standard plasma physics formula, e.g. [78]

$$\omega_{Pe} \equiv \left(\frac{n_e e^2}{\varepsilon_0 m}\right)^{1/2} \qquad \text{......(3.3)}$$

where ω_{pe} is the electron plasma frequency, n_e is the electron density, e is the electron charge, ε_0 is the vacuum permittivity (8.854 x 10-12 F/m) and m is the mass of electron.

Combining equations (3.1,2 & 3), it is obviously shown that the absorption coefficient is directly proportional to the electron density. In other words, the absorption of laser radiation by the plasma increases not only the ionization of the plasma but also the electron density. In addition, similar correlation between the plasma absorption and the electron density was shown by Miyamoto's equation [79].

$$A_p = 2.21 \times 10^{-29} \times \frac{n_e^2}{T_e^{3/2}} \qquad \text{......(3.4)}$$

where n_e is the electron density and T_e is the electron temperature.

Therefore, in order to reduce the shielding effect of the plasma, the electron density must be maintained in a low level.

3.1.2 Relation of electron density to beam defocusing

It has been shown that the other one of the perturbing effects of laser-produced plasma in high power CO_2 laser welding is the beam defocusing [79]. Poueyo-Verwaerde [10] stated that the deflection angle of a laser beam propagating along the plasma plume for the CO_2 laser can be calculated by the following equation.

$$\theta = \frac{n_e L}{2R} \times 10^{-19} \qquad \text{......(3.5)}$$

where n_e is the electron density (in cm^{-3}), L is the propagation length corresponding to the length of the plasma and R is the radius of the plasma plume. Equation (3.5) indicates that the level of the electron density in the plasma is directly affecting the beam defocusing.

Based on the above theoretical analysis, reduction of electron density in plasma fume may be used to increase the penetration depth and improve the welding efficiency.

3.2 EFFECT OF THE MAGNETIC FIELD ON PLASMA

As mentioned before, the plasma absorption ratio and the extent of beam defocusing increase with the increase of the level of the electron density in the plasma. Therefore, in order to reduce the shielding effect of the plasma, the electron density must be controlled in a low level. In fact, it has been shown that the electron density of the plasma can be affected by magnetic field [18-20, 80, 81]. Generally, according to the direction of magnetic field lines, either perpendicular or parallel to axis of the laser beam illuminating the target, the effect of the magnetic field on laser-produced plasma can be divided into two cases (Figure 3.1).

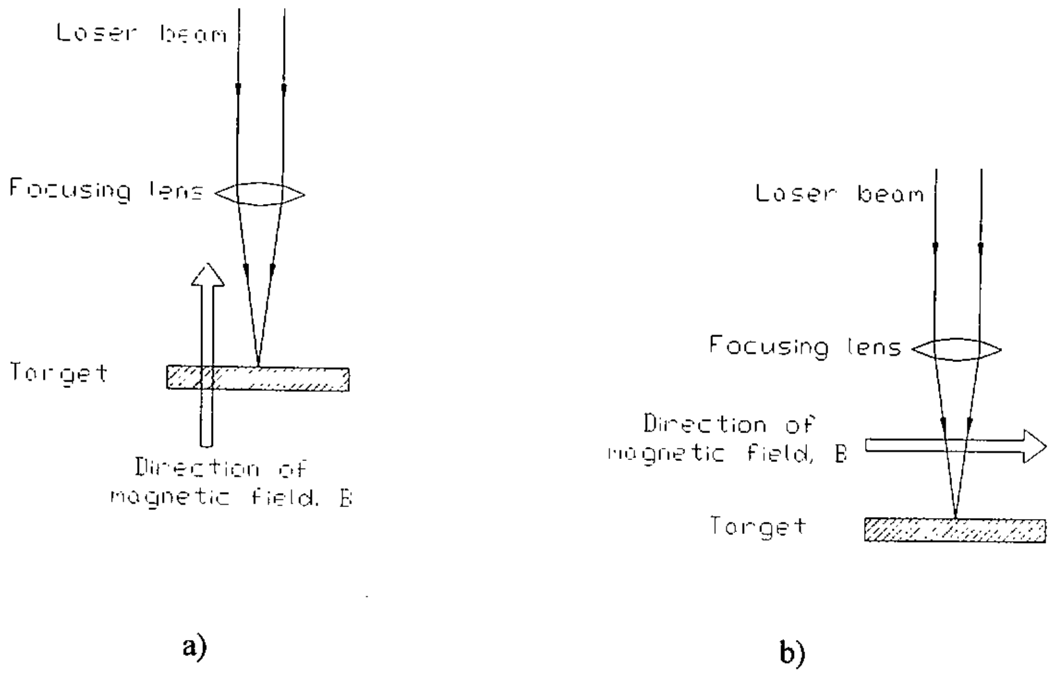
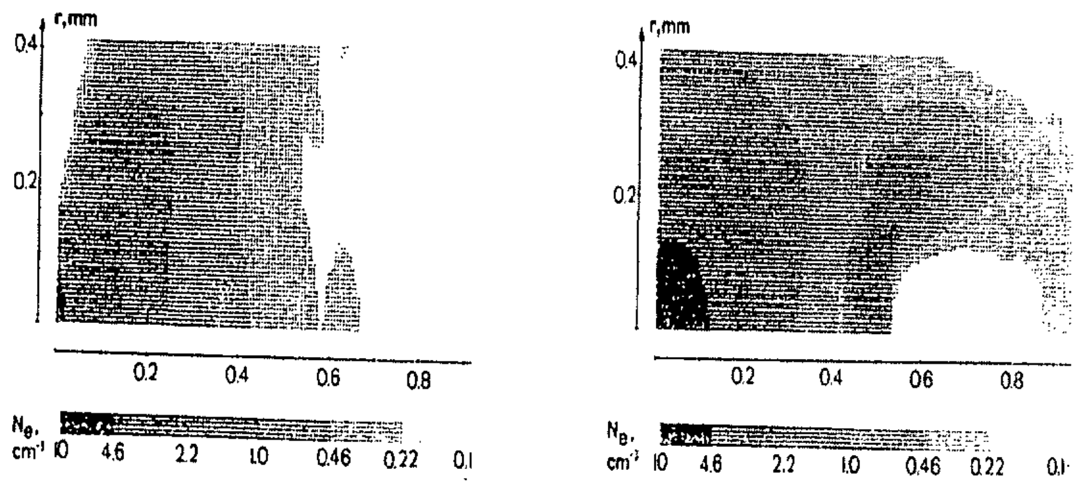


Figure 3. 1: Direction of magnetic field lines a) A target surface is oriented perpendicular to the magnetic filed lines b) A target surface is orientated parallel to the magnetic field lines

3.2.1 A target surface is oriented perpendicular to the magnetic field lines

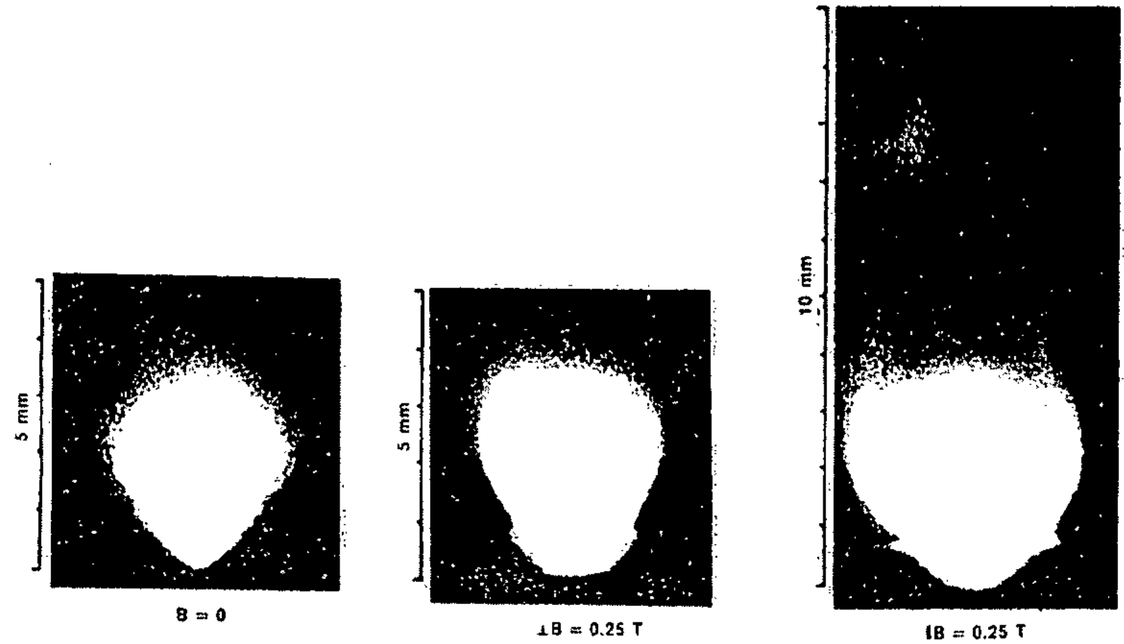
Pisarczyk et. al. showed that a magnetic field can force a plasma generated by means of a laser pulse to expand along to the magnetic lines and form an elongated and uniform plasma column. It was found that the electron density of the plasma with the applied magnetic field is higher than that without the applied magnetic field in the same place and for the same time moment (Figure 3.2). It was because that the radially expanding laser plasma is confined by the external magnetic field. In fact, Liu [20] found that the absorption ratio of the workpiece to the laser energy increases by 1.75 times based on similar theory. However, the application of this plasma control method is constrained by the size of the workpiece and the mechanical design of the machine table because the magnetic field has to be applied perpendicular to the workpiece.



a) b)

Figure 3. 2: Electron density level of the plasma expanding a) without magnetic field (B=0) b) with magnteic filed (B=18T) [80]

3.2.2 A target surface is orientated parallel to the magnetic field lines



a) b) c)

Figure 3. 3: Photographs of the laser-produced plasma evolution a) without magnetic field b) with magnetic field B=0.25T (Direction of observation perpendicular to the magnetic field) c) with magnetic field B=0.25T (Direction of observation parallel to the magnetic field) [18]

The behavior of laser-produced plasma in the magnetic field orientated parallel to the target surface at different filed strength was studied by U.S. Begimkulov et al [18]. It was shown that a plasma generated by means of a laser pulse (8J, 10ns) expands into a cone with an opening angle of about 90° without the applied magnetic field (Figure 3.3a). While in the presence of magnetic field, the dimension of the radial plasma increases and the plasma evolves to ball-like shape (Figure 3.3b). Moreover, a weakly luminescent "tail" extending perpendicular to the magnetic field was also observed in the plane parallel to the field (Figure 3.3c). In other words, the electron density in the plasma cloud decreases with increasing the dimension of the plasma. Theoretically, it is possible to control the plasma for laser welding by using this method. However, above findings were obtained under the pulse mode and no continuous wave laser welding data associated with this plasma control technique was reported.

3.3 EFFECT OF THE ELECTRIC FIELD ON PLASMA

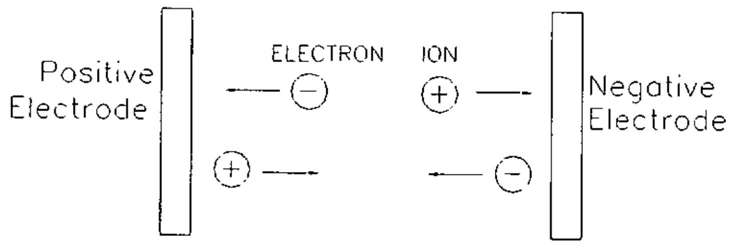


Figure 3. 4: Charged particle motions in an electric field.

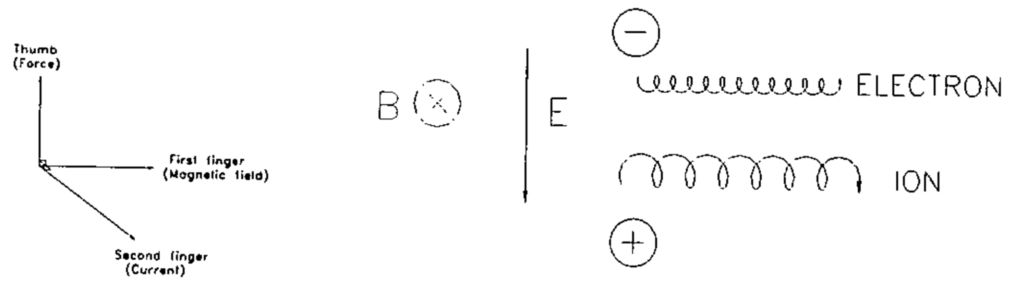
It has been known that laser-produced plasma is a partially ionized plasma containing charged particles. Moreover, based on the basic principle "Like charges repel; unlike charges attract", by adding the electric field can affect the plasma behaviors. In fact, the application of using the effect of electric field is currently used for diagnosing plasma. Langmuir electrostatic probe [74] is one of the earliest and useful tools to make measurement of emission current for determining plasma density and temperature of plasma [82, 83]. In 1989, Rosso et al [84] has tried to use this probe to diagnose the plasma during laser materials processing. In 1996, based on the similar theory, Li [85] developed a more reliable non-contact method (or Plasma Charge Sensor) for on-line monitoring laser welding process and detecting the weld quality. In the past decade, the application of electric probe is mainly for monitoring the laser welding process. In fact, some research studies [77, 85] have revealed that large electric probe can disturb the plasma condition. Therefore, the diameter of the commonly used electric probe is smaller than 0.25mm. In other words, using large electrode may affect the laser-produced plasma as well as its electron density. Furthermore, it has been known that the shielding effect of the plasma is decreased with the decrease in electron density. In conclusion, by adding the electric field may alter the ions and electrons distribution as well as the density of the laser-produced plasma. In fact, based on similar theory, Hamoudi et al. [21] showed that the depth of a hole can be increased by 36% when performing drilling under an electric field (Table 3.1).

Laser energy (J)	Depth increase (%)	
	Ordinary drilling	Drilling under electric field
0.25	0	11
0.60	0	36
0.80	0	13
1.20	0	27
1.70	0	35
1.80	0	27
2.30	0	24

Table 3. 1: Laser energy versus depth increase (%) in laser drilling of low carbon steel under electric field [21]

3.4 EFFECT OF THE MAGNETIC AND ELECTRIC FIELDS ON PLASMA

3.4.1 Particle motions in the uniform electric and magnetic fields



a) Left hand rule

b) Particles drifts in crossed electric and magnetic fields (the magnetic field points into the plane of the paper).

Figure 3. 5: Particle motions in the uniform electric and magnetic fields

The orbits for ion and electron are shown in Figure 3.5. Positive ion gyrates in the uniform electric and magnetic fields according to the left-hand rule and electron gyrates according to the right-hand rule. They end up drifting in the same direction. In fact, it has been known that laser produced plasma is an ionized vapor containing high density of ions and electrons. Based on this theory, under the effect of both electric and magnetic fields, the plasma can be moved forward and the shielding effect can be suppressed. Moreover, the front fresh metal can be pre-heated by the plasma.

3.4.2 Electrical conductivity of plasma plume

The electrical conductivity may be calculated from standard plasma physics equation, e.g. [86]

$$\sigma = \frac{n_e e^2 \tau}{m_e} \qquad \text{......(3.6)}$$

where σ is the electrical conductivity, n_e is the density of electrons, e is the charge of electron, τ is the mean time between successful collision of an electron, m_e is the mass of electron (or 9.1095×10^{-31}kg). Equation 3.6 shows that the conductivity increases with increasing electron density and indicates that plasma is a good conductor. It has been known that in a simple dc motor the conductivity of a coil is an important parameter affecting the turning effect of the coil. If a plasma is moved like the coil is rotated under the effect of the electric and magnetic fields, the plasma at the high density level can be moved quickly from the laser-material interaction zone. In other words, the shielding effect can be prevented.

3.5 EFFECT OF SHIELDING GAS ON PLASMA CONTROL

During high power laser welding, the main functions of using shielding gas are to: remove any metal vapor, cover the weld area and eliminate oxidation. In fact, the shielding effect of the plasma can be reduced for those gases having a high ionization potential. For example, using helium as a coaxial shielding, the size of plasma can be decreased 80% compared with argon [5]. In other words, deeper penetration depth can be made. Therefore, in order to control the plasma, the gas used for shielding is another important parameter. In addition, air, argon and helium were used for coaxial shielding to verify the results obtained by the new technique.

4.0 EXPERIMENTAL DETAILS

4.1 MATERIALS

AISI 304 stainless steel was used as the welding material due to its high weldability. The steel was cut into bars of dimensions of 100mm × 20mm × 10mm. The composition and the physical properties of the stainless steel 304 are shown in Table 4.1 and Table 4.2.

Composition (weight %)						
C	Cr	Ni	Si	P	S	N
0.08	18.00-20.00	8.00-10.00	2.0	1.0	0.030	0.10

Table 4. 1: Nominal composition of AISI 304 [87]

Material	**Density** ρ **kg/m³**	**Latent heat of fusion** L_f **KJ/kg**	**Latent heat of vaporiza-tion** L_v **KJ/kg**	**Heat capacity of solid** C_p **J/kg**	**Melting tempe-rature** T_m **C**	**Vaporiza-tion tempe-rature** T_v **C**	**Thermal conduc-tivity** K **W/mK**
Stainless Steel (AISI 304)	8030	~300	6500	500	1450	3000	20

Table 4. 2: Physical properties of stainless steel 304 [4]

4.2 EQUIPMENT

4.2.1 Carbon dioxide laser

A CO_2 laser (PRC) with XYZ table was used to carry out the experiments. It is a gas laser with output wavelength of 10.6um and the maximum power output is 3.5kW. In fact, the type of the laser is an axial discharge with fast axial flow laser. In this experiment, only continuous-wave mode was used and the beam mode is a TEM01 type, which is shown in Figure 4.1.

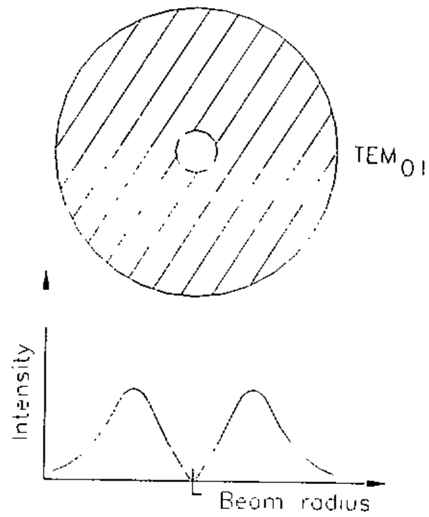


Figure 4. 1:Power distribution in TEM_{01}

4.2.2 Gauss meter

Gauss meter "Sanwa Denshi DC10-19990" was used to measure the magnetic field. The measuring range of this DC meter is from 10G to 19.99kG.

4.2.3 Magnet

In this investigation, ten permanent magnets (iron oxide) were used. The dimension of the magnets is about 40mm × 25mm × 10mm and the field strength is about 50G (if the probe of gauss meter is positioned 10mm above the magnet).

4.3 EXPERIMENTAL PROCEDURES

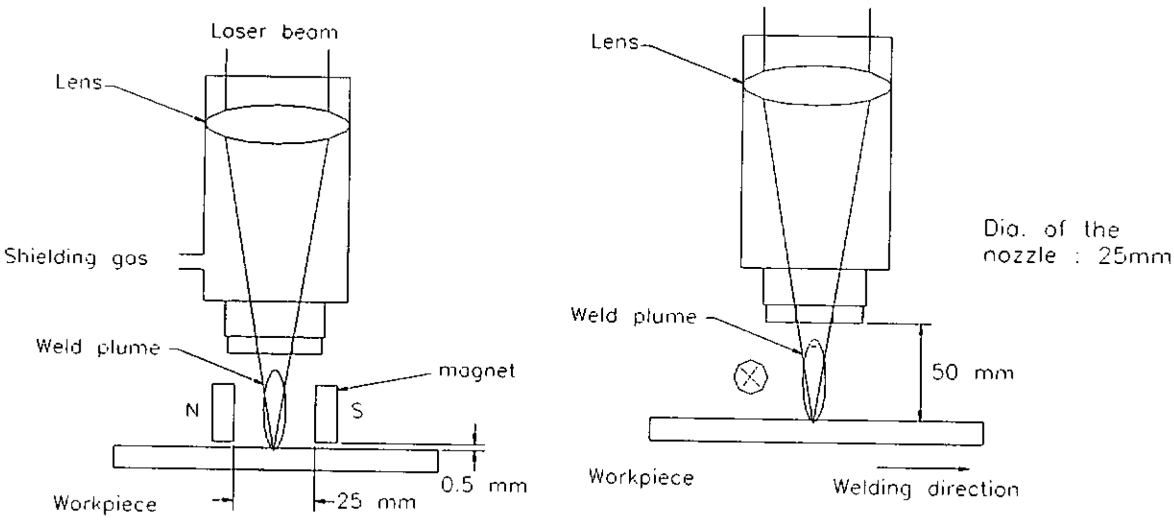
4.3.1 Experimental procedures for study the effect of magnetic field on plasma control

A continuous wave CO_2 laser with a TEM_{01} mode and a plano-convex ZnSe lens of focal length of 190mm were used in this investigation. The experimental setup is shown in Figure 4.2. Shielding gas used for protecting the lens from weld spatter and [88, 89] the weld track from oxidation was delivered to the workpiece coaxially with a flow rate 30 l/min using a nozzle of 25mm diameter. Moreover, in order to reduce the blowing effect of shielding gas, the welding nozzle was located 50mm above the workpiece. Two groups of permanent magnets were positioned 0.5mm above the workpiece as shown in Figure 4.2a. The field strength was determined by adjusting the number of magnets in each group and measured by a Sanwa digital gauss meter (SG-100). AISI 304 stainless steel was used to make the bead-on-plate welds. In the presence of the magnetic field, the laser beam was focused on the surface of the workpiece. The weld depth and width were measured by metallographic examination of the cross-section of each weld. Penetration depth and width were determined by taking the average of data of three separate weld cross-sections of the same weld bead.

In this investigation, the following relations were studied.

- Effect of the magnetic field (0-1000G) on weld beam profile at 750mm/min and 1500W
- The influence of laser power (1000-2200W) on the effectiveness of using magnetic field for plasma control at 750mm/min

- The influence of welding speed (500 -1500mm/min) on the effectiveness of using magnetic field for plasma control at 1500W
- The influence of magnetic field direction (front, back, left, right) on the effectiveness of using magnetic field for plasma control at 1500W and 750mm/min
- The influence of shielding gas (helium, argon) on the effectiveness of using magnetic field for plasma control at 1500W and 750mm/min

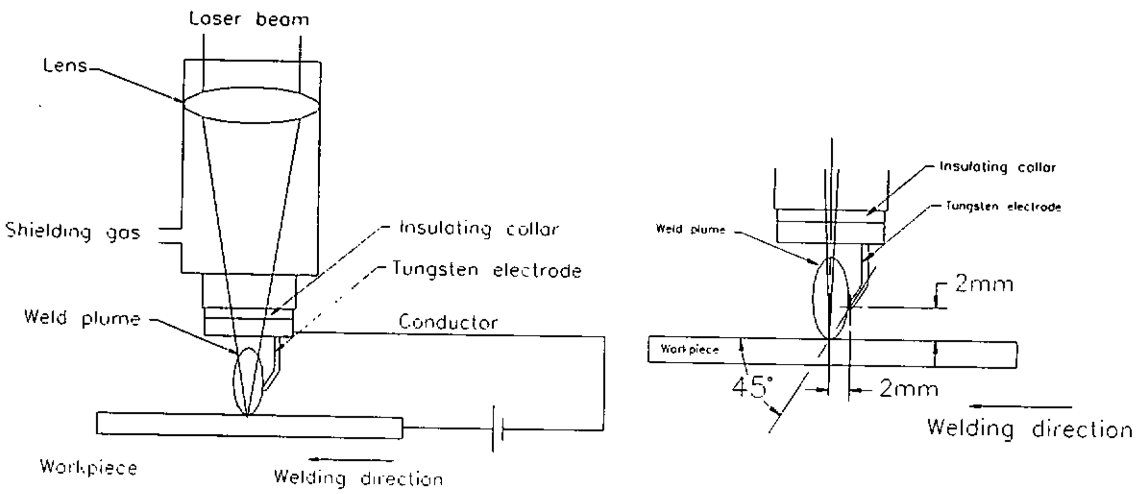


a) front view

b) side view
(the magnetic field points into the plane of the paper)

Figure 4. 2: Setup for studying the effect of magnetic field

4.3.2 Experimental procedures for study the effect of electric field on plasma control



a) side view

b) Electrode arrangement

Figure 4. 3: Setup for studying the effect of electric field.

The experimental setup is as shown in figure 4.3. In fact, the setup is similar to our previous setup except without adding magnetic field. Moreover, a DC power supply was connected to the nozzle & workpiece and a tungsten electrode of 1mm diameter was fixed to the welding nozzle, as shown in Figures 4.3a & 4.3b respectively. In the presence of the electric field, the laser beam was focused on the surface of the workpiece. The penetration depth and width were measured by metallographic examination of the cross-section of each weld and determined by taking the average of data from four separate weld cross-sections of the same weld track. The following relations were found.

- Effect of electric field (0-50V) on weld bead profile at 750mm/min and 2000W

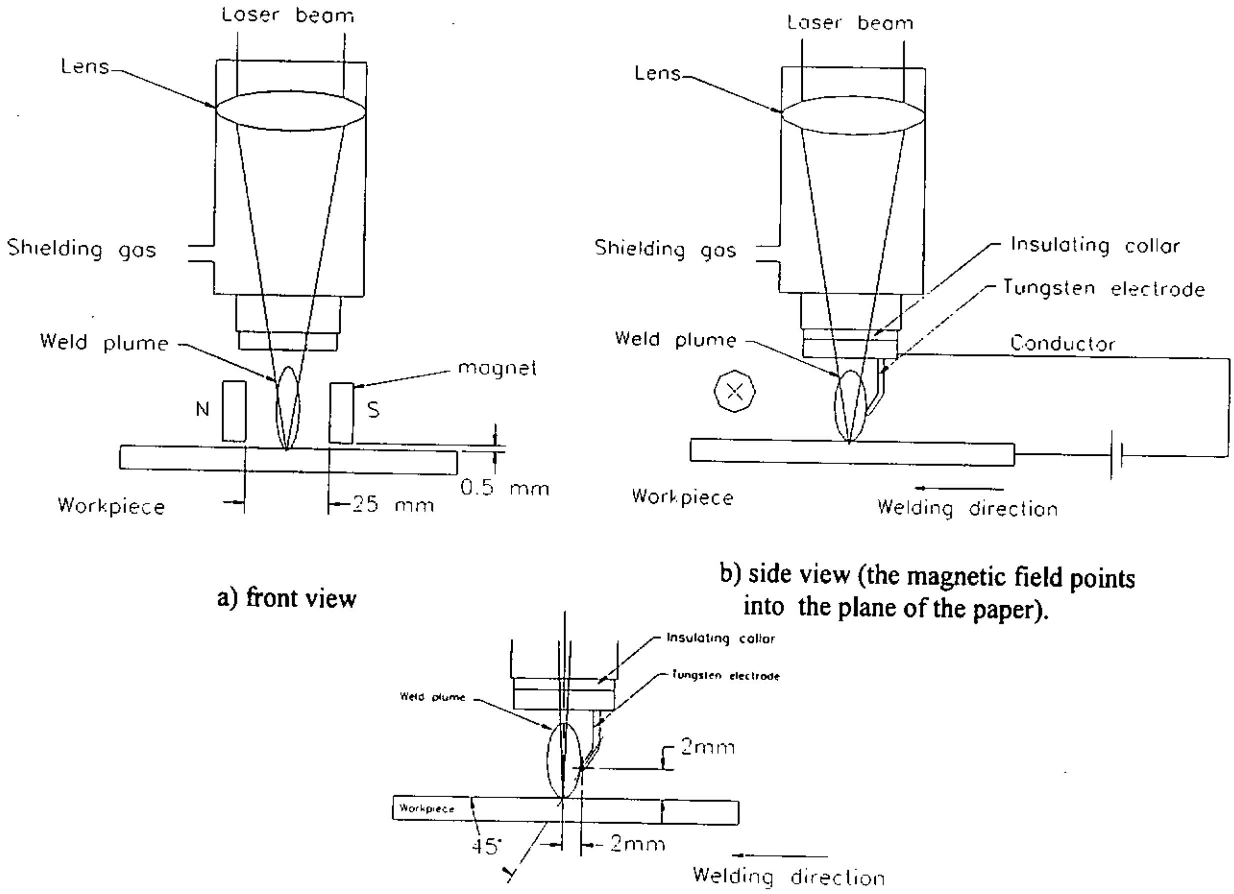
- The influence of laser power (1500-2000W) on the effectiveness of using magnetic field for plasma control at 750mm/min
- The influence of field direction (positive and negative) on the effectiveness of using magnetic field for plasma control at 750mm/min

4.3.3 Experimental procedures for study the effect of both magnetic and electric fields on plasma control

The bead on plate welding process was also carried out using a continuous wave CO_2 laser beam with TEM_{01} mode. In order to minimize the plasma control effect from the shielding gas, a big nozzle with 25mm diameter was used. A gas flow rate at 30 l/min was applied. To reduce the blowing effect of the gas stream, the nozzle was located at 50mm above the workpiece. In other words, the shielding gas applied was used to protect the lens from weld spatter and protect the melt pool from oxidation only. It did not contribute to the plasma control at all as in some plasma control technique that uses a relatively high pressure and velocity inert gas jet for plasma disruption. A 190mm focal length plano-convex ZnSe lens was used for focussing. Two groups of permanent magnets were placed at 0.5mm above the workpiece, as shown in figure 4.4a. The gap width between the magnets was 25mm. The field strength was determined by adjusting the number of magnets in each group and measured by a Sanwa digital gauss meter (SG-100). A tungsten electrode of 1mm diameter was fixed to the welding nozzle. An electric circuit was connected, as shown in Figure 4.4b, and a DC power supply was used. AISI 304 stainless steel in the form of 8-mm thick plates was used to make the welds. The laser beam was focused on the surface of the workpiece. The weld depth and width were measured by metallographic examination of the cross-section of each weld. The penetration depth and width were determined by taking the average of data from four separate weld cross-sections of the same weld track.

In this experiment, the following relations were showed.

- Effect of both electric field (10V) and magnetic field (100-800G) on weld bead profile at 750mm/min and 1500W
- The influence of potential difference (10-30V) on the effectiveness of using both fields for plasma control at 750mm/min and 1500W
- The influence of magnetic field direction (positive and negative) on the effectiveness of using both fields for plasma control at 750mm/min and 1500W



a) front view

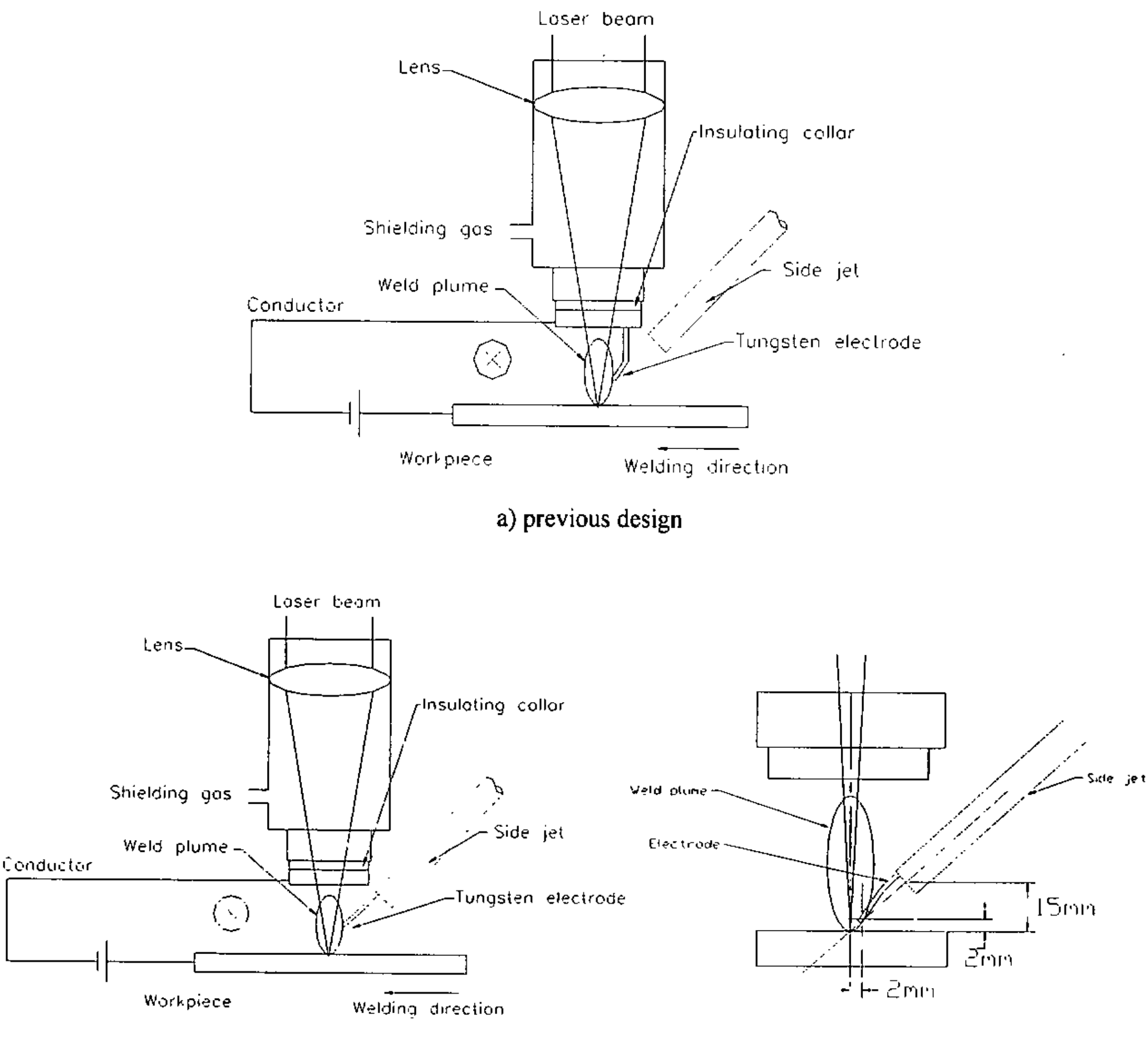
b) side view (the magnetic field points into the plane of the paper).

c) electrode arrangement

Figure 4. 4: Setup for studying the effect of electric and magnetic fields

4.3.4 Experimental procedures for study the effect of both fields and side jet on plasma control

The experimental procedures are similar to the previous setup except with adding a side-jet gas. By varying the gas flow rate of the side jet (0-60l/min). The effects of magnetic field only, electric field only and both electric and magnetic fields on the penetration depth and bead width were studied. The experimental setup is as shown in figure 4.5. The location of the tungsten electrode was re-designed in order to prevent the side-jet gas disturbed by the electrode. The weld depth, bead width and cross-sectional area were measured by metallographic examination of the cross-section of each weld. The penetration depth and width were determined by taking the average of data from four separate weld cross-sections of the same weld track. . The influences of fields (B only, E only and both E & B fields), coaxial shielding gas and side jet gas on the weld bead profile were studied



a) previous design

b) new design

c) Electrode arrangement

Figure 4. 5: Setup for studying the effect of electric and magnetic fields

4.4 ANALYSIS TECHNIQUES

In the project, total 600 weld tracks under different conditions were made and the method to measure the depth of penetration and the width of beam was mainly by 4X-magnification microscope. First of all, the welded specimens were cut to about 10mm length. In addition, four cross-section specimens were prepared for each weld. Second, the specimens were mounted in cold setting epoxy. When all these mounted specimens were set, fine grinding and rough polishing were carried out on specimen grinder with silicon carbide paper in steps from coarse to fine and polisher with 6u diamond abrasive. Then, etching was carried out by immersing the specimens in the enchant (15ml HCl, 10ml HNO_3) for 5 seconds. Last, the etched specimens were examined under the magnification microscope and photographed.

5.0 RESULTS AND DISCUSSIONS

5.1 EFFECT OF THE MAGNETIC FIELD ON PLASMA CONTROL DURING CO_2 LASER BEAM WELDING

5.1.1 Effect of the magnetic field on the weld bead profile

Experimental results of the effect of the magnetic field on the weld bead profile are shown in Figures 5.1-5.3. In order to increase the accuracy, penetration depth and width were determined by averaging ten cross section penetration values obtained from the same weld at different locations. It was found that at an optimum magnetic field strength the penetration depth can be increased. It could be because the dimension of the radial plasma is increased in the presence of magnetic field. In other words, the electron density in the plasma cloud decreases and the laser coupling efficiency increases for the keyhole effect. As a result, the penetration depth is increased. However too large magnetic field can distort the laser produced plasma and reduce the energy coupling efficiency by the plasma into the workpiece.

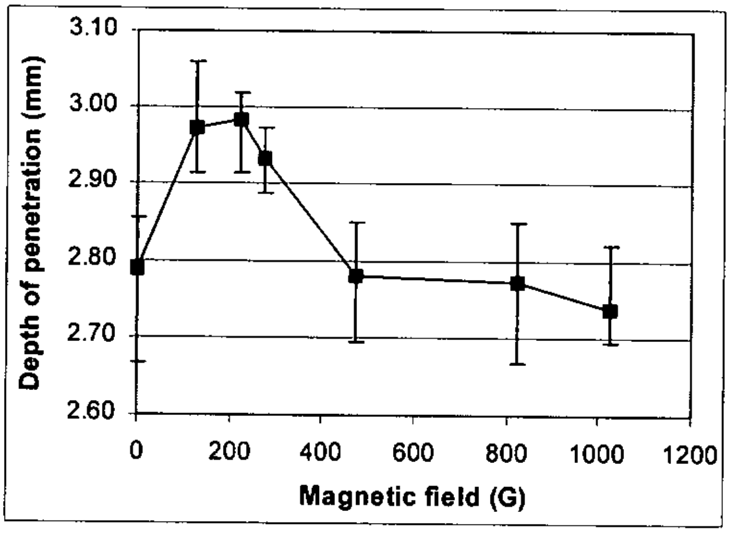


Figure 5. 1: The effect of magnetic field on the penetration depth at 750 mm/min and 1500W.

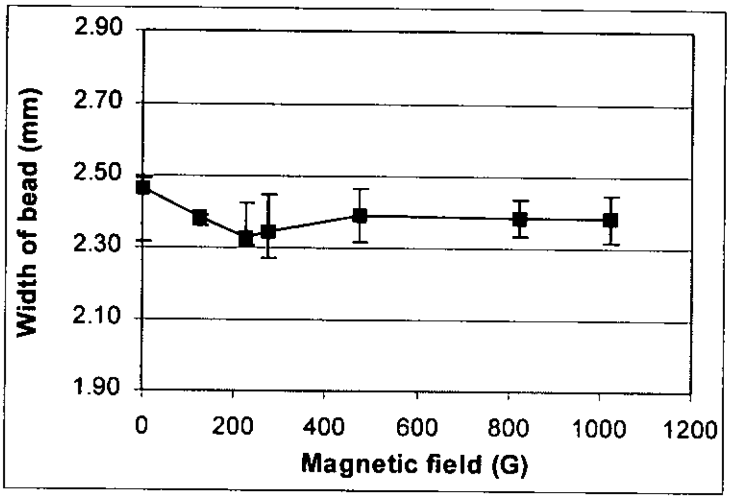


Figure 5. 2: The effect of magnetic field on the bead width at 750 mm/min and 1500W.

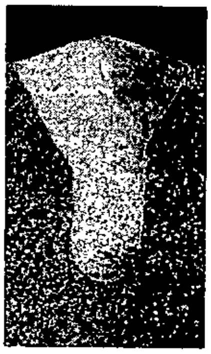
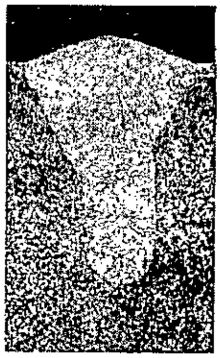
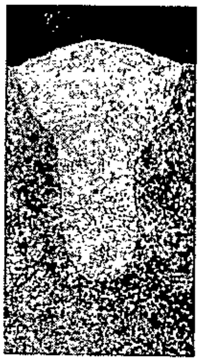
Applied magnetic field strength	**a.** 0B	**b.** 100B	**c.** 200B
Cross-section			
Applied magnetic field strength	**d.** 300G	**e.** 500G	**f.** 700G
Cross-section 1mm			

Figure 5. 3: The effect of magnetic field on the weld bead profile at 750 mm/min and 1500W.

It has been shown by many researchers that the width of the weld bead is directly proportional to the size of the plasma. However, our experimental results showed that the effect of magnetic field on the width of bead is not significant even when the size of the plasma has been changed. It is because, according to Begimkulov's findings [18], the change in the dimension of the laser-produced plasma at the bottom part is small. In fact, the plasma is elongated from bottom to top in the presence of the magnetic field. Therefore, no significant difference on the bead width was found.

5.1.2 The influence of laser power on the effectiveness of using magnetic field for plasma control

Figure 5.4 shows the influence of the magnetic field at different power levels, at a welding speed of 750 mm/min. The effect of the magnetic field on the penetration depth is not significant at low power level. It is because the plasma formation decreases with the decrease in laser power level. The effectiveness of using a magnetic field for plasma control is directly proportional to the size of the plasma. In addition, experimental results showed that the influence of the magnetic field on the bead width is less (Figure 5.5).

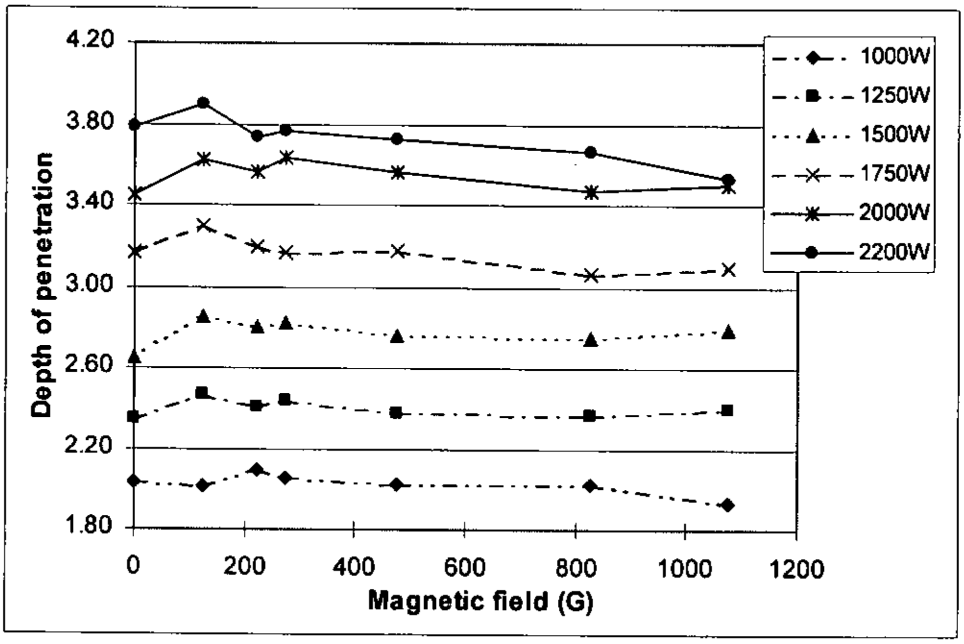


Figure 5. 4: The influence of magnetic field on the penetration depth, welding speed of 750mm/min and different power levels.

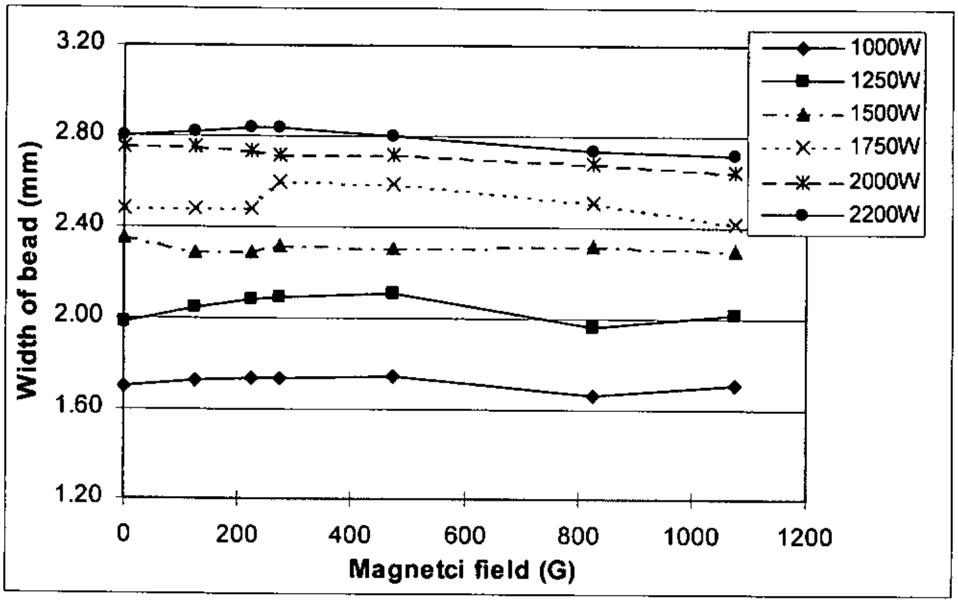


Figure 5. 5: The influence of magnetic field on the bead width, welding speed of 750mm/min and different power levels.

5.1.3 The influence of welding speed on the effectiveness of using magnetic field for plasma control

Figures 5.6 & 5.7 show the influence of the magnetic field on the weld profile, at different welding speeds at a laser power level of 1.5kW. Under the processing parameters considered, the maximum increase in penetration depth obtained was about 7% (at a welding speed of 750 mm/min and a magnetic field between 175G and 225G). Moreover, it was found that the improvement in the penetration depth of the weld produced at a low welding speed can be achieved at low magnetic field strength. Conversely, if the weld is produced at a high welding speed, a stronger magnetic field is required to obtain the optimum penetration depth. In fact, Figure 7 shows that the optimum magnetic field producing the deepest penetration depth is shifting from left to right with the increase in welding speed. In addition, it was also shown that the influence of the magnetic field on the bead width is small.

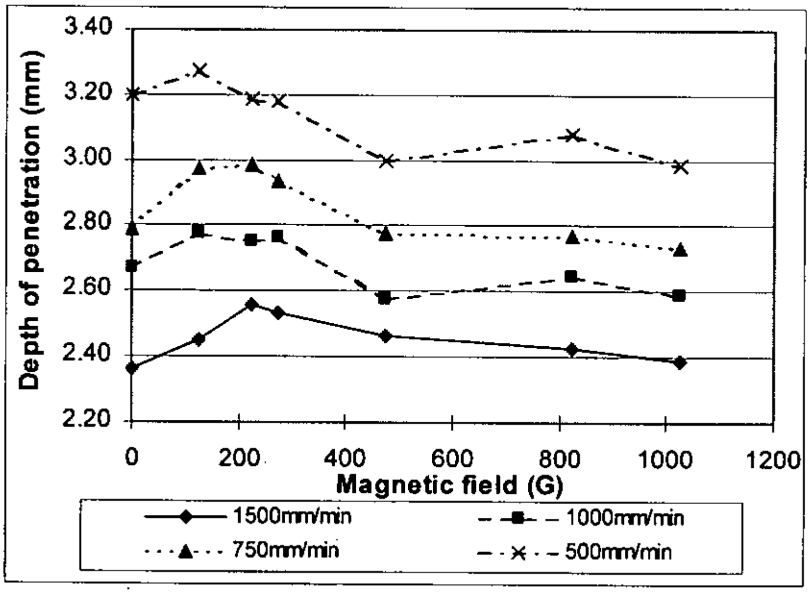


Figure 5. 6: The influence of magnetic field on the penetration depth at 1500W and different welding speeds.

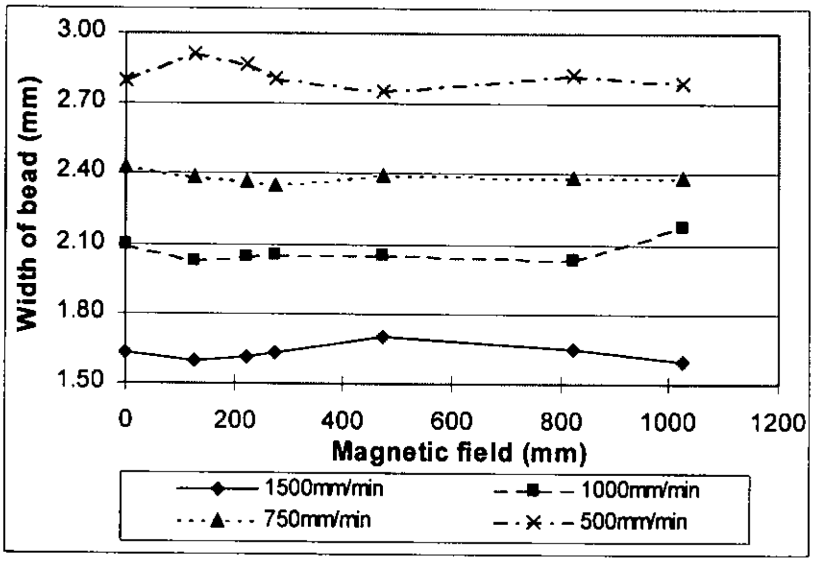


Figure 5. 7: The influence of magnetic field on the bead width at 1500W and different welding speeds.

5.1.4 The influence of the field position on the effectiveness of using magnetic field for plasma control

Two magnets were positioned in four different arrangements as shown in Figure 5.8. Experimental results showed that the difference of bead profile of welds produced under different field directions is small (Figures 5.9 & 5.10). In addition, the results also proved that the effectiveness of using magnetic field for plasma control is significant at low magnetic field strength.

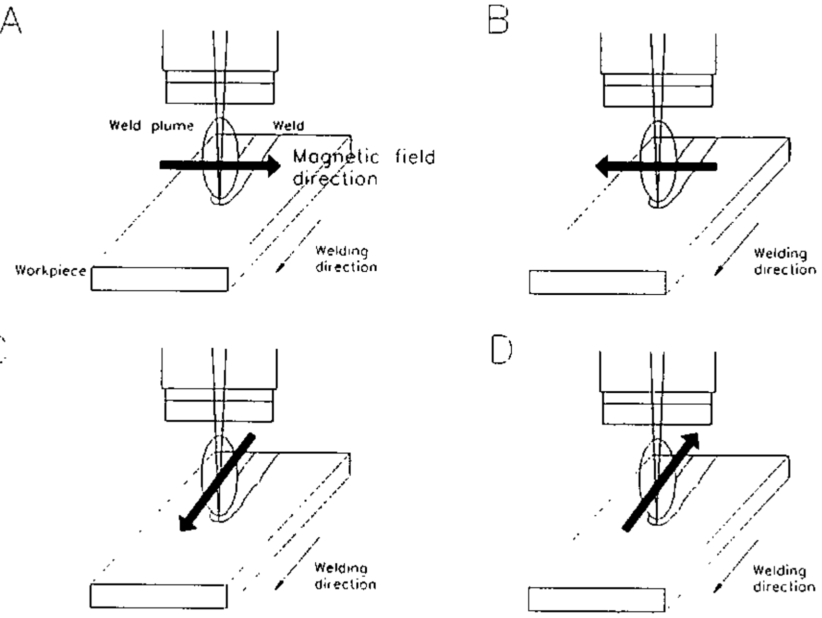


Figure 5. 8: Four different magnetic field directions

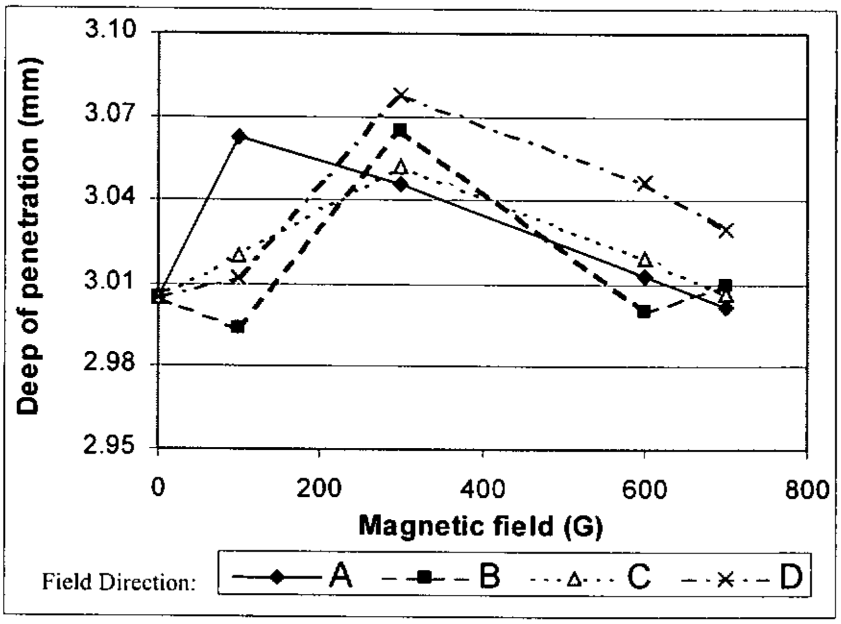


Figure 5. 9: The influence of field direction on the penetration depth at 1500W and 750mm/min.

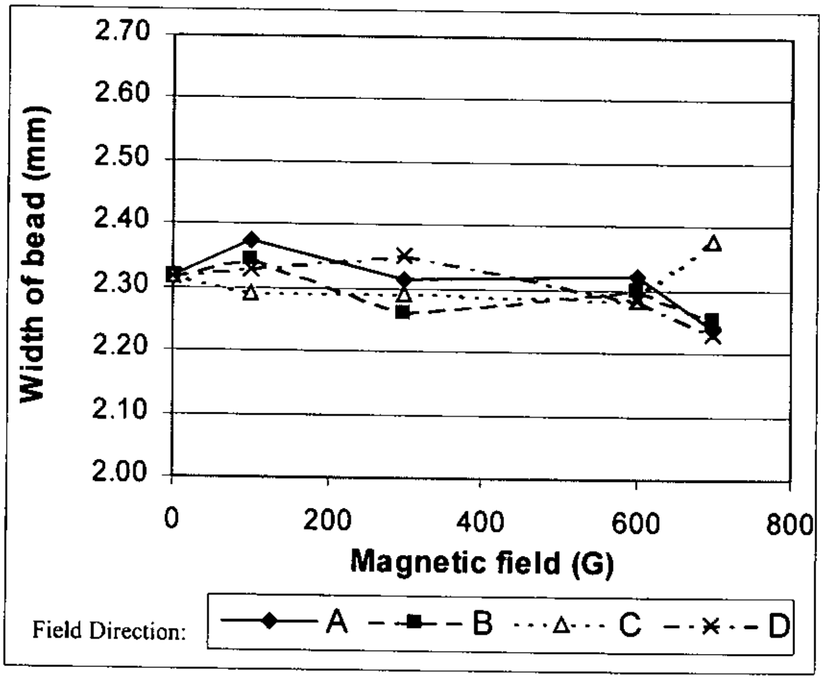


Figure 5. 10: The influence of field direction on the bead width at 1500W and 750mm/min.

5.1.5 The influence of shielding gas on the effectiveness of using magnetic field for plasma control

The findings mentioned in Section 5.1.1 were obtained under compressed air shielding. In real industrial application, compressed air is not suitable as a shielding gas. Therefore, another experiment was carried out to study the effectiveness of using magnetic field for plasma control under different shielding conditions. Experimental results showed that in the presence of a magnetic field the penetration depth can be increased by about 3% if argon gas is used for coaxial shielding (Figures 5.11-5.14). However, if helium gas is used for shielding, the magnetic field has a negative effect to the penetration depth. It is because the size of plasma plume is affected by the shielding condition [5]. In the ascending order of helium and argon, the plasma becomes bigger and the electron density level becomes higher. Furthermore, it has been known that if helium gas is used for shielding, the plasma formation is suppressed due to the high ionization potential of the helium gas. On the other hand, as mentioned before, the effectiveness of using magnetic field for plasma control is directly proportional to the size or the electron density level of the plasma. Therefore, in the presence of magnetic field, the penetration depth can be increased significantly under argon atmosphere.

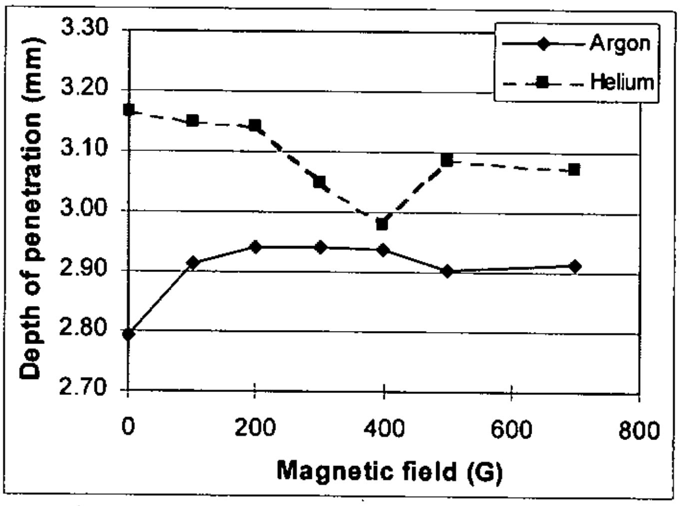


Figure 5. 11: The effect of magnetic field on the penetration depth under different shielding conditions at 750 mm/min & 1.5kW.

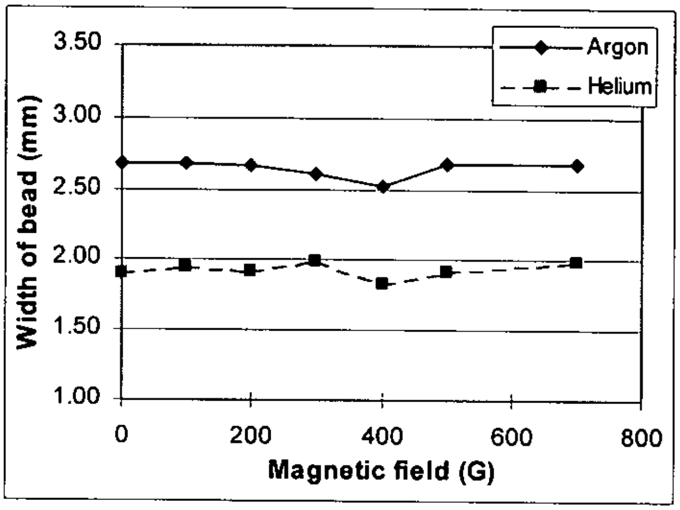


Figure 5. 12: The effect of magnetic field on the bead width under different shielding conditions at 750 mm/min & 1.5kW.

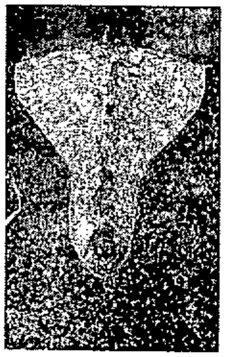
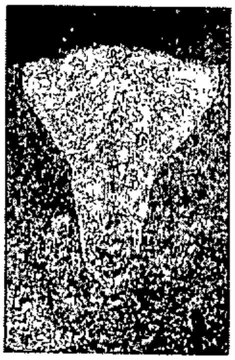
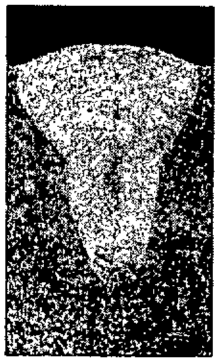
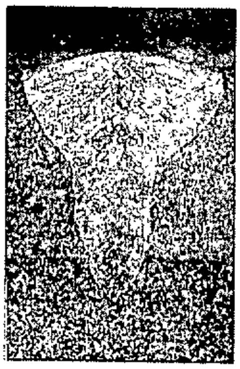
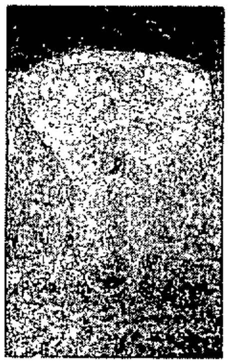
Applied magnetic field strength	a. 0B	b. 100B	c. 300B
Cross-section			
Applied magnetic field strength	**d.** 400G	**e.** 500G	**f.** 700G
Cross-section 1mm			

Figure 5. 13: The effect of magnetic field on the weld bead profile at 750mm/min and 1500W under argon coaxial shielding.

Applied magnetic field strength	**a.** 0B	**b.** 100B	**c.** 300B
Cross-section			
Applied magnetic field strength	**d.** 400G	**e.** 500G	**f.** 700G
Cross-section 1mm			

Figure 5. 14: The effect of magnetic field on the weld bead profile at 750mm/min and 1500W under helium coaxial shielding.

5.2 EFFECT OF THE ELECTRIC FIELD ON PLASMA CONTROL DURING CO_2 LASER WELDING

5.2.1 Effect of the electric field on width bead profile

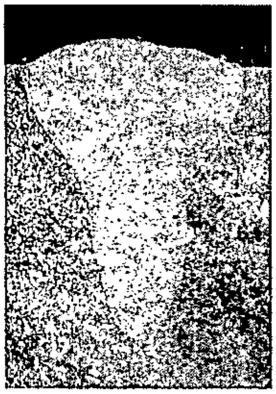
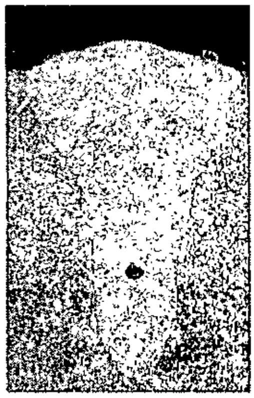
Applied electric field (Potential difference between electrode & workpiece)	**a.** 0V	**b.** 10V	**c.** 20V
Cross-section			
Applied electric field (Potential difference between electrode & workpiece)	**d.** 30V	**e.** 40V	**f.** 50V
Cross-section 1mm			

Figure 5. 15: The effect of electric field on the weld bead profile (750mm/min; 2kW)

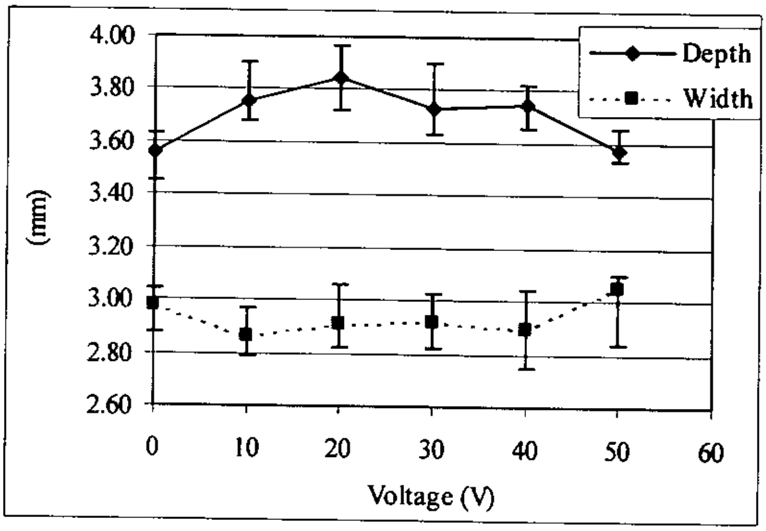


Figure 5. 16: The effect of electric field on the penetration depth and the bead width (750mm/min; 2kW)

Figures 5.15 & 5.16 shows that the effect of applying electric field on the weld bead profile. It was found that at an optimum field parameter the penetration depth can be increased by 8%. It is probably because, on the one hand, some electrons in the plasma are repelled forward due to the presence of the negative electrode. On the other hand, some electrons are collected by the positive electrode (or workpiece). In fact, it has been known that electrode may perturb its local surroundings. Noah [90] showed that one of the parameters determining the extent of the perturbation is the probe geometry, especially the probe size. According to his rough estimation of such perturbation, the charged particle loss to the probe is directly proportional to the effective collection surface area of the probe (Equation 5.1). In other words, the local plasma density will be reduced greatly when the particles are collected by a large probe.

$$\frac{nV}{\tau} = n_0 u A \qquad \text{......(5.1)}$$

where n_0 is the plasma density, V is the plasma volume, τ is the particle loss time and u is the particle velocity.

On the other hand, similar correlation was also shown by J.E. Allen [82]. Equation 5.2 shows that the number of electrons removed from the plasma is enhanced with an increase in the probe surface area.

$$\nu = \frac{n_e \bar{c}}{4} = \frac{n_0 \bar{c}}{4} \exp\left(\frac{eV}{kT_e}\right) \qquad \ldots\ldots(5.2)$$

where ν is the number of electrons striking the probe per unit area per second, n_0 is the plasma density, n_e is the electron density, c is the mean velocity of the electrons, e is the electron charge, V_p is the applied potential, k is the Boltzmann constant & T_e is the electron temperature.

Generally, in order to reduce or minimize such perturbation, the radius of typical Langmuir probe is smaller than Debye length ($a<\lambda_{De}$) [77]. In addition, the Debye length is determined by the vacuum permittivitty ε_0 (or 8.854×10^{-12} F/m), the electron temperature T_e, the electron charge e and the plasma density n_0.

$$\lambda_{De} = \left(\frac{\varepsilon_0 T_e}{e n_0}\right)^{1/2} \qquad \ldots\ldots(5.3)$$

Poueyo et al. [91] determined that the electron temperature and the plasma density at 1 to 2mm above the target surface are about 7000K and 10^{17}cm^{-3}. Substituting these values into Equation 5.3 gives the Debye length is about 2×10^{-5}mm. Compared with the typical Langmuir probe, the radius or size of the used electrode is very large. Therefore, it perturbs or affects the plasma greatly.

According to the above expression and experimental results, the applying electric field can reduce the electron density of the laser-produced plasma. Furthermore, it has been known that the shielding effect of plasma decreases with the decrease in the electron density [79]. Therefore, the penetration depth is increased. However, too strong electric field can reduce the effectiveness for plasma control. According to the standard plasma physics equation (Eq.5.4), the velocity of electrons increases with an increase in electric field strength. The equation shows that particle motion increases with increasing electric field strength. For example: a positive charged particle accelerates in the direction of the electric field, and a negative charged particle or electron accelerates in the opposite direction of the field.

$$m\frac{d\boldsymbol{v}}{dt} = e\boldsymbol{E} \qquad \text{......(5.4)}$$

where m is the mass of an electron, $\boldsymbol{v}$ is the velocity of an electron, e is the electric charge and $\boldsymbol{E}$ is the electric field.

In fact, Russon [84] has shown that the correlation about the enhancement of electron density in the presence of the applied electric field. Therefore, under the influence of the electric field, although the electrodes remove some charged particles, the ionization process produces more electrons at the same time. In other words, when the field strength is above a critical value, the shielding effect is increased. As a result, the penetration depth is decreased.

5.2.2 The influence of laser power on the effectiveness of using electric field for plasma control

The influence of the electric field on bead profile at different laser power levels at a welding speed of 750mm/min are shown in figures 5.16-5.19. It was found that the improvement in the penetration depth of the weld produced at a high power level can be achieved at low electric field. However, too high electric field may reduce the effectiveness of using electric field for plasma control. As mentioned before, it is due to the effect of field induced electron. On the other hand, at a low power level, the improvement in the penetration depth can also be achieved even at high electric field strength (50V). It is because the enhancement of the electron density is still less. In fact, the electron density and the electron temperature decrease with the decrease in the laser power [92]. Also, Russon [84] revealed that the field induced electron density is directly proportional to the plasma density in the presence of applied electric field.

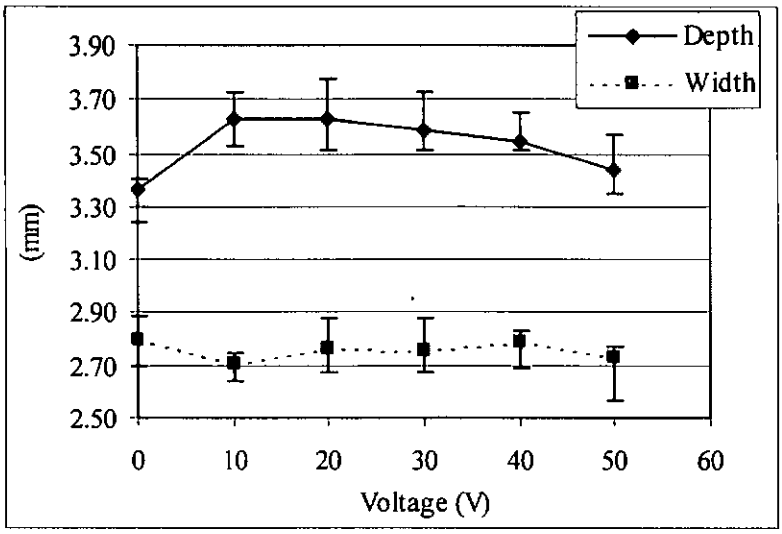


Figure 5. 17: The effect of electric field on the penetration depth and bead width (750mm/min; 1.75kW)

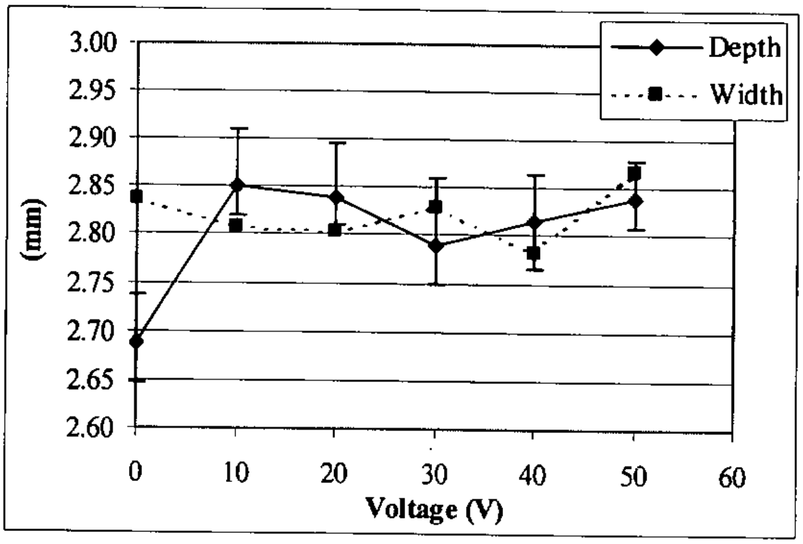


Figure 5. 18: The effect of electric field on the penetration depth and the bead width (750mm/min; 1.5kW)

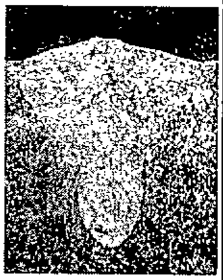
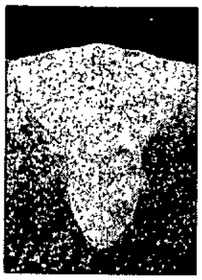
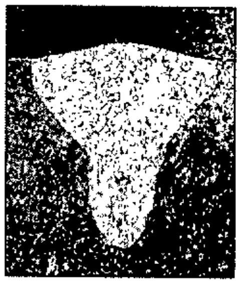
Applied electric field (Potential difference between electrode & workpiece)	a. 0V	b. 10V	c. 30V	d. 50V
Cross-section [1mm]				

Figure 5. 19: The effect of electric field on the weld bead profile (750mm/min; 1.5kW)

5.2.3 Effect of field direction on the effectiveness of using electric field for plasma control

Figures 5.20-5.22 show the effect of field direction on the effectiveness of using electric field for plasma control (at a welding speed of 750mm/min and a power level of 2000W). The negative potential difference represents the reverse direction of the electric field. In this case, the tungsten electron is positive. Experimental results showed that the penetration depth can also be increased as the field direction is reversed. However, the improvement is less. When the potential difference is decreased to –50V, both penetration depth and bead width are decreased. In addition, during making such weld track, the power supply was automatically turned off and the "short circuit" signal appeared. It may be due to the large increase in electron density. Therefore, the conductivity of the laser-produced plasma is increased dramatically. However, no such circumstance was observed as the potential difference was positive (or the electrode was negative). In addition, figures also obviously show the interrelation between the penetration depth and bead width. The penetration depth increases with decreasing bead width.

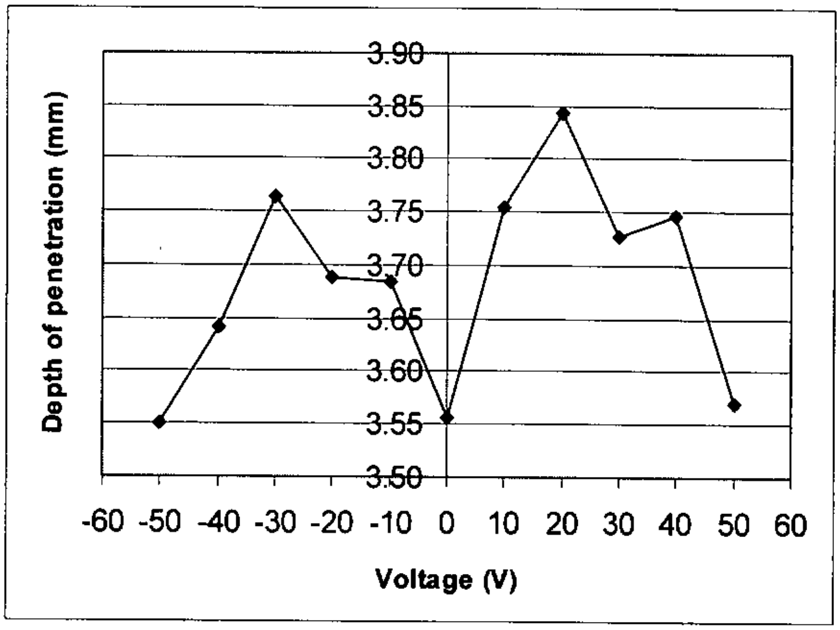


Figure 5. 20: The effect of field direction on the penetration depth (750mm/min; 2kW)

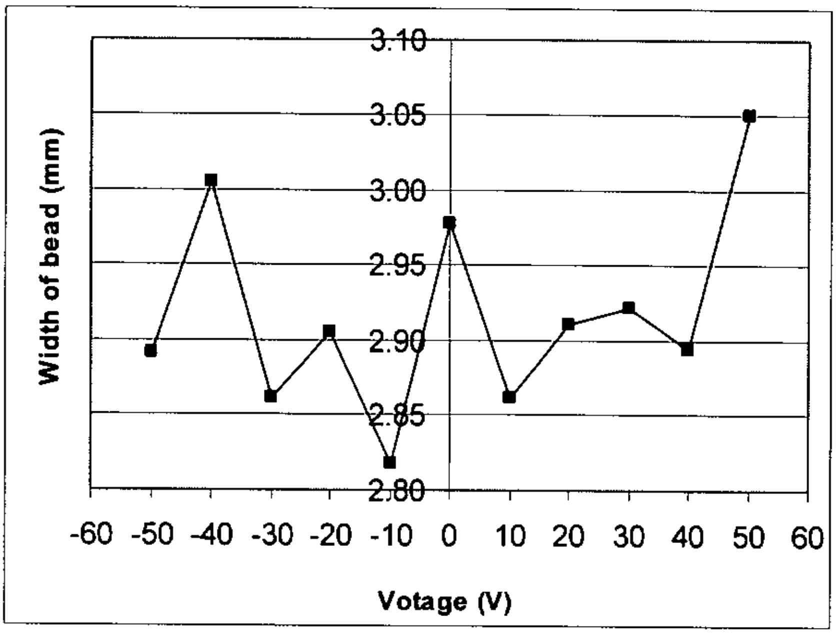


Figure 5. 21: The effect of field direction on the bead width (750mm/min; 2kW)

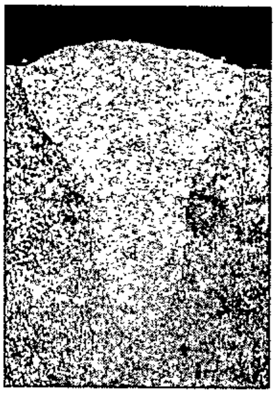
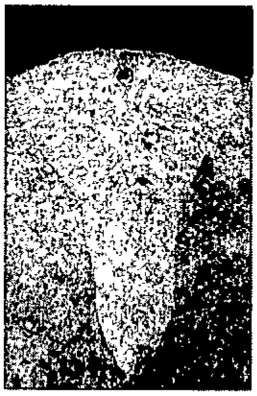
Applied electric field (Potential difference between electrode & workpiece)	a. 0V	b. 30V	c. -30V
Cross-section 1mm			

Figure 5. 22: The effect of electric field direction on the weld bead profile (750mm/min; 2.0kW)

5.3 Effect of Electric and Magnetic Fields on Plasma Control during CO_2 Laser Welding

5.3.1 Effect of the electric and magnetic fields on the weld profile

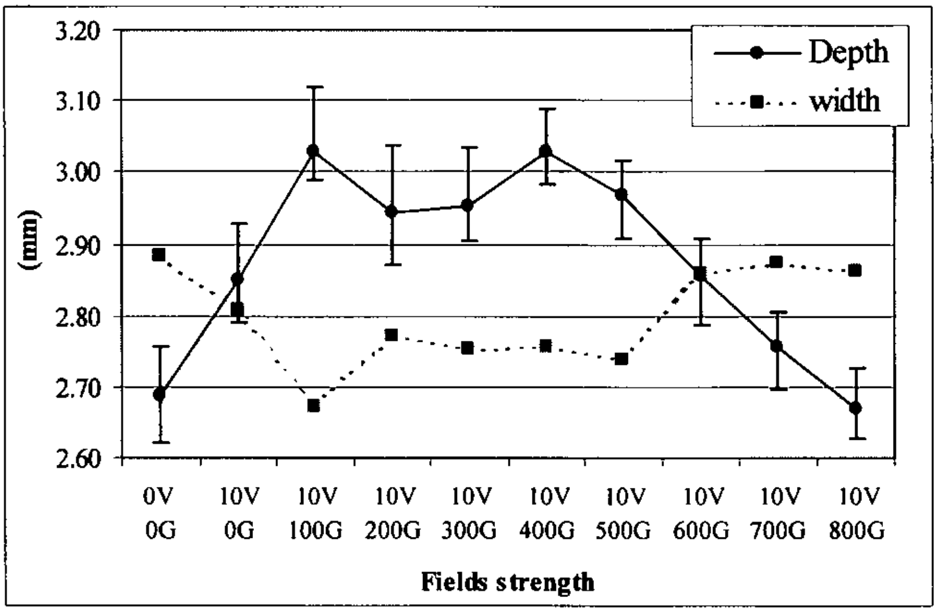


Figure 5. 23: The effect of electric and magnetic fields on the penetration depth and the bead width (P.d. between the electrode and workpiece 10V; 750mm/min; 1.5kW)

Experimental results of the effect of applying both electric and magnetic (E & B) fields on the weld bead profile are shown in Figure 5.23. It was found that at optimum field parameters the penetration depth can be increased by about 13%. It is probably because the positive ions and electrons in the plasma are moved ahead of the interaction point forward in the presence of the electric and magnetic fields (according to Fleming's left hand rule). On one hand, the fresh metal ahead of the interaction cavity is pre-heated by the moved particles, and on the other hand, the electron density in the plasma cloud is reduced. In fact, it has been known that the shielding effect of plasma decreases with the decrease in the electron density level [79]. Hence, the coupling efficiency of the laser beam is increased and the penetration depth is increased. However, too strong magnetic field strength can reduce the effectiveness for plasma control. It has been known that under the effect of high power laser radiation, the lighter electrons are accelerated to the electron thermal velocity [77]

$$u = \sqrt{\left(\frac{eT_e}{m}\right)} \qquad \text{......(5.5)}$$

where u is the electron thermal velocity, e is the electron charge, T_e is the electron temperature & m is the electron mass. Aand they randomly collide with the heavy ions and neutral particles. In the presence of the electric and the magnetic fields, according to standard plasma physics equation [93], the velocity of electrons increases with an increase in field strengths.

$$m\dot{\mathbf{v}} = e[\mathbf{E} + \mathbf{v} \times \mathbf{B}] \qquad \text{......(5.6)}$$

where $\boldsymbol{v}$ is the velocity of an electron, $\boldsymbol{E}$ is the electric field & $\boldsymbol{B}$ is the magnetic field. On the other hand, the collision frequency is given by any standard plasma text [93] as

$$\nu = n_n \sigma u \qquad \text{......(5.7)}$$

where n_n is the density of the target particles, σ is the cross section area for the interaction and u is the relative velocity before collision.

Equation (5.7) shows that the collision frequency increases with the increase in the electron velocity. It has been known that the collision process consists of elastic and inelastic collisions. The inelastic collisions result in excitation and ionization processes [94]. Furthermore, according to A.R.Bell's expression [78], the absorption of laser beam energy by the plasma is calculated by equation (5.8):

$$A_p = \frac{n_e m_e v_{osc}^2}{2\tau_e} \qquad \text{......(5.8)}$$

where A_p is the plasma absorption rate, n_e is the electron density, m_e is the mass of a electron, v is the oscillating velocity of the electron in the electromagnetic fields of the laser beam and τ_e is the electron collision time.

The absorption of laser beam energy by the plasma increases with the increase in collision frequency ($1/\tau_e$). In fact, the absorption of the laser energy increases the ionization of the plasma and thus the electron density. Therefore, under the effect of the electric and the magnetic fields, although some charged particles are moved forward from the interaction point, more electrons are produced in the plasma cloud due to the ionization process at the same time. In other words, when the magnetic field strength is above a critical value, the coupling efficiency of the laser beam is reduced and the penetration depth is decreased.

Figure 5.24 shows the interrelation between the penetration depth and the width bead. Under the effect of electric and magnetic fields, on one hand, at weak magnetic field strength, the penetration depth increases with a decrease in bead width. On the other hand, at strong field strength, the depth decreases with an increase in bead width. In fact, many researchers have proved that the weld bead profile is directly related to the size of plasma or the density of electron. Therefore, this finding is evidence to support the changes in electron density in the plasma under the effect of electric and magnetic fields.

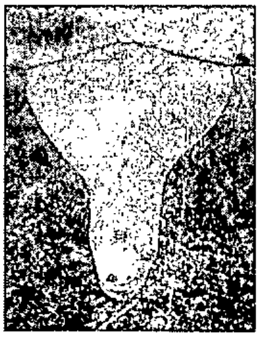
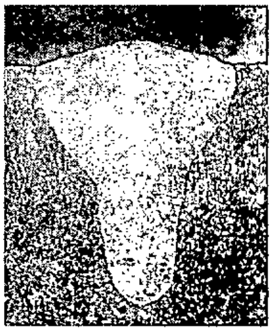
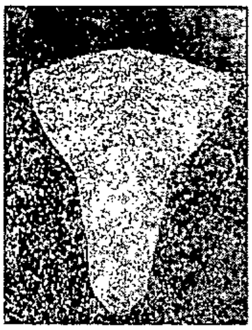
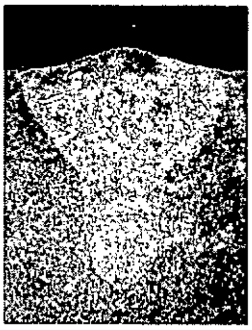
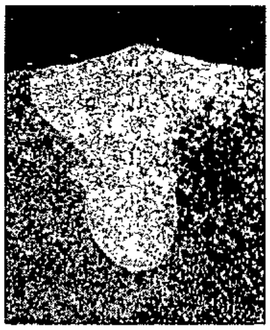
Field condition (i) P.d. between electrode and workpiece (ii) Applied magnetic field strength	**a.** (i) 0V (ii) 0B	**b.** (i) 30V (ii) 100B	**c.** (i) 30V (ii) 200B
Cross-section			
Field condition (i) P.d. between electrode and workpiece (ii) Applied magnetic field strength	**d.** (i) 30V (ii) 400G	**e.** (i) 30V (ii) 600G	**f.** (i) 30V (ii) 700G
Cross-section 1mm			

Figure 5. 24: The effect of electric and magnetic fields on the weld bead profile (P.d. between the electrode and workpiece 30V; 750mm/min; 1.5kW)

5.3.2 The effect of potential difference on the effectiveness of using both fields for plasma control

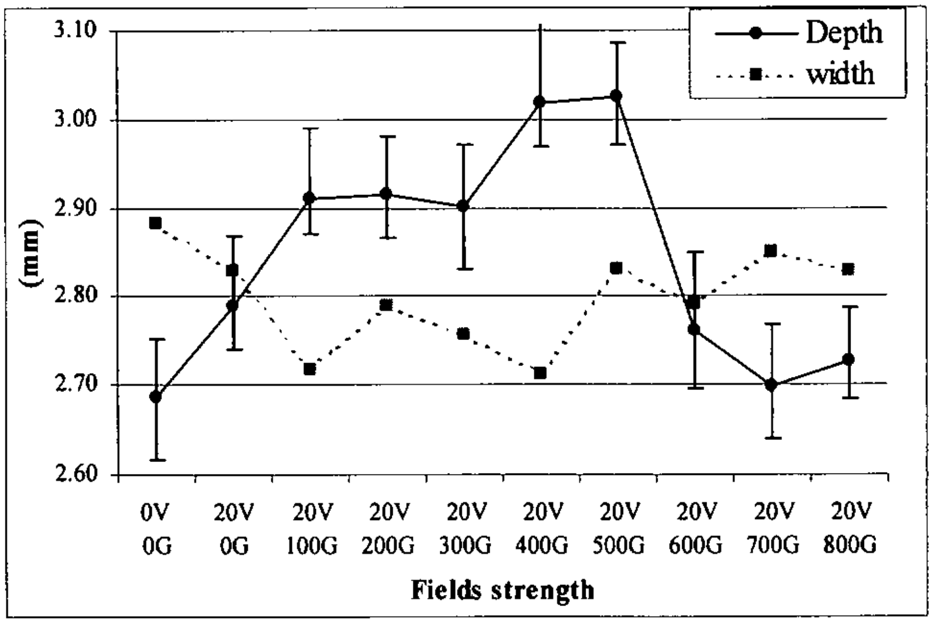


Figure 5. 25: The effect of electric and magnetic fields on the weld bead profile (P.d. between electrode and workpiece 20V; 750mm/min; 1.5kW)

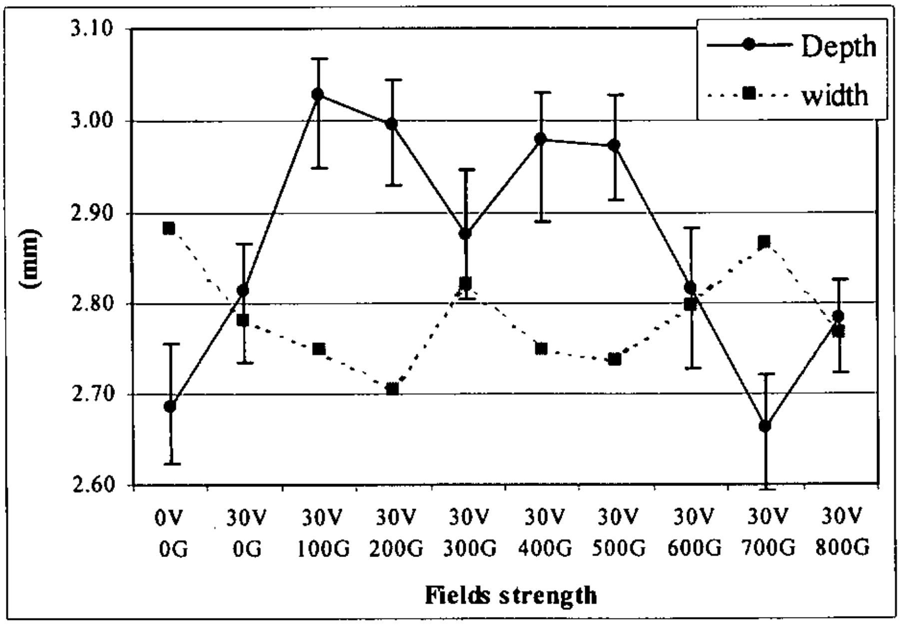


Figure 5. 26: The effect of electric and magnetic fields on the weld bead profile (P.d. between electrode and workpiece 30V; 750mm/min; 1.5kW)

Figures 5.21, 5.23-25 show that the effect of potential differences on the penetration depth is not significant. It is because the potential differences used are in low level range. In addition, experimental results show that the maximum penetration depths at different electric field strengths are close to or about 3 mm.

The effect of both fields at different potential differences on the bead width is also shown in Figures 5.23, 5.25-27. Although the fluctuation of the measured values of bead width is large, a trend is obviously shown. The width of weld bead decreases with the increase in magnetic field strength provided that the field strength is in low level range. Conversely, if the magnetic field is too strong, the weld bead is increased and close to the initial value (obtained without the effect of both fields). As mentioned above, it is due to the effect of the electron density level.

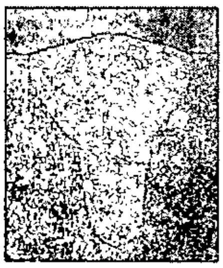
Field condition (i) P.d. between electrode and workpiece (ii) Applied magnetic field strength	**a.** (i) 0V (ii) 0B	**b.** (i) 10V (ii) 400B	**c.** (i) 20V (ii) 400B	**d.** (i) 30V (ii) 400B
Cross-section 1mm				

Figure 5. 27: The effect of both fields at different potential differences on the weld bead profile.

5.3.3 The influence of magnetic field direction on the effectiveness of using both fields for plasma control

In order to find out the effect of magnetic field direction on the effectiveness of using both fields for plasma control, the magnetic field direction was changed from positive to negative. Experimental results showed that the difference of bead profile of welds produced under these two different conditions is small (Figure 5.28-5.30). It is because, in the presence of the electric and the magnetic fields, the ionized species can also be moved from the laser-workpiece interaction point although the direction of the magnetic field is changed. However, the second arrangement is not suitable for plasma control. The hot electrons are moved backward to the electrode and easily damage the electrode.

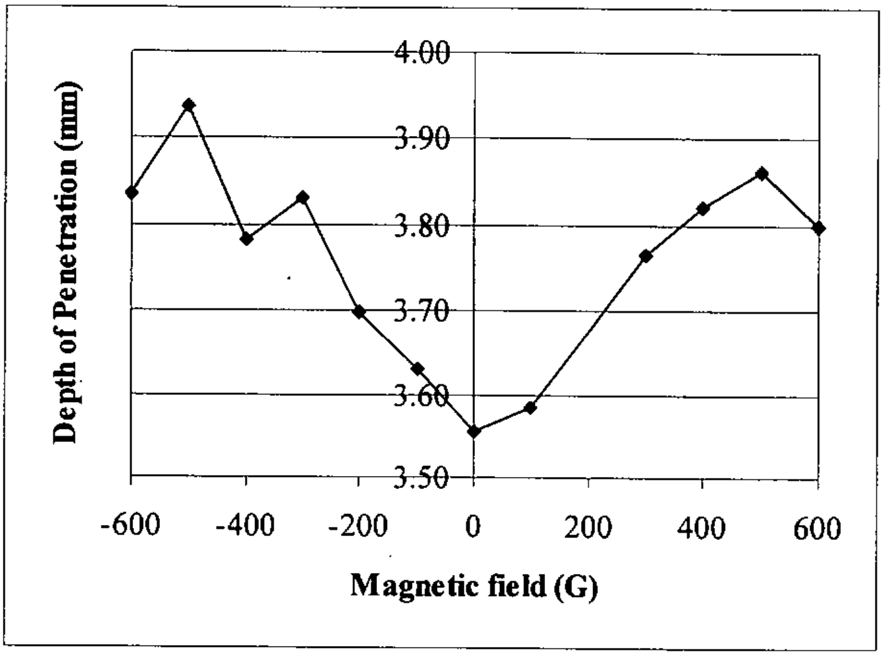


Figure 5. 28: The influence of field direction on the penetration depth at 2000W and 750mm/min.

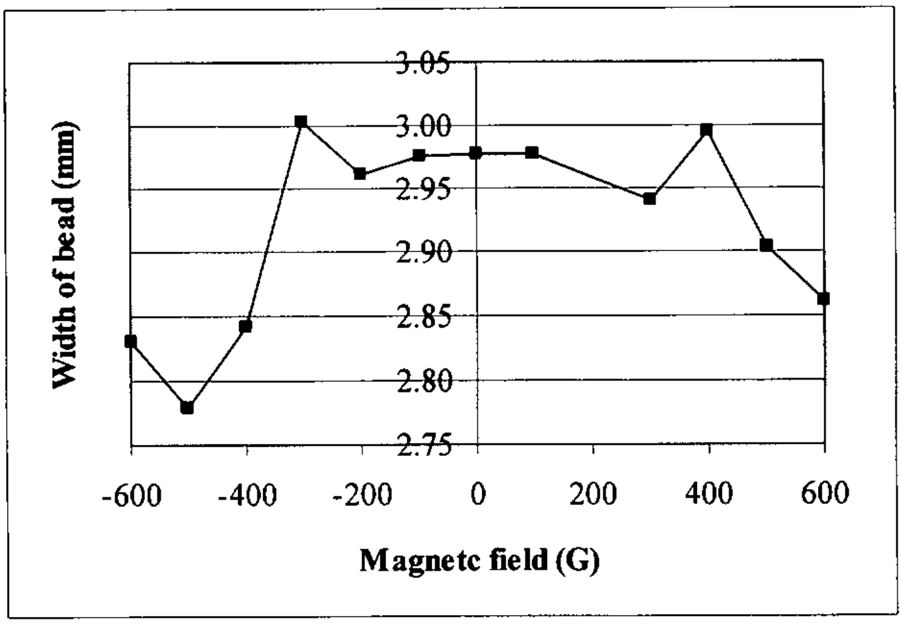


Figure 5. 29: The influence of field direction on the width bead at 2000W and 750mm/min.

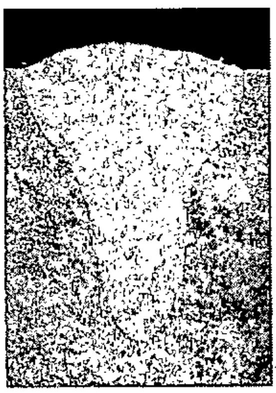
Field condition (i) P.d. between electrode and workpiece (ii) Applied magnetic field strength	a. (i) 0V (ii) 0B	b. (i) 30V (ii) 600B	c. (i) 30V (ii) -600B
Cross-section 1 mm			

Figure 5. 30: The effect of field direction on the weld bead profile (750mm/min; 2.0kW)

5.3.4 The influence of laser power on the effectiveness of using both fields for plasma control

Figures 5.31 & 5.32 show the influence of the both fields on bead profiles at two different laser power levels, at a welding speed of 750 mm/min. Experimental results showed that the at high power level, a stronger magnetic field is required to obtain the optimum penetration depth. In fact, the optimum magnetic field producing the deepest penetration depth is shifting from left to right with the increase in laser power. It is because the plasma formation increases with the increase in laser power level. However, as mentioned before, too strong field strength may affect the effectiveness of using both fields for plasma control. Therefore, when the magnetic field strength is above a critical value, the penetration depth is decreased. In addition, results also obviously show the interrelation between the penetration depth and the width bead.

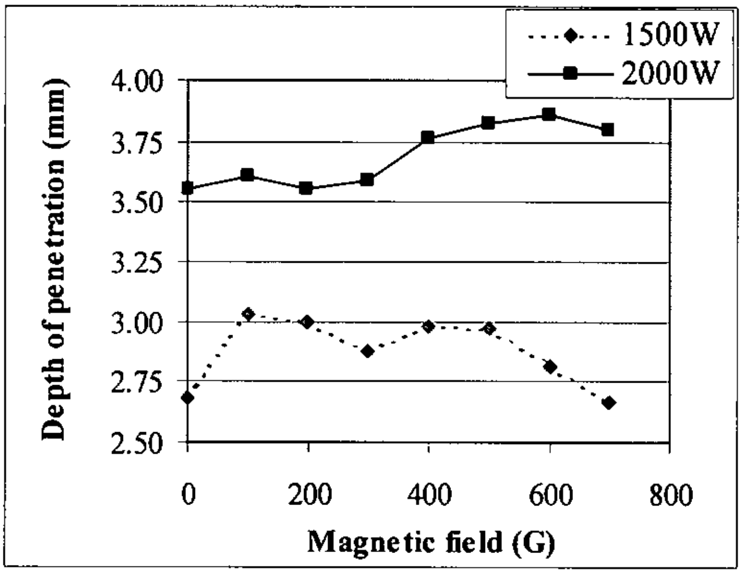


Figure 5. 31: The influence of field strength on the penetration depth (welding speed 750 mm/min and different power levels)

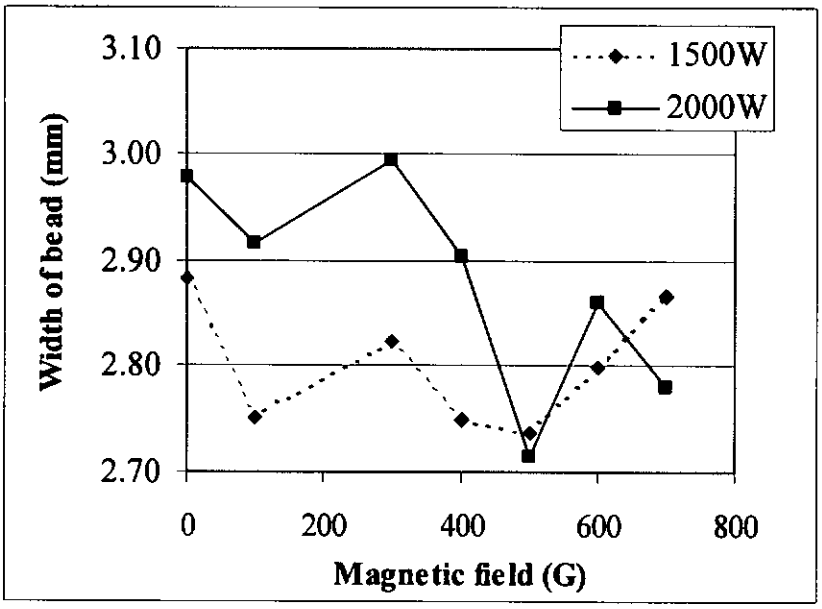


Figure 5. 32: The influence of field strength on the bead width (welding speed 750 mm/min and different power levels)

5.4 COMPARISON OF USING FIELDS FOR PLASMA CONTROL

5.4.1 Comparison on the weld bead profiles

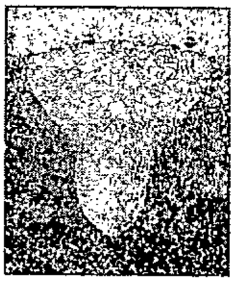
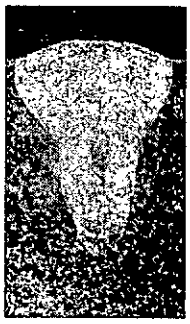
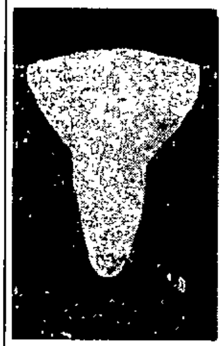
Field condition (i) P.d. between electrode and workpiece (ii) Applied magnetic field strength	**a.** (i) 0V (ii) 0B	**b.** (i) 0V (ii) 400B	**c.** (i) 10V (ii) 400B	**d.** (i) 10V (ii) 0B
Cross-section 1mm				

Figure 5. 33: Effect of field conditions on weld bead profile (750mm/min; 1.5kW)

Figure 5.33 shows the weld bead profiles produced under identical welding parameters (750mm/min, 1.5kW and argon coaxial shielding), except under different field conditions. The difference between the bead profiles produced under no field and magnetic field conditions is not significant. In fact, according to Begimkulov et al's finding [18], in the presence of the magnetic field, the plasma is elongated only but not removed from the laser-workpiece interaction point. Therefore, the improvement in penetration depth is small.

Conversely, it is easy to distinguish the bead profiles of welds *c* & *d* (which produced under electric field only and both electric and magnetic fields) from the weld *a*. Compared with the large but round nail-head profile of weld *a*, the bead profiles of weld *c* & *d* show a slightly sharp root having significantly deeper penetration. In fact, the penetration depth of the welds produced under either the effect of electric field only or the effect of both electric and magnetic fields can be increased by more than 10%. As mentioned before, it is due to the reduction of electron density in the plasma plume under the effect of electric and magnetic fields.

5.4.2 Comparison on the welding efficiency

Field condition i) P.d. between electrode & workpiece ii) Applied magnetic field strength	**a.** (i) 0V (ii) 0B	**b.** (i) 0V (ii) 400B	**c.** (i) 10V (ii) 400B	**d.** (i) 10V (ii) 0B
Mean of measured cross-section areas (mm^2)	4.476	4.598	4.822	4.856
Welding efficiency (%)	3.067%	3.153%	3.307%	3.331%
Improvement in welding efficiency (Compared with the weld produced under no field condition)	-	~3%	~8%	~8.5%

Table 5. 1: Effect of field conditions on melted area (750mm/min; 1.5kW)

Beside the penetration depth of a weld, the volume of material melted is another important parameter determining the efficiency of welding. According to standard energy balance equation 5.7 [36], energy required to melt material is as shown below:

$$U = \rho V[CT_m + L_f] \qquad \ldots\ldots(5.7)$$

where U is the energy required to melt the material, ρ is the density of the material, V is the melted volume, C is the heat capacity, T_m is the melting temperature and L_f is the latent heat of fusion.

Modifying equation 5.7, the power used to produce a weld can be calculated from Equation 5.8.

$$U = \rho V[CT_m + L_f]$$
$$Pt = \rho V[CT_m + L_f]$$
$$\frac{Pt}{t} = \frac{\rho Ad[CT_m + L_f]}{t}$$
$$P = \rho A f[CT_m + L_f] \qquad ......(5.8)$$

where is A is the cross-section area of the weld and f is the welding speed.

In fact, the welding efficiency is determined by the ratio of the calculated power P to the applied laser power. The welding efficiency of each weld produced under different field conditions was calculated and tabulated in table 5.1. It was found that the welding efficiency of the weld produced under no field condition is very small. It is because the majority of laser power is needed to compensate the heat condition losses as well as the energy losses due to the shielding effect of the plasma.

The improvement in welding efficiency is significant under the effect of electric field only or both electric & magnetic fields and is about 8%. However, the improvement under the effect of magnetic field only is small.

5.4.3 Comparison of using fields for plasma control with Helium coaxial shielding

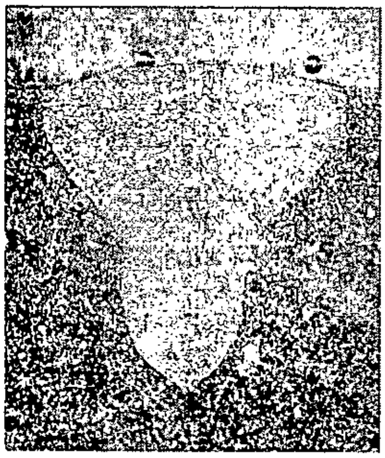
Coaxial shielding gas used	**a.** Argon	**b.** Helium
Cross-section 1mm		

Figure 5. 34: Effect of type of shielding gas on weld bead profile

Experimental results showed that when helium is used as a coaxial shielding gas, the penetration depth is increased by 16%. Moreover, the bead width is dramatically reduced by about 30%. It is due to the high ionization potential of helium. In fact, this phenomenon is consistent for previous researcher's findings. Although using fields (E field only and both E & B fields) for plasma control can only increase the penetration depth about 10%, the operating cost of using this method for laser welding is cheaper than the helium shielding method's. Using fields for plasma control, only argon is used as coaxial shielding. In fact, the unit price of argon is about 60% less than Helium's. For a simple cost analysis, using fields for laser welding can save HK$2300 for 8-hour shift (Table 5.2). In other words, the operating cost can be largely reduced. In addition, this saving can be more significant if deeper penetration welding is performed. It is because the shielding effect of plasma is more profound in high power level.

Cost Analysis	**Case 1** - Helium is used as coaxial shielding gases (a flow rate 30 l/min) - No adding field	**Case 2** - Argon is used as coaxial shielding (a flow rate 30 l/min) - adding both electric & magnetic fields
Operating cost for 8-hour shift (for shielding gas only)	$260 × 0.03 × 480 = HK$3744	$100 × 0.03 × 480 = HK$1440
Difference	-	HK$2304

Table 5. 2: Cost analysis of using Helium side-jet & fields for plasma control

5.4.4 Comparison of using fields for plasma control with side-jet

It has been known that using side-jet during laser welding can reduce the shielding effect of laser-produced plasma and increase the penetration depth. In fact, experimental results showed that the penetration depth can be increased by more than 20% if using argon as both coaxial shielding and side-jet gases. However, when the gas flow rate of side-jet is above a critical value, the improvement on penetration depth is reduced. On the other hand, it was found that the side-jet offers a little advantage for welding when helium is used as coaxial shielding and side-jet gas. The difference between the penetration depth obtained under these two shielding conditions is small.

Although experimental results showed that the improvement in weld bead profile by using E field or E & B fields is less than the side-jet, the new plasma control method is applicable to profile welding. In fact, due to the directional property of the side-jet, profile or multi-directional welding is not possible by the side-jet method. It is because the laser-produced plasma is blown forward by the gas jet and it only pre-heats the material in front. Therefore, the side-jet is not applicable to profile welding. On the other hand, the fields (E field or E & B fields) affect mainly the electron density distribution in the plasma. Comparatively, the directional property of using field for plasma control can be neglected.

5.4.5 Comparison of using both fields and side-jet gas

Another experiment was carried out to study the effectiveness of using both fields (E field or E & B fields) and side-jet for plasma control and the results are summarized in figures 5.35 & 5.36. It was found that the penetration depth obtained under E field only or E & B fields is close to the penetration depth obtained with the side-jet of 10l/min gas flow rate. In other words, the new methods can be used to reduce the argon consumption. However, when the flow rate is above critical value, no improvement on the penetration depth under field effect can be found. It is because the movement of the laser-produced plasma is mainly governed by the side-jet pressure not the E field or E & B fields. Furthermore, E field only or both E & B fields affects the ionized species only but the side-jet affects not only ions and electrons but also neutral atoms in the plasma. As a result, the side-jet gas can obtain the deeper penetration easier.

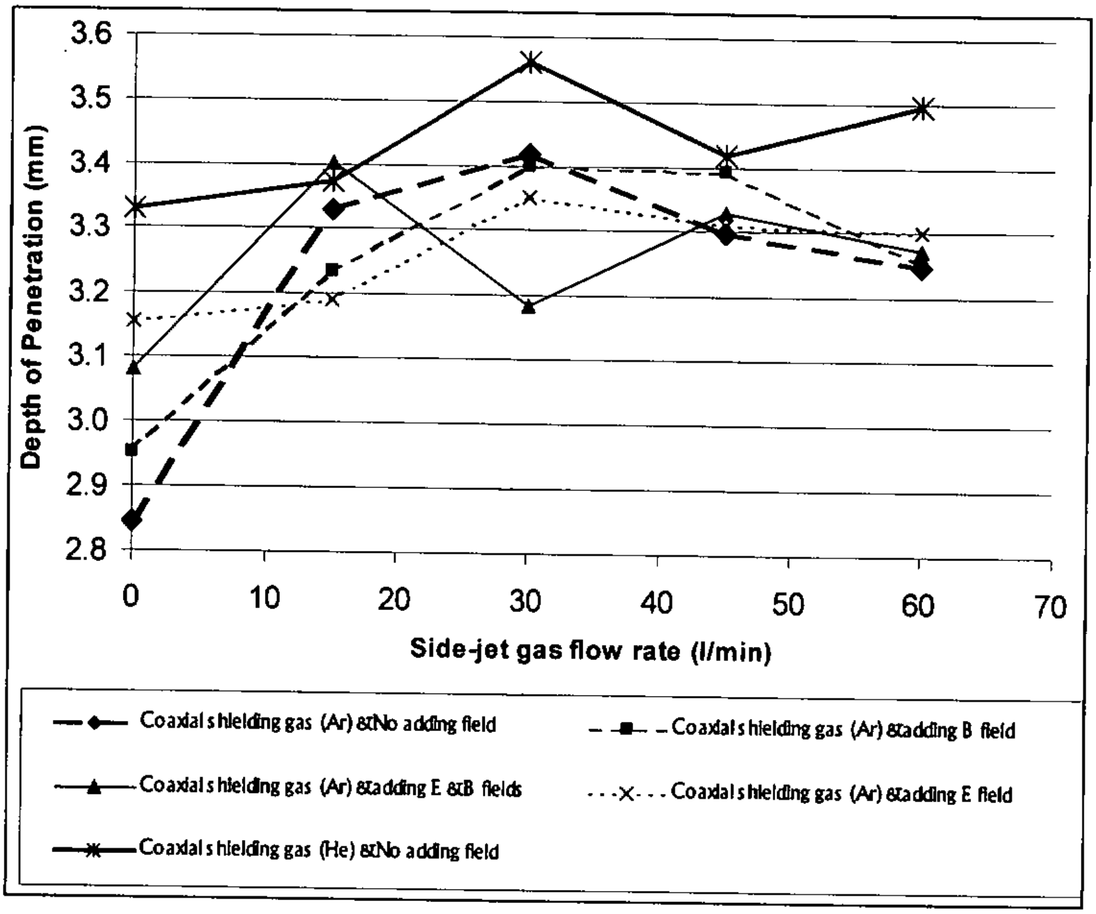


Figure 5. 35: Effect of side-jet gas flow rate on the penetration depth under different field conditions

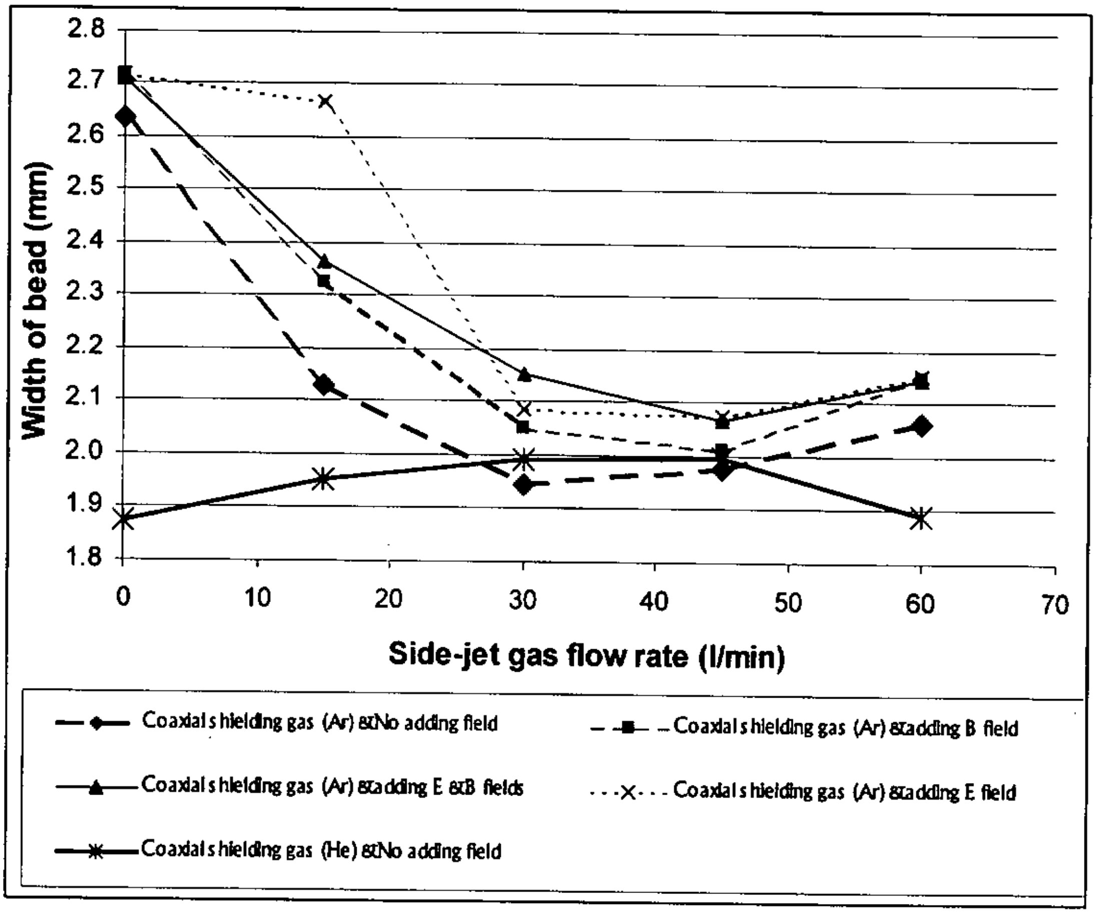


Figure 5. 36: Effect of side-jet gas flow rate on the penetration depth under different field conditions

6.0 CONCLUSIONS

The possibilities of using magnetic field, electric field, and both electric & magnetic fields for plasma control during laser welding have been studied. The following conclusions can be drawn from the experimental results.

6.1 Effect of Magnetic Field on Plasma Control

Experimental results showed that the magnetic field can influence the shielding effect of the plasma. Under the processing parameters considered, the maximum increase in penetration depth obtained was about 7% (at a welding speed of 750 mm/min, a magnetic field between 175G & 225G and under compressed air shielding), but no significant difference on the bead width was found. Moreover, the effect of the magnetic field on the penetration depth is significant at high power level and low welding speed conditions. Also, it was found that in the presence of magnetic field the penetration depth can be increased about 3% under argon atmosphere. In addition, if helium gas is used for coaxial shielding the magnetic field has a negative effect to the penetration depth.

6.2 Effect of Electric Field

The possibility of using electric field for plasma control was also studied. It has been shown that under the parameters considered, the maximum increase in penetration depth obtained was about 8% (at a welding speed of 750mm/min, a power level of 2000W, an electric field between 30-40V and under argon coaxial shielding).

Moreover, experimental results showed that the penetration depth increases with decreasing the bead width. However, at a high power level, too strong electric field can reduce the effectiveness for plasma control. On the other hand, the effect of field direction was also studied. Results showed that the negative electric field (the tungsten electrode was positive) can also increase the penetration depth but the improvement is smaller than the positive electric field's. In addition, a "short circuit" circumstance was observed when the potential difference between the electrode and the workpiece was lower than −50V.

6.3 EFFECT OF BOTH ELECTRIC AND MANGETIC FIELDS

It was found that both electric and magnetic fields can influence the shielding effect of the plasma. Under the field parameters considered, the maximum increase in penetration depth obtained was about 13%. Moreover, experimental results also show that at weak magnetic field strength, the penetration depth increases with decreasing the bead width. However, too strong magnetic field strength can reduce the effectiveness for plasma control. Although some charged particles are moved from the interaction point under the effect of the fields, more electrons are produced due to the ionization process at the same time. In other words, when the field strength is above a critical value, the coupling efficiency of the laser beam is reduced and the penetration depth is decreased.

Experimental results also showed that the difference of bead profile of welds produced under two different field directions is small. Moreover, at high power level, a stronger magnetic field is required to obtain the optimum penetration depth.

6.4 ADVANTAGES OF USING FIELDS FOR PLASMA CONTROL

It was found that under the effect of magnetic field, electric field or both electric & magnetic fields, the penetration depth as well as the welding efficiency can be improved. In the ascending order of the effect of B field, E field and both E & B fields, the electronic density in the laser-produced plasma becomes lower and the penetration becomes deeper. In addition, the improvements in penetration depth are 3%, 8% and 13% under argon shielding. In fact, using E field and both E & B fields can obtain higher welding efficiency. On the other hand, experimental results showed that no significant improvements in weld bead profile are found when using fields and side-jet together for plasma control. But the new methods are applicable under coaxial shielding.

Compared with using helium as a side-jet gas, using fields for plasma control has superior advantages. First of all, the operating cost of laser welding can be reduced due to using comparatively cheap argon as a coaxial shielding gas. Moreover, the profile welding is possible. It is because no directional property of using fields for plasma control.

7.0 SUGGESTED TOPICS FOR FURTHER INVESTIGATIONS

Based on the experimental results of this research study, the following works are recommended for further investigations of using field for plasma control.

7.1 MEASURING THE DENSITY OF LASER-PRODUCED PLASMA UNDER DIFFERENT FIELD CONDITIONS

In this study, the effect of fields to the density of laser-produced plasma was indirectly shown by the penetration depth and bead width. In fact, the plasma density under the effect of fields was not determined. Although some researchers have done such measurements, the laser mode used was in pulsed not continuous-wave or the studies were not for welding application. Therefore, it is recommended to diagnostic the plasma behaviors under these field conditions, e.g. electron temperature, plasma density, electron density and etc. In addition, it is suggested to photograph the laser-produced plasma under the effect of fields.

7.2 EFFECT OF ELECTRODE SIZE

It was found that electric field does offer positive effects to the laser plasma. However, the size of the used electrode is only 1mm diameter. In fact, it has been shown that the number of electrons collected is directly proportional to the surface area of electrode. On the other hand, the maximum applied potential difference was only 60V. Higher the applied voltage, the stronger effect to the laser plasma will be. Therefore, further investigations should be focused on:

- the effect of the size of electrode

- the effect of the position of electrode
- the effect of higher potential difference

7.3 Coaxial shielding

It was found that using electric field or both electric & magnetic fields for plasma control is not suitable under side-jet shielding. In fact, the optimum improvement in penetration depth and bead width was obtained under coaxial shielding only. Therefore, further investigations should be highlighted on the gas flow rate of the coaxial nozzle.

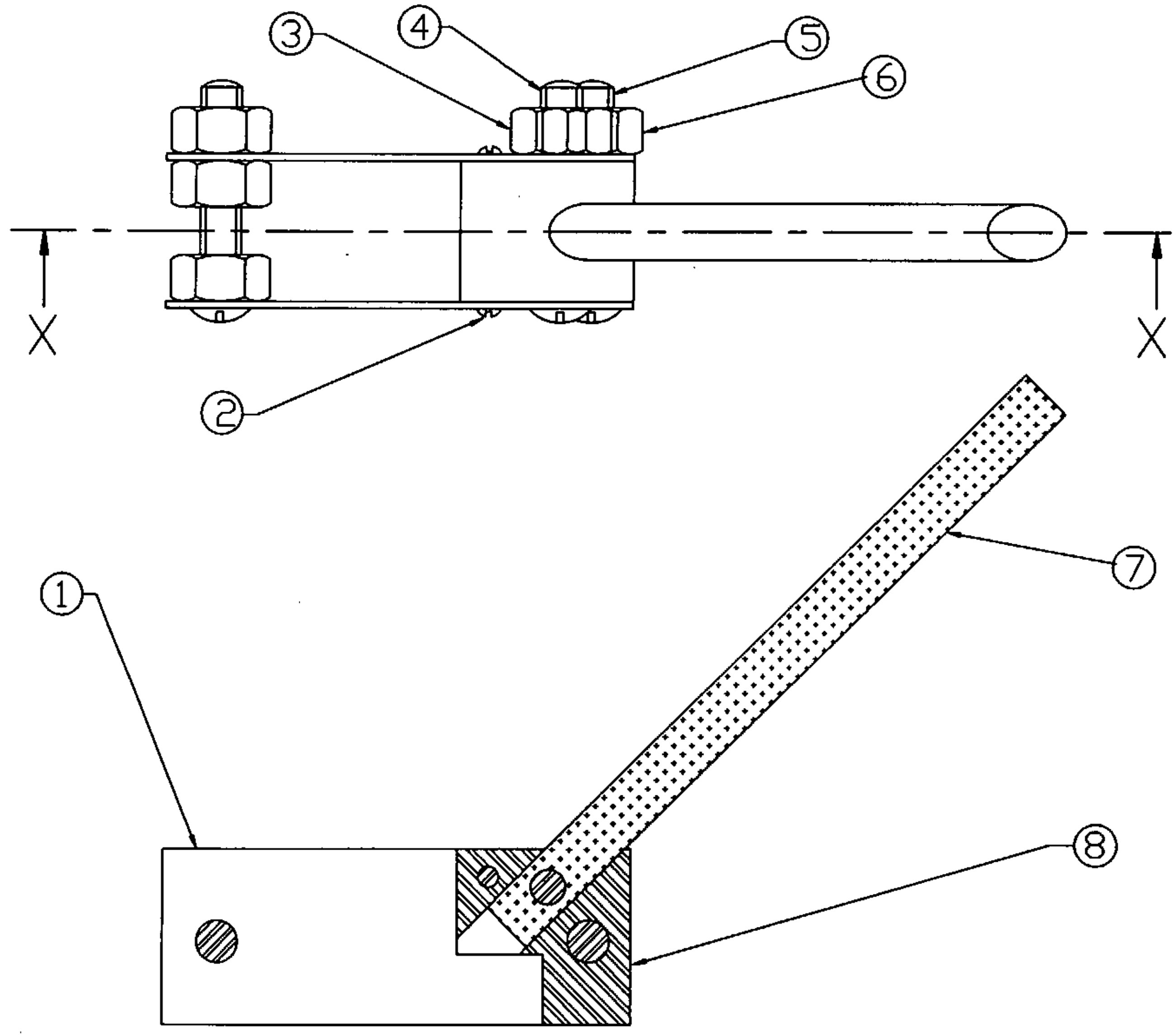
APPENDIXES

APPENDIX 1.0: DRAWINGS LIST

Ref. No.	Title	Drawing No.	Rev. No.
Appendix 1.1	Magnets holder 1	ASS01	0
Appendix 1.2	Magnets holder 2	ASS02	0
Appendix 1.3	Electrode holder 1	ASS03	0
Appendix 1.4	Magnets & electrode holder 1	ASS04	0
Appendix 1.5	Magnets, electrode & side-jet holder 1	ASS05	0
Appendix 1.6	Magnets, electrode & side-jet holder 2	ASS06	0
Appendix 1.7	Separating block (P/N:V56801-0)	0005	0
Appendix 1.8	Separating plate (P/N:V56802-0)	0002	0
Appendix 1.9	Connecting rod (P/N:V56803-0)	0003	0
Appendix 1.10	Welding nozzle 1 (P/N:V56810-0)	0010	0
Appendix 1.11	Separating plate (P/N:V56811-0)	0011	0
Appendix 1.12	Welding nozzle 2 (P/N:V56815-0)	0015	0
Appendix 1.13	Electrode 1 (P/N:V56817-0)	0017	0
Appendix 1.14	Side jet holder (P/N:V56820-0)	0020	0
Appendix 1.15	Separating plate 3 (P/N:V56821-0)	0021	0
Appendix 1.16	Side jet 1 (P/N:V56830-0)	0030	0
Appendix 1.17	Side jet 2 (P/N:V56831-0)	0031	0

APPENDIX 1.1

Title	Magnets holder 1
Drawing No.	ASS01
Rev. no.	0
Description	It is a preliminary design. This tool is used to study the effect of magnetic field on plasma control during laser welding. A mounting device is required to position this tool.



No	Description	Qty.
1	Separating plate (P/N:V56802-0)	2
2	Round head screw (M3x15mm)	1
3	M5 nut	1
4	Round head screw (M5x30mm)	4
5	Round head screw (M6x30mm)	2
6	M6 nut	1
7	Connecting rod (P/N:V56803-0)	1
8	Separating block (P/N:V56801-0)	2

PROJECTION

MACHINING TOLERANCE UNLESS OTHERWISE STATED
UNDER 4mm: ±0.1mm
4 - 16mm: ±0.2mm
16 - 64mm: ±0.3mm
64 -256mm: ±0.5mm
ANGLE : ±0.5°

TITLE Magnets Holder 1

The Hong Kong Polytechnic University

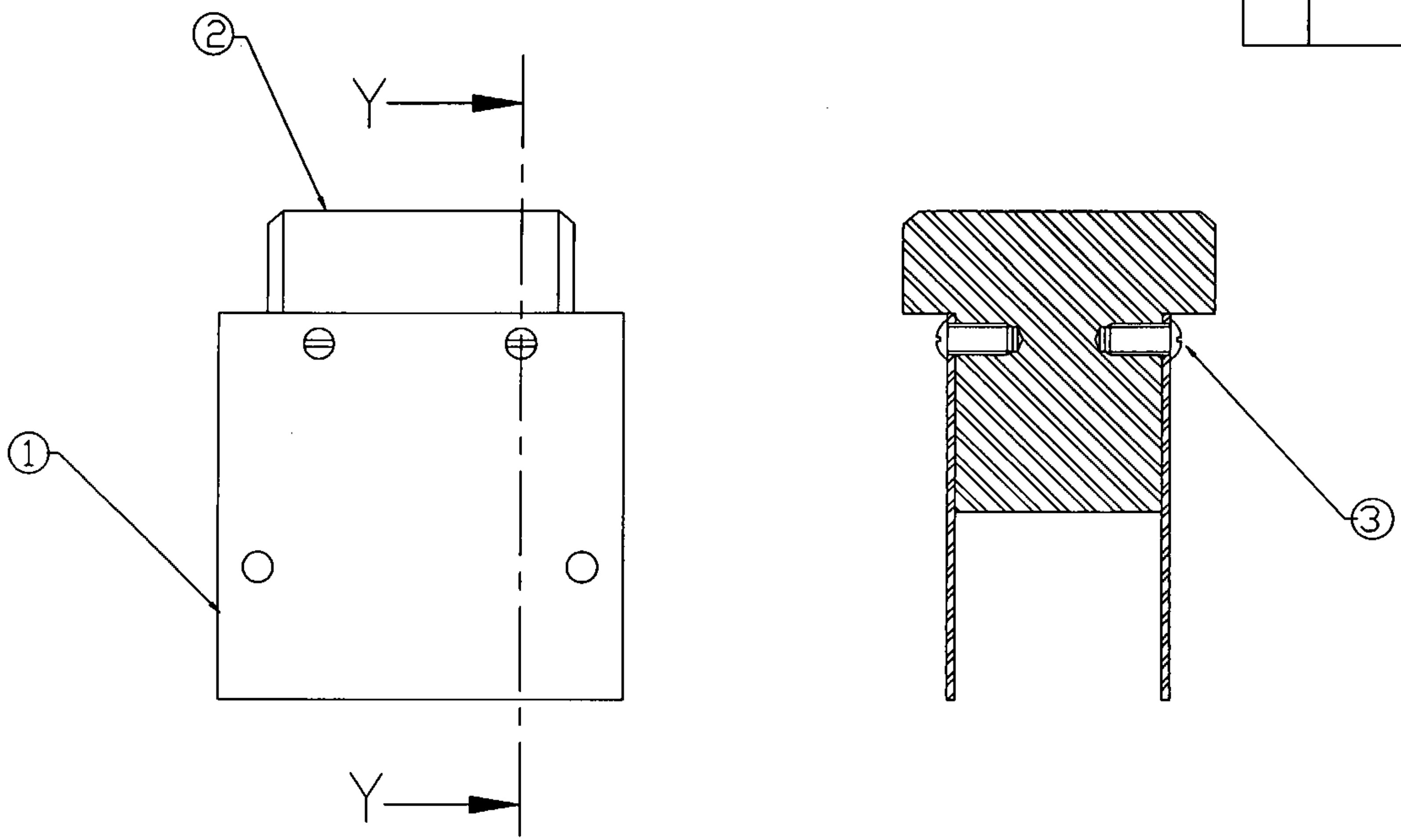
DRN BY	HC TSE	DATE	28-6-98	MATL	-
CHK BY	HC TSE	DATE	28-6-98	FINISH	-
APV BY	HC TSE	DATE	28-6-98		

SCALE Not in scale
DRN NO ASS01
REV NO 00

APPENDIX 1.2

Title	Magnets holder 2
Drawing No.	ASS02
Rev. no.	0
Description	This tool is used to study the effect of magnetic field on plasma control during laser welding. This tool can directly be mounted on the laser machine.

No	Description	Qty.
1	Separating plate (P/N:V56811-0)	2
2	Welding nozzle 1 (P/N:V56810-0)	1
3	Round head screw (M3x10mm)	4

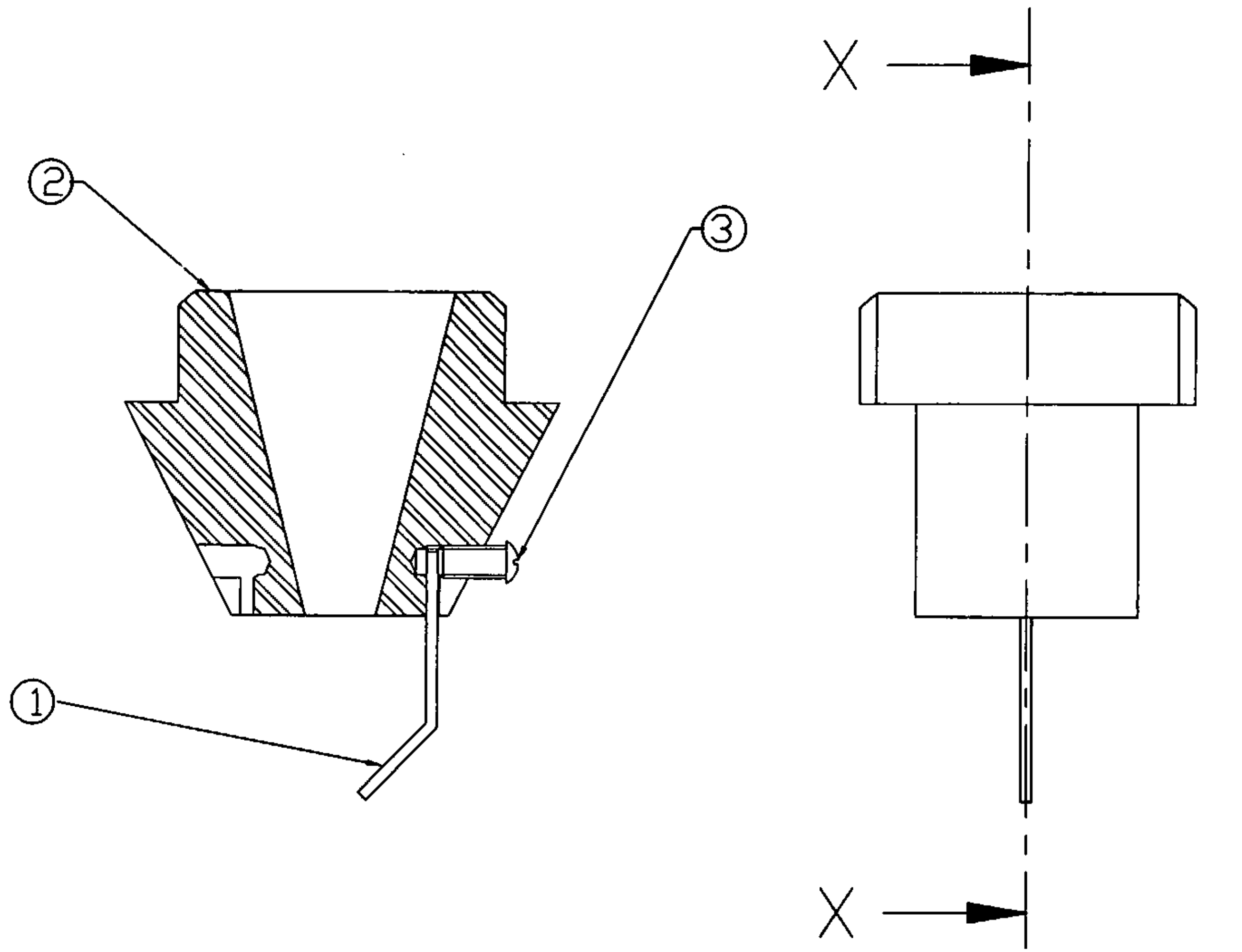


PROJECTION	MACHINING TOLERANCE UNLESS OTHERWISE STATED UNDER 4mm: ±0.1mm 4 - 16mm: ±0.2mm 16 - 64mm: ±0.3mm 64 -256mm: ±0.5mm ANGLE : ±0.5°	TITLE Magnets holder 2		The Hong Kong Polytechnic University		
		DRN BY HC TSE	DATE 28-6-98	MATL -	SCALE	DRN NO ASS02
		CHK BY HC TSE	DATE 28-6-98	FINISH -	Not in scale	REV NO 00
		APV BY HC TSE	DATE 28-6-98			

APPENDIX 1.3

Title	Electrode holder 1
Drawing No.	ASS03
Rev. no.	0
Description	This tool is used to study the effect of electric field on plasma control during laser welding. This tool can directly be mounted on the laser machine.

No	Description	Qty.
1	Electrode 1 (P/N:V56817-0)	1
2	Welding nozzle 2 (P/N:V56815-0)	1
3	Round head screw (M3x5mm)	1

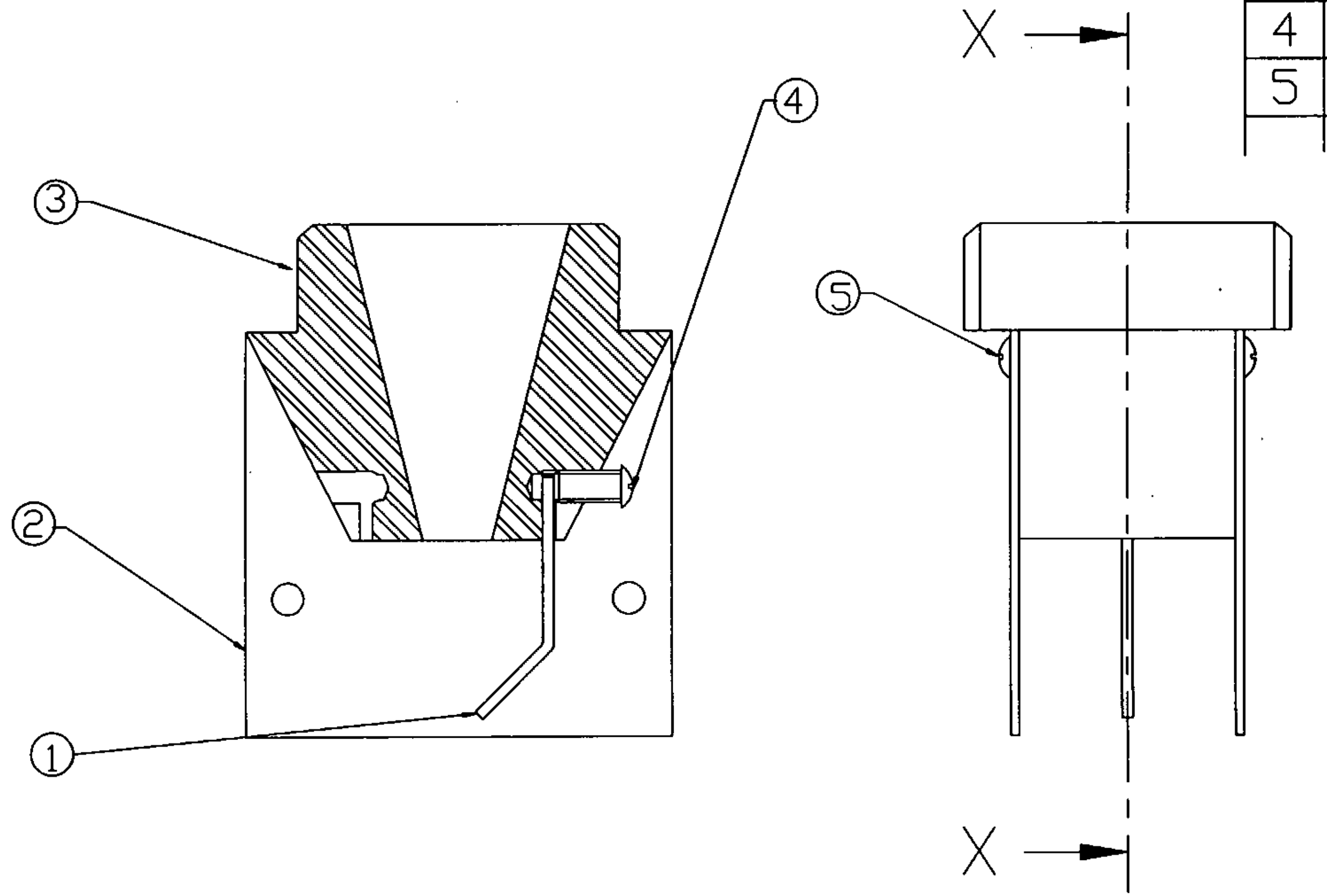


PROJECTION	MACHINING TOLERANCE UNLESS OTHERWISE STATED UNDER 4mm: ±0.1mm 4 – 16mm: ±0.2mm 16 – 64mm: ±0.3mm 64 –256mm: ±0.5mm ANGLE : ±0.5°	TITLE Electrode holder 1		The Hong Kong Polytechnic University	
		DRN BY HC TSE	DATE 28-6-98	MATL -	SCALE Not in scale
		CHK BY HC TSE	DATE 28-6-98	FINISH -	DRN NO ASS03
		APV BY HC TSE	DATE 28-6-98		REV NO 00

APPENDIX 1.4

Title	Magnets & electrode holder 1
Drawing No.	ASS04
Rev. no.	0
Description	This tool is used to study the effect of both electric and magnetic fields on plasma control during laser welding. This tool can directly be mounted on the laser machine.

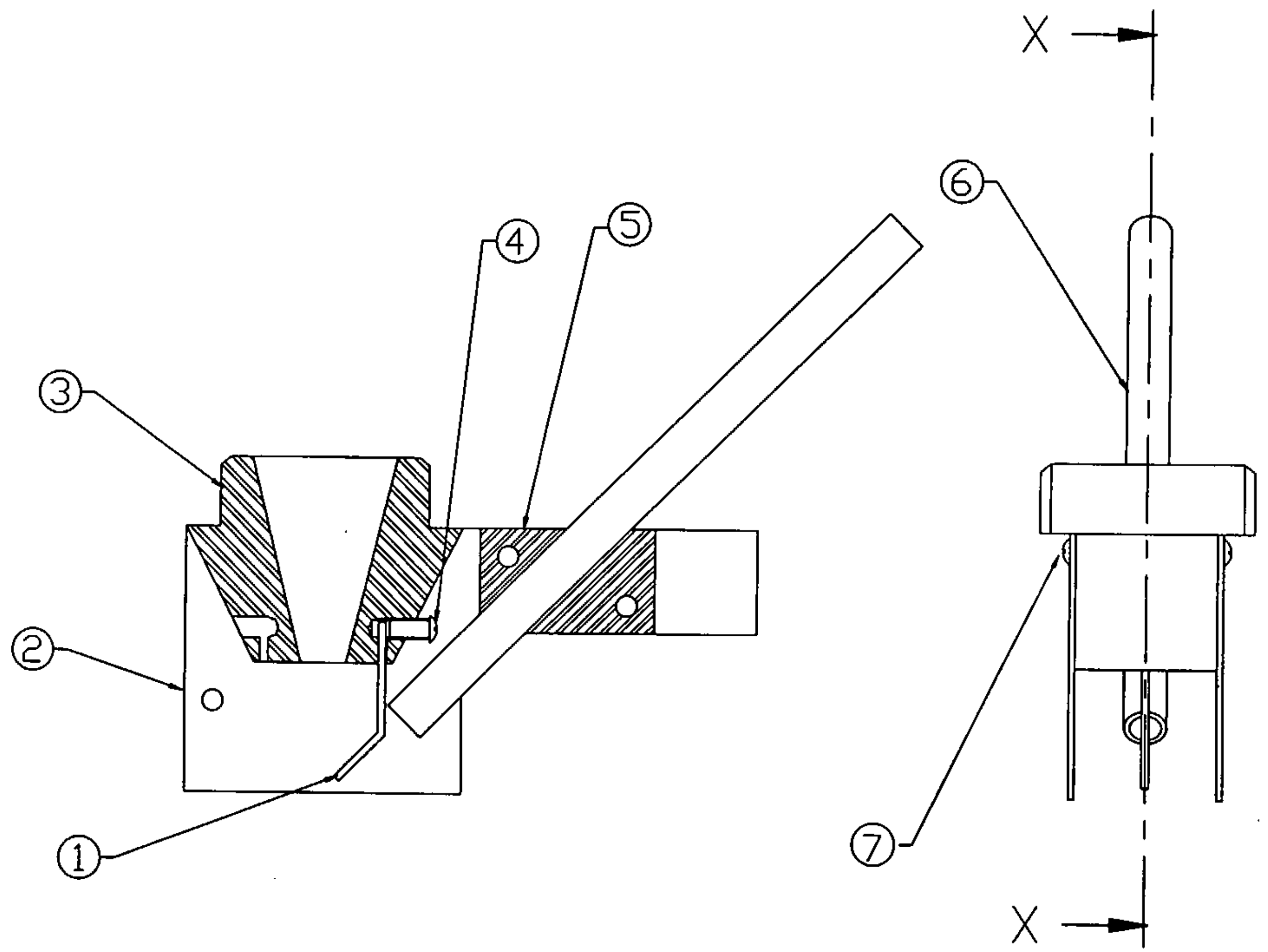
No	Description	Qty.
1	Electrode 1 (P/N:V56817-0)	1
2	Separating plate (P/N:V56811-0)	2
3	Welding nozzle 2 (P/N:V56815-0)	1
4	Round head screw (M3x5mm)	1
5	Round head screw (M3x10mm)	4



PROJECTION	MACHINING TOLERANCE UNLESS OTHERWISE STATED UNDER 4mm: ±0.1mm 4 – 16mm: ±0.2mm 16 – 64mm: ±0.3mm 64 –256mm: ±0.5mm ANGLE : ±0.5°	TITLE Magnets & electrode holder 1		The Hong Kong Polytechnic University	
		DRN BY HC TSE	DATE 28-6-98	MATL -	SCALE Not in scale	DRN NO ASS04
		CHK BY HC TSE	DATE 28-6-98	FINISH -		REV NO 00
		APV BY HC TSE	DATE 28-6-98			

APPENDIX 1.5

Title	Magnets, electrode & side-jet holder 1
Drawing No.	ASS05
Rev. no.	0
Description	It is preliminary design. This tool is used to study the effect of both electric & magnetic fields and side-jet on plasma control during laser welding. This tool can directly be mounted on the laser machine.

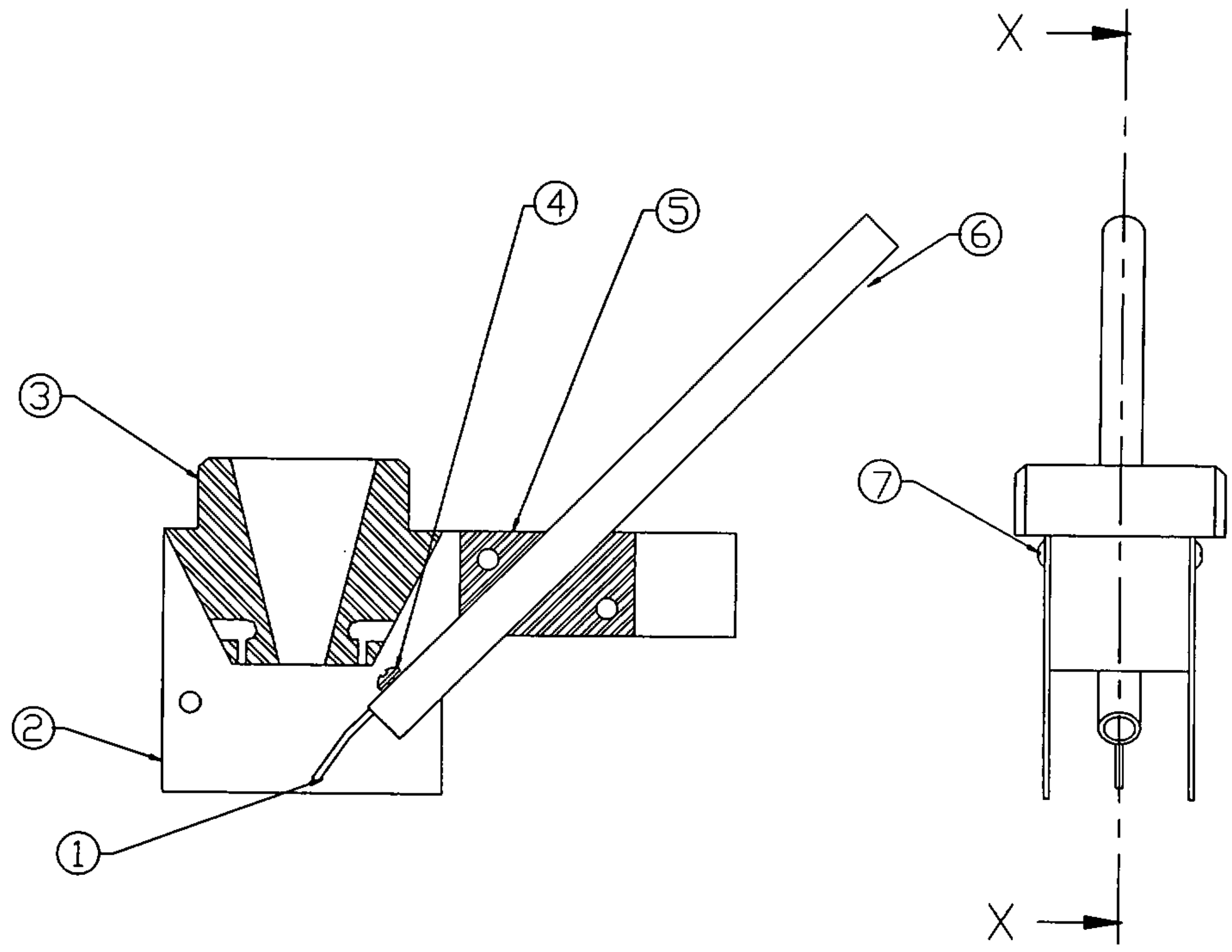


No	Description	Qty.
1	Electrode 1 (P/N:V56817-0)	1
2	Separating plate 3 (P/N:V56821-0)	2
3	Welding nozzle 2 (P/N:V56815-0)	1
4	Round head screw (M3x5mm)	1
5	Side jet holder (P/N:V56820-0)	1
6	Side jet 1 (P/N:V56830-0)	1
7	Round head screw (M3x10mm)	6

PROJECTION	MACHINING TOLERANCE UNLESS OTHERWISE STATED UNDER 4mm: ±0.1mm 4 - 16mm: ±0.2mm 16 - 64mm: ±0.3mm 64 -256mm: ±0.5mm ANGLE : ±0.5'	TITLE Magnets, electrode & side-jet holder 1		The Hong Kong Polytechnic University	
		DRN BY HC TSE	DATE 28-6-98	MATL -	SCALE Not in scale
		CHK BY HC TSE	DATE 28-6-98		DRN NO ASS05
		APV BY HC TSE	DATE 28-6-98	FINISH -	REV NO 00

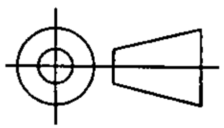
APPENDIX 1.6

Title	Magnets, electrode & side-jet holder 2
Drawing No.	ASS06
Rev. no.	0
Description	This tool is used to study the effect of both electric & magnetic fields and side-jet on plasma control during laser welding. This tool can directly be mounted on the laser machine.



No	Description	Qty.
1	Electrode 1 (P/N:V56817-0)	1
2	Separating plate 3 (P/N:V56821-0)	2
3	Welding nozzle 2 (P/N:V56815-0)	1
4	Round head screw (M2x4mm)	1
5	Side jet holder (P/N:V56820-0)	1
6	Side jet 2 (P/N:V56831-0)	1
7	Round head screw (M3x10mm)	4

PROJECTION



MACHINING TOLERANCE UNLESS OTHERWISE STATED
UNDER 4mm: ±0.1mm
4 - 16mm: ±0.2mm
16 - 64mm: ±0.3mm
64 -256mm: ±0.5mm
ANGLE : ±0.5°

TITLE: Magnets, electrode & side-jet holder 2

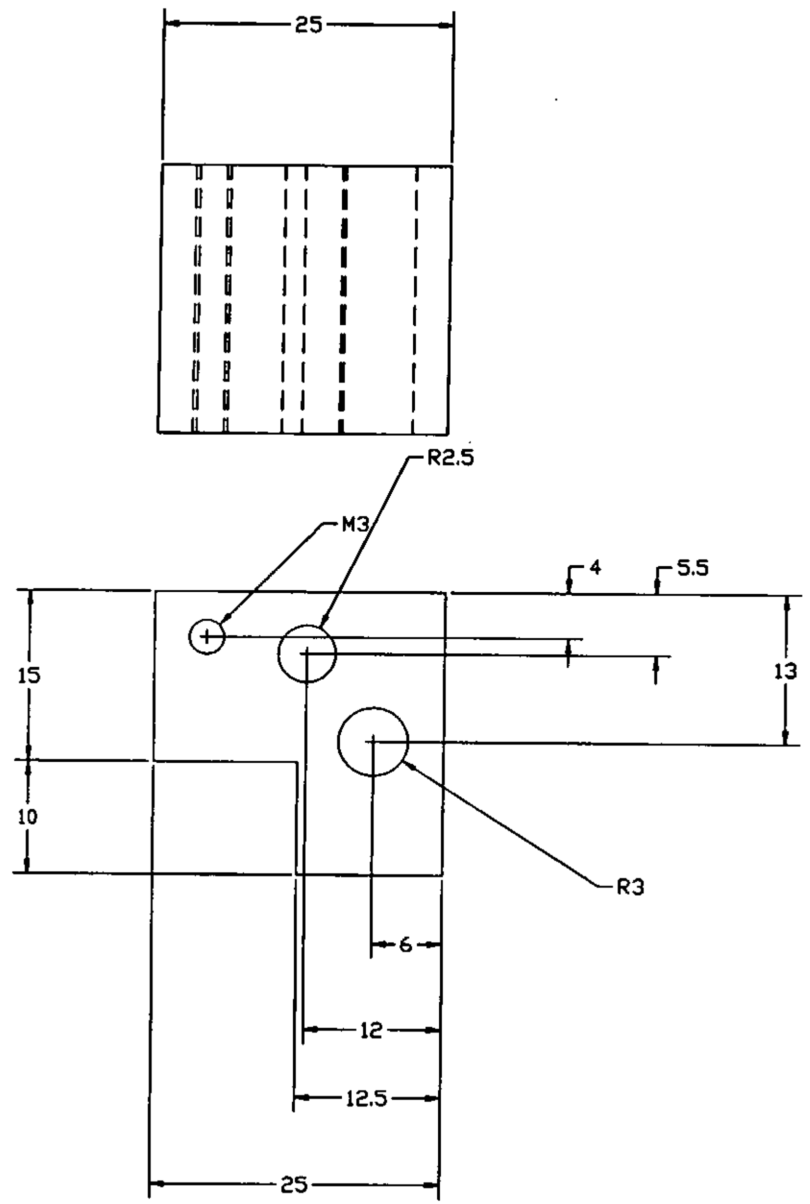
The Hong Kong Polytechnic University

DRN BY	HC TSE	DATE	28-6-98	MATL	-
CHK BY	HC TSE	DATE	28-6-98	FINISH	-
APV BY	HC TSE	DATE	28-6-98		

SCALE: Not in scale	DRN NO ASS06
	REV NO 00

APPENDIX 1.7

Title	Separating block (P/N:V56801-0)
Drawing No.	0005
Rev. no.	0
Description	-

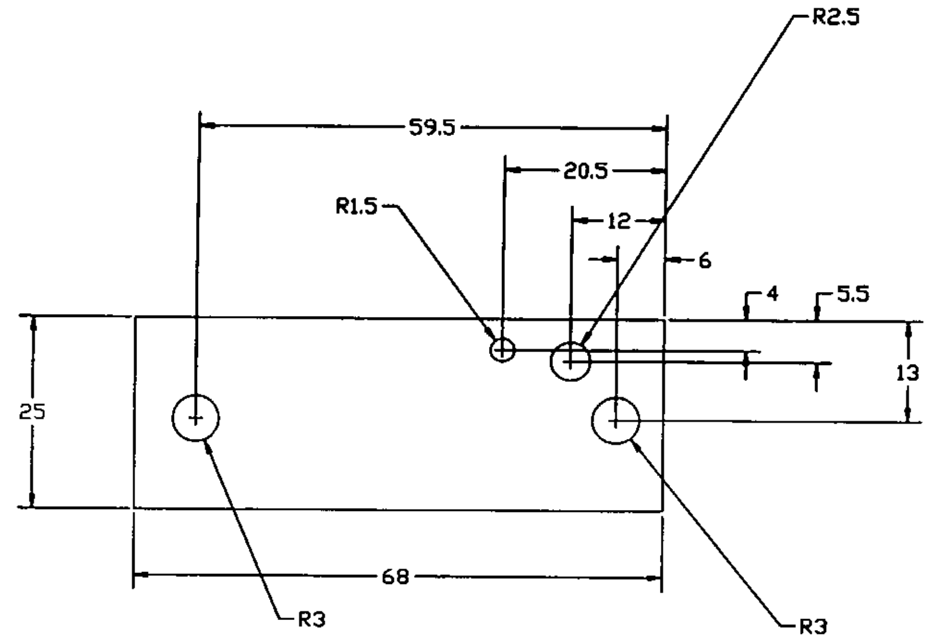


PROJECTION	MACHINING TOLERANCE UNLESS OTHERWISE STATED UNDER 4mm: ±0.1mm 4 - 16mm: ±0.2mm 16 - 64mm: ±0.3mm 64 -256mm: ±0.5mm ANGLE : ±0.5°	TITLE Separating block (P/N:V56801-0)		The Hong Kong Polytechnic University	
		DRN BY HC TSE	DATE 28-6-98	MATL Acrylic	SCALE Not in scale	DRN NO 0005
		CHK BY HC TSE	DATE 28-6-98	FINISH -		REV NO 00
		APV BY HC TSE	DATE 28-6-98			

APPENDIX 1.8

Title	Separating plate (P/N:V56802-0)
Drawing No.	0002
Rev. no.	0
Description	-

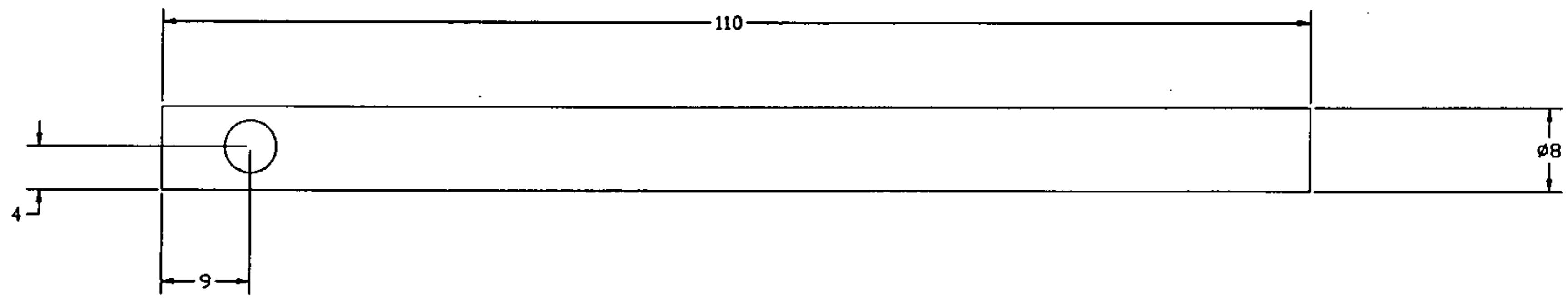
Thickness: 0.8mm



PROJECTION	MACHINING TOLERANCE UNLESS OTHERWISE STATED	TITLE				The Hong Kong Polytechnic University	
	UNDER 4mm: ±0.1mm 4 - 16mm: ±0.2mm 16 - 64mm: ±0.3mm 64 -256mm: ±0.5mm ANGLE : ±0.5'	Separating plate (P/N:V56802-0)					
		DRN BY HC TSE	DATE 28-6-98	MATL Mild steel		SCALE	DRN NO 0002
		CHK BY HC TSE	DATE 28-6-98			Not in scale	
		APV BY HC TSE	DATE 28-6-98	FINISH -			REV NO 00

APPENDIX 1.9

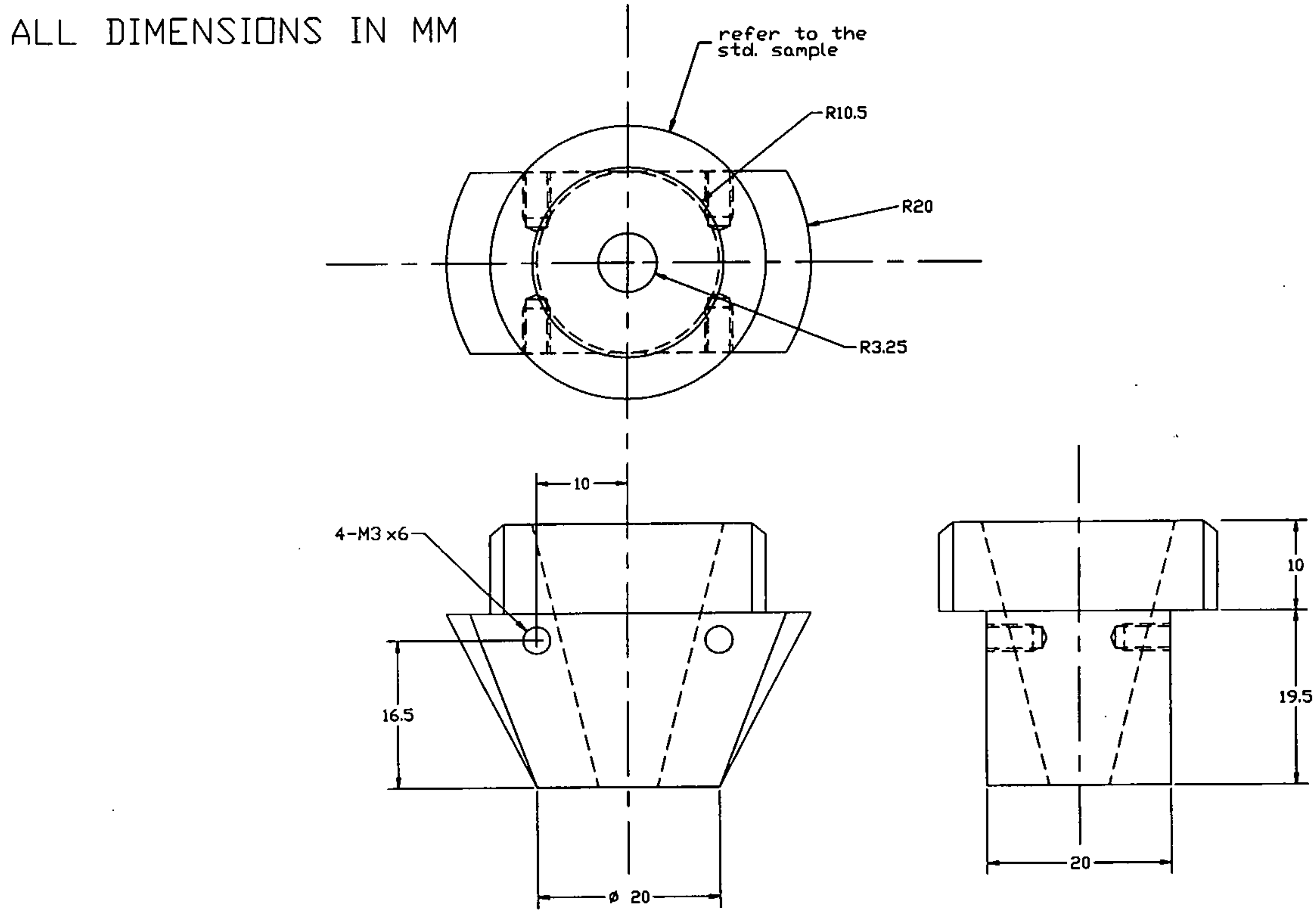
Title	Connecting rod (P/N:V56803-0)
Drawing No.	0003
Rev. no.	0
Description	-



PROJECTION	MACHINING TOLERANCE UNLESS OTHERWISE STATED UNDER 4mm: ±0.1mm 4 - 16mm: ±0.2mm 16 - 64mm: ±0.3mm 64 -256mm: ±0.5mm ANGLE : ±0.5°	TITLE Connecting rod (P/N:V56803-0)		The Hong Kong Polytechnic University	
		DRN BY HC TSE	DATE 28-6-98	MATL Mild steel	SCALE Not in scale	DRN NO 0003
		CHK BY HC TSE	DATE 28-6-98	FINISH -		REV NO 00
		APV BY HC TSE	DATE 28-6-98			

APPENDIX 1.10

Title	Welding nozzle 1 (P/N:V56810-0)
Drawing No.	0010
Rev. no.	0
Description	-



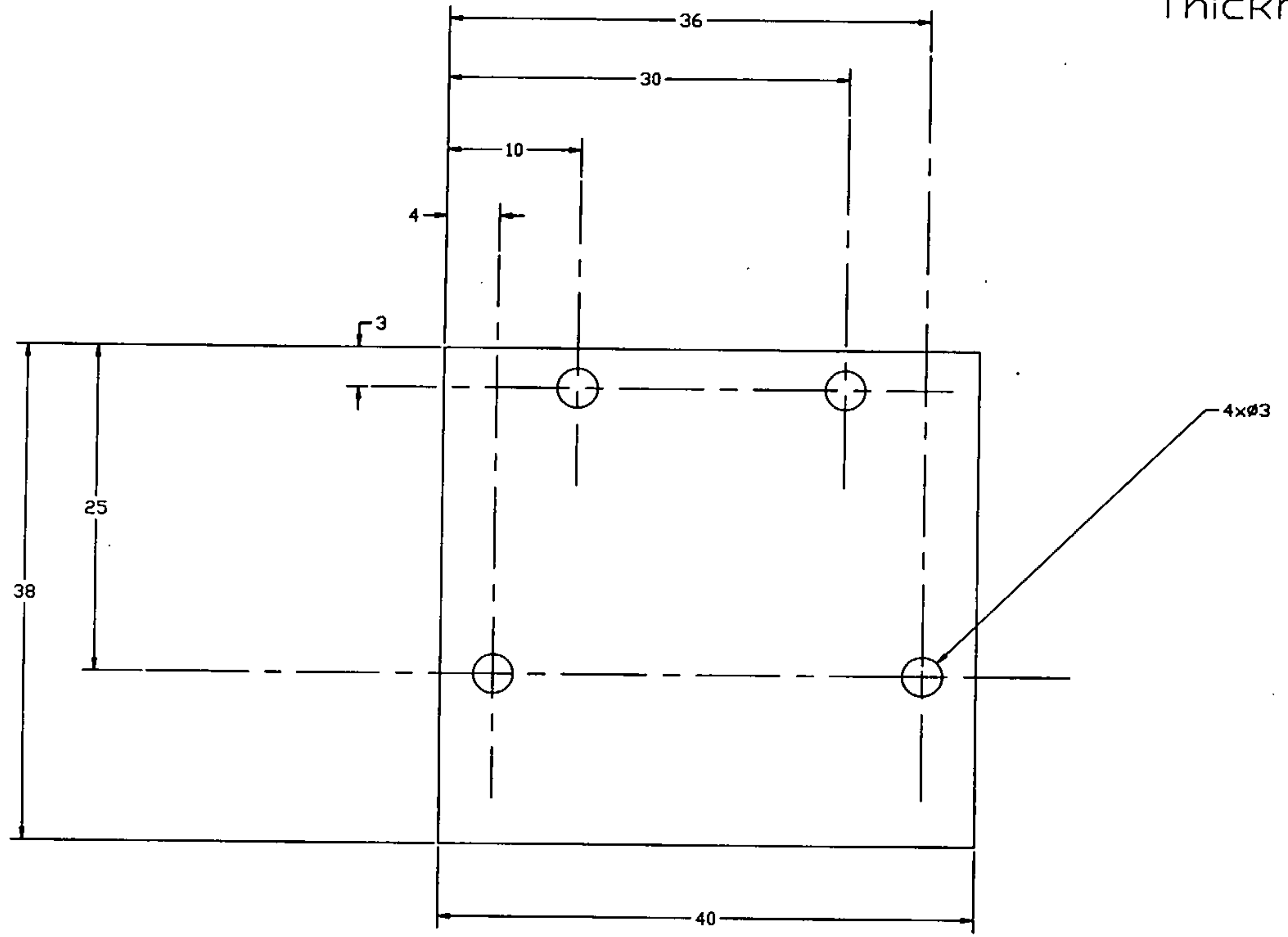
PROJECTION	MACHINING TOLERANCE UNLESS OTHERWISE STATED	TITLE Welding nozzle 1 (P/N:V56810-0)		The Hong Kong Polytechnic University		
	UNDER 4mm: ±0.1mm 4 - 16mm: ±0.2mm 16 - 64mm: ±0.3mm 64 -256mm: ±0.5mm ANGLE : ±0.5°	DRN BY HC TSE	DATE 28-6-98	MATL Aluminium	SCALE Not in scale	DRN NO 0010
		CHK BY HC TSE	DATE 28-6-98	FINISH -		REV NO 00
		APV BY HC TSE	DATE 28-6-98			

APPENDIX 1.11

Title	Separating plate (P/N:V56811-0)
Drawing No.	0011
Rev. no.	0
Description	-

ALL DIMENSIONS IN MM

Thickness: 0.8mm

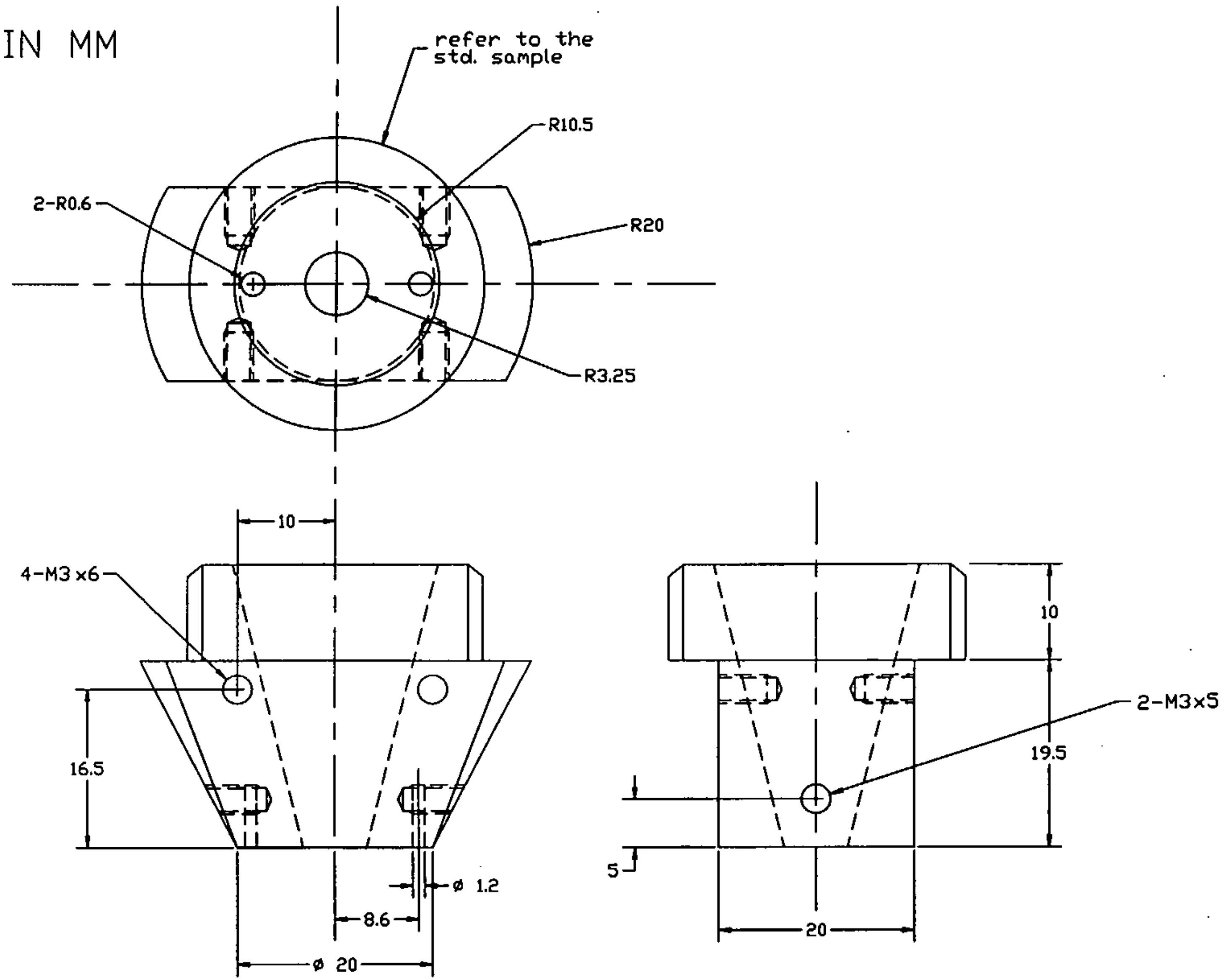


PROJECTION	MACHINING TOLERANCE UNLESS OTHERWISE STATED	TITLE					
	UNDER 4mm: ±0.1mm 4 - 16mm: ±0.2mm 16 - 64mm: ±0.3mm 64 -256mm: ±0.5mm ANGLE : ±0.5°	Separating plate (P/N:V56811-0)		The Hong Kong Polytechnic University			
		DRN BY HC TSE	DATE 28-6-98	MATL Mild steel	SCALE Not in scale	DRN NO 0011	
		CHK BY HC TSE	DATE 28-6-98	FINISH -		REV NO 00	
		APV BY HC TSE	DATE 28-6-98				

APPENDIX 1.12

Title	Welding nozzle 2 (P/N:V56815-0)
Drawing No.	0015
Rev. no.	0
Description	-

ALL DIMENSIONS IN MM

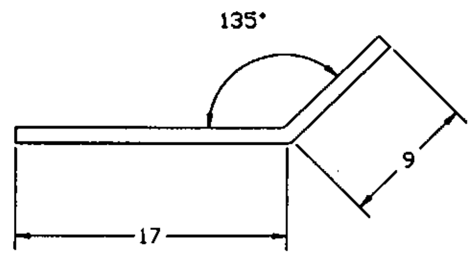


PROJECTION	MACHINING TOLERANCE UNLESS OTHERWISE STATED	TITLE				
	UNDER 4mm: ±0.1mm 4 - 16mm: ±0.2mm 16 - 64mm: ±0.3mm 64 -256mm: ±0.5mm ANGLE : ±0.5°	Welding nozzle 2 (P/N:V56815-0)		The Hong Kong Polytechnic University		
		DRN BY HC TSE	DATE 28-6-98	MATL Aluminium	SCALE Not in scale	DRN NO 0015
		CHK BY HC TSE	DATE 28-6-98	FINISH -		REV NO 00
		APV BY HC TSE	DATE 28-6-98			

APPENDIX 1.13

Title	Electrode 1 (P/N:V56817-0)
Drawing No.	0017
Rev. no.	0
Description	-

ALL DIMENSIONS IN MM

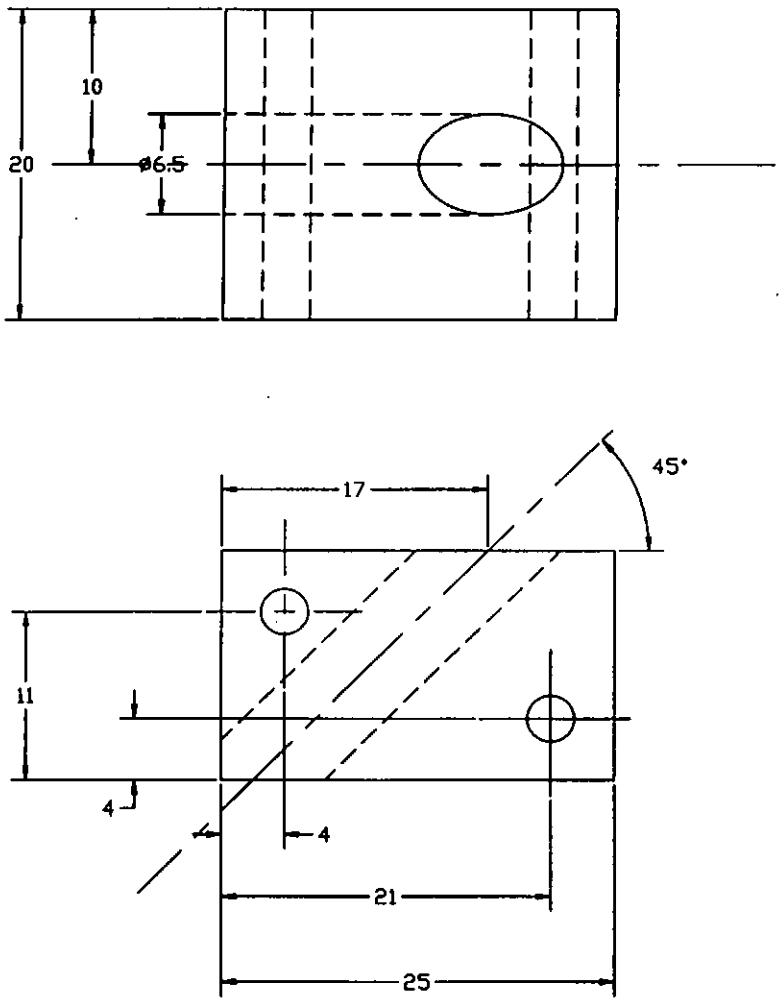


PROJECTION	MACHINING TOLERANCE UNLESS OTHERWISE STATED UNDER 4mm: ±0.1mm 4 - 16mm: ±0.2mm 16 - 64mm: ±0.3mm 64 -256mm: ±0.5mm ANGLE : ±0.5°	TITLE Electrode 1 (P/N:V56817-0)		The Hong Kong Polytechnic University	
		DRN BY HC TSE	DATE 28-6-98	MATL Tungsten Carbide	SCALE Not in scale	DRN NO 0017
		CHK BY HC TSE	DATE 28-6-98			
		APV BY HC TSE	DATE 28-6-98	FINISH -		REV NO 00

APPENDIX 1.14

Title	Side jet holder (P/N:V56820-0)
Drawing No.	0020
Rev. no.	0
Description	-

ALL DIMENSIONS IN MM



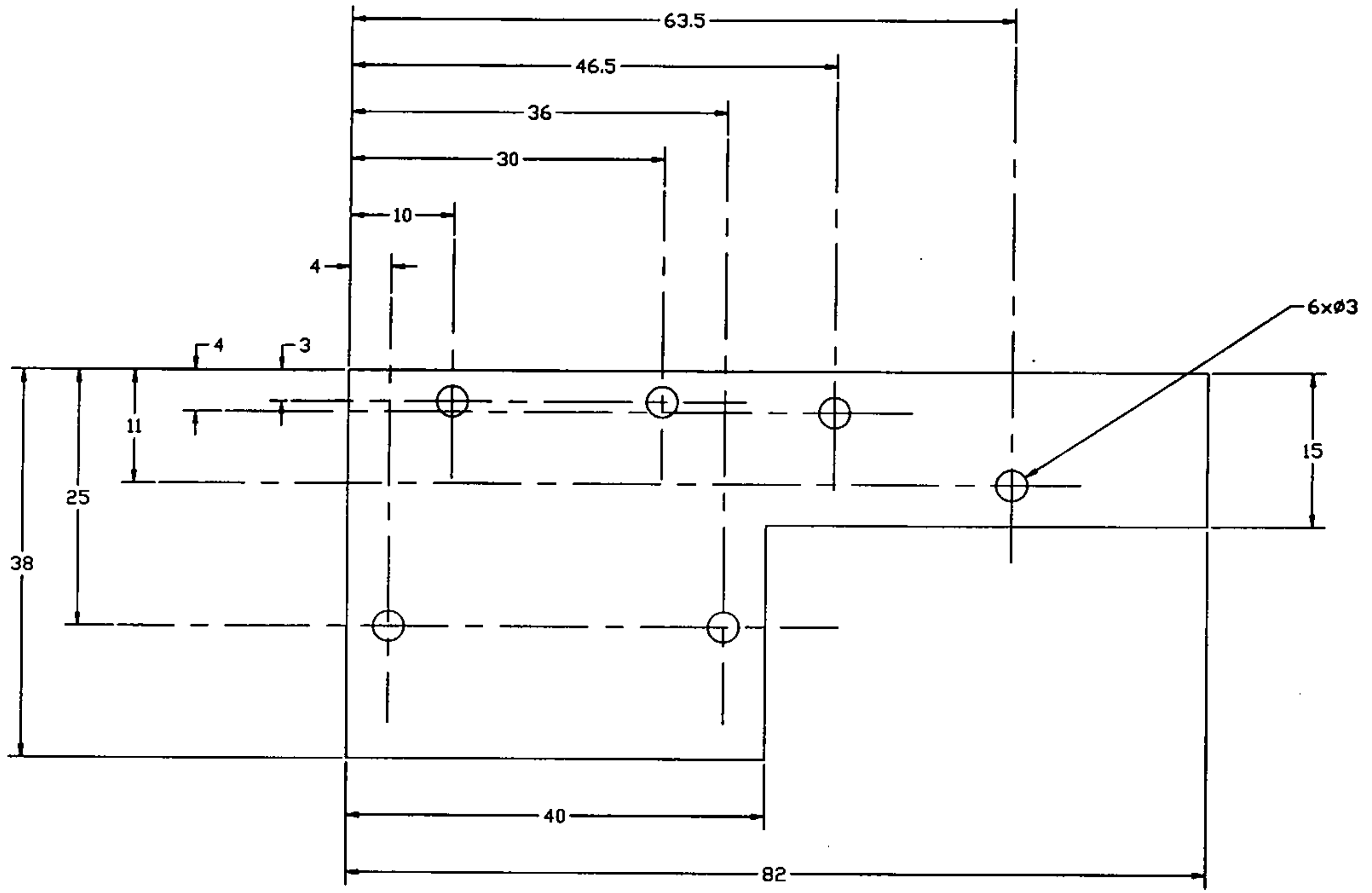
PROJECTION	MACHINING TOLERANCE UNLESS OTHERWISE STATED	TITLE					
	UNDER 4mm: ±0.1mm 4 - 16mm: ±0.2mm 16 - 64mm: ±0.3mm 64 -256mm: ±0.5mm ANGLE : ±0.5°	Side jet holder (P/N:V56820-0)		The Hong Kong Polytechnic University			
		DRN BY HC TSE	DATE 28-6-98	MATL Aluminium	SCALE	DRN NO 0020	
		CHK BY HC TSE	DATE 28-6-98	FINISH -	Not in scale	REV NO 00	
		APV BY HC TSE	DATE 28-6-98				

APPENDIX 1.15

Title	Separating plate 3 (P/N:V56821-0)
Drawing No.	0021
Rev. no.	0
Description	-

ALL DIMENSIONS IN MM

Thickness: 0.8mm

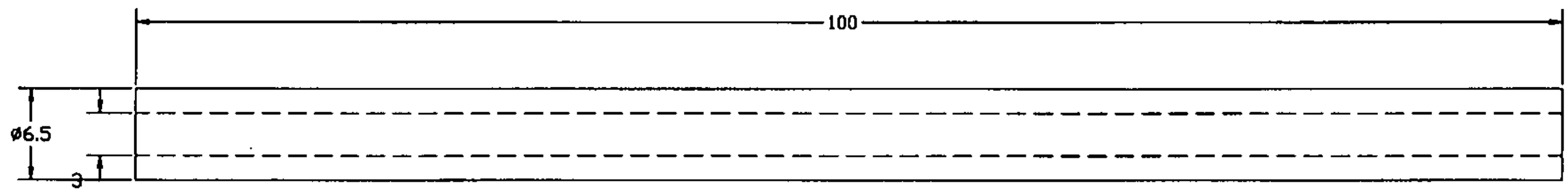


PROJECTION	MACHINING TOLERANCE UNLESS OTHERWISE STATED	TITLE					
	UNDER 4mm: ±0.1mm 4 - 16mm: ±0.2mm 16 - 64mm: ±0.3mm 64 -256mm: ±0.5mm ANGLE : ±0.5°	Separating plate 3 (P/N:V56821-0)			The Hong Kong Polytechnic University		
		DRN BY HC TSE	DATE 28-6-98	MATL Aluminium		SCALE Not in scale	DRN NO 0021
		CHK BY HC TSE	DATE 28-6-98	FINISH -			REV NO 00
		APV BY HC TSE	DATE 28-6-98				

APPENDIX 1.16

Title	Side jet 1 (P/N:V56830-0)
Drawing No.	0030
Rev. no.	0
Description	-

ALL DIMENSIONS IN MM

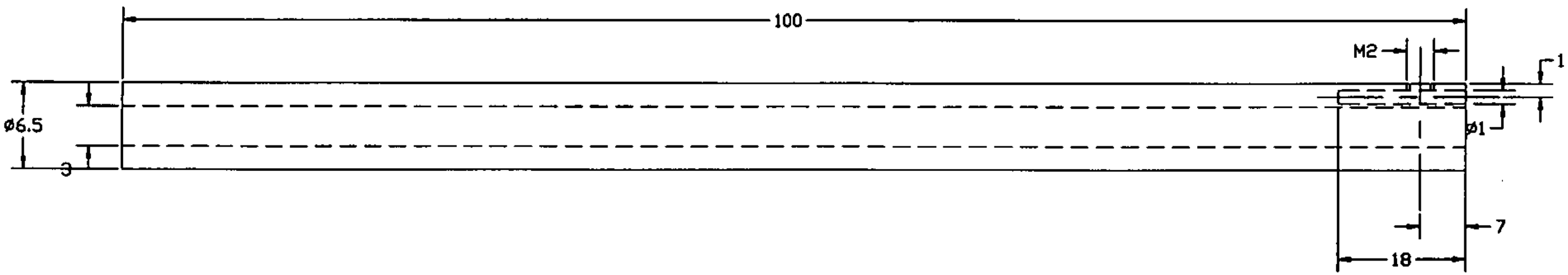


PROJECTION	MACHINING TOLERANCE UNLESS OTHERWISE STATED	TITLE			
	UNDER 4mm: ±0.1mm 4 - 16mm: ±0.2mm 16 - 64mm: ±0.3mm 64 -256mm: ±0.6mm ANGLE : ±0.5°	Side jet 1 (P/N:V56830-0)	The Hong Kong Polytechnic University		
		DRN BY HC TSE	DATE 28-6-98	MATL Copper	SCALE Not in scale
		CHK BY HC TSE	DATE 28-6-98	FINISH -	DRN NO 0030
		APV BY HC TSE	DATE 28-6-98		REV NO 00

APPENDIX 1.17

Title	Side jet 2 (P/N:V56831-0)
Drawing No.	0031
Rev. no.	0
Description	-

ALL DIMENSIONS IN MM



PROJECTION	MACHINING TOLERANCE UNLESS OTHERWISE STATED	TITLE				
	UNDER 4mm: ±0.1mm 4 - 16mm: ±0.2mm 16 - 64mm: ±0.3mm 64 -256mm: ±0.5mm ANGLE : ±0.5°	Side jet 2 (P/N:V56831-0)		The Hong Kong Polytechnic University		
		DRN BY HC TSE	DATE 28-6-98	MATL Copper	SCALE Not in scale	DRN NO 0031
		CHK BY HC TSE	DATE 28-6-98	FINISH -		REV NO 00
		APV BY HC TSE	DATE 28-6-98			

PUBLICATIONS TO DATE

Conference:

1/ Effect of the magnetic field on plasma control during CO_2 laser welding.
(in *Proceedings of ICALEO'98*,p.268-277)

Journal:

2/ Effect of magnetic field on plasma control during CO_2 laser welding.
(in *Optics & Laser Technology*, Vol. 31, pp.363-368 (1999))

3/ Effect of electric & magnetic fields on plasma control during CO_2 laser welding.
(accepted and to be published in *Optics and Lasers in Laser Engineering*)

4/ Effect of electric field on plasma control during CO_2 laser welding.
(submitted to *Optics & Lasers in Engineering* and under review)

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