Design and Development of Microwave Plasma Torch

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Certificate

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Dedication

Our work is dedicated to our beloved parents.

Acknowledgement

We thank Allah, the Greatest, for His countless blessings. He gave us strength and ability to complete this project.

We thank our supervisor Dr. Umair Manzoor from SCME and Dr. Anisullah Baig from PINSTECH for helping and guiding us in our project. They were very supportive.

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Abstract

A 800W, 2.45GHz argon gas microwave Plasma torch (MPT) has been designed and fabricated, working at atmospheric Pressure. The Plasma is sustained in a 25-mm internal diameter fused Quartz tube, which penetrates perpendicularly through the wide walls of a tapered and shorted WR-340 (85mm x 45mm cross section) waveguide. The Plasma temperature was enough to melt the copper wire tip i.e. >1000°C. The effect of gas flow rate and length of Quartz tube on the flame has been studied. The experiments for Microwave Power coupling were also conducted. Material processing techniques like heat treatment and nitriding were also performed.

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Chapter 1: Introduction

1.1 Electromagnetic waves

Heinrich Rudolf Hertz, a German scientist first proved the existence of electromagnetic waves theorized by James Clerk in his electromagnetic theory of light. Hertz's doctoral desertion was to study and prove the theory of electromagnetic waves. Firstly it was said that light only constitute nature of wave but by the time the particulate nature of light was associated with a great development in the field of electromagnetic waves. Electromagnetic waves consist of eclectic and magnetic fields that's are perpendicular to each other and the direction of propagation of wave front. They can be subdivided into number of waves according to the frequency of the waves. They usually range between 200 MHz to 300 GHz.

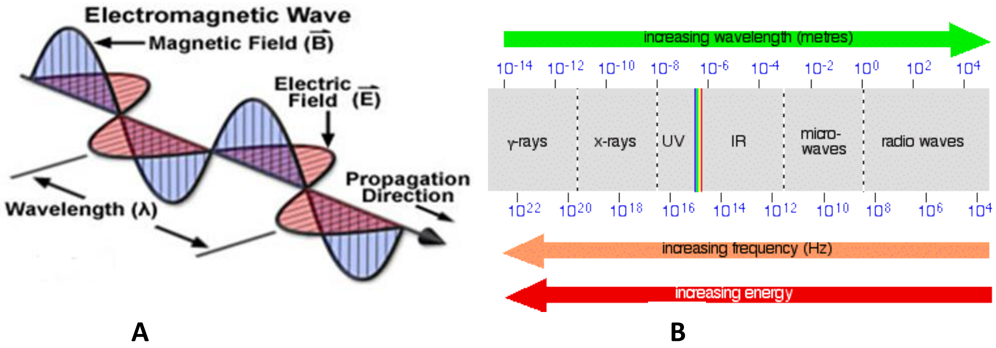

Figure 1.1: Propagation of electromagnetic waves (A) Frequency Distribution of electromagnetic waves (B)

1.2 Microwaves

Later in 1888, after the discovery of electromagnetic waves, microwaves were discovered and detected by the same scientist named Heinrich Hertz . after the discovery of dual behaviour of the electromagnetic waves, it was difficult to distinguish wave and particle nature according to the frequency. It was referred as a clear possibilty that interaction with matter converts energy into mechanical force sometimes and other energy forms as well. We refer them as energy packets called "phonons". In most of the transmission techniques, the Electromagnetic field is described as wave like nature. This could easily be understood by illustrating that specific energy is required for resonating molecules of different materials. The mechanical vibration in material is caused by microwave or millimeter rangeof waves. While the second type of interaction in which we can observe orbital shift of electron is observed in wide range of higher frequencies like UV, infrared, visible wavelengths. In lower frequecy we can only have conversion of energy into heat thus can only be used for heating applications. While orbital shifting of electron gives florescence effect referred as light.

Usually “millimeter waves” are used to explain any microwaves of higher frequencies but there are is a diverse classification for different range of frequency of microwaves. For instance different designated microwaves along with their range are discussed and explained. For example EHF is used for microwaves ranging within 1mm to 1cm and are called “millimeter waves”. We also have have waves with frequencies greater than 300 GHZ (i.e. greater than that of millimeter waves) and are regarded as “Sub-millimeter waves” as wavelength gets lower than one millimeter. Increasing frequency to 1THz we have Tetra hertz frequencies and are named as “Very long wave Infrared”. Various infrared waves are named according to their frequencies in between 300GHz to 300 THz. But visual sensitivity is observed around 480 THz (625nm) as deep red colour. Table below summarizes all the above discussion:

Table 1: Wavelength and Frequency distribution of microwaves

Band	**Frequency**		**Wavelength**	
	Starts at	Ends at	Starts at	Ends at
VHF	30 MHz	300 MHz	10 m	1 m
UHF	300 MHz	3 GHz	1 m	10cm
SHF	3 GHz	30 GHz	10 cm	1 cm
EHF	30 GHz	300 GHz	1cm	1mm
Sub millimeter	300 GHz	Infinity	1mm	Zero

1.2.1 Sources of microwaves

Usually any equipment is produced keeping in view cost, efficiency, power and reliability of the product. Naturally, they appear from sun and cosmic background waves. Microwaves can also be generated by a tubular type machine. They usually include artificial devices like circuits, transmission towers, radars, masers and magnetron. The most successful way by the review of experts from 40 years is magnetron available in household microwave oven working at low frequency and is abundantly produced. We also have industrial magnetrons having high performance.

In 1975, group of scientists predicted that solid state devices would replace traditional magnetrons by 1985. Similarly, in 1995, another paper promised replace the same with solid state or multiple beam klystrons but failed to match the performance with that of cooking magnetron. It is now emphasized that magnetrons are the standardized device for microwaves production and are widely produced worldwide with exactly the same characteristics.

Currently, household microwaves are designed within the range of 800-1000 W and industrial magnetrons are its derivatives working at 300-3000 W or at high power at 25-100 kW and even more. Cooker magnetrons provide approximately 800-1000 W usually at 2.45 GHz. It has efficiency of 70 %operating at 4 KV and 0.3 1 Amperes. They are supplied by Japan, Korea, Thailand, Russia and China at 30-40 millions tubes per annum. Industrial magnetrons are only available in market with 915 MHz frequency. 2.45 GHz sources are cost as well as easy to use and withstand reflection to some limits. Industrial ones are sensitive and require numerous other devices to use them.

1.2.2Uses of Microwaves

Microwaves are used for numerous applications like communication including broadcasting, radar etc. Later by the study of their interaction with matter it was concluded and regulated by FCC in the U.S and the ITU worldwide, their use for microwave diathermy or heating. The interaction of microwaves with material is dependent upon the permeability of the material “ε”. It gives the absorption limit and transfer of energy characteristics of the material. They can also ionize the gas thus producing mixture of ions, electrons i.e. Plasma.

1.3 Plasma

Earth’s atmosphere is primarily of nitrogen and oxygen. However, if we move upwards from the Earth’s surface, the environment changes and no longer fits this description. At about 80 km above the Earth’s surface, the atmosphere is no longer made up of gas. Instead, it is made up of ionized gas, which consists of a balanced mix of electrons, positive ions and neutral particles. This state is called plasma commonly known as the ‘fourth state of matter’. It is said that 99.9 percent of total observable matter of universe is plasma. It is observed naturally in plasma lightning, solar wind, the Earth's ionosphere, stars (including the Sun), tail of a comet, interstellar gas clouds and a fireball of a nuclear explosion. Moreover, it can also be artificially be generated by ionizing matter as in aurorae (the excited low-pressure gas inside neon signs and fluorescent lights), welding arcs etc.

1.3.1 Plasma properties

Plasma is a high energy state and is mixture of gaseous ions. Its properties resemble to those of gas but differ in some ways. Salient properties include:

- Plasma has a very high electrical conductivity.
- Plasma is more readily influenced by electric and magnetic fields than by gravity
- The motion of electrons and ions in plasma produces its own electric and magnetic fields.
- Because of the totally chaotic and highly energetic state of the constituent particles of plasma, it produces its own electromagnetic radiation.

To produce and maintain the highly energetic state that exists within plasma, there must be a continual supply of energy.

1.3.2 Artificial plasma – hot and cold

Hot or thermal plasma is produced in atmospheric arcs, sparks and flames. The highly ionized plasma consists of large numbers of electrons and positive ions, with the temperature of both being extremely high. Depending on their power, plasma-cutting torches operate at very high temperatures between 5000 and 10 000°C.

Cold or non-thermal plasma is less well ionized, and although the electrons are high temperature, the positive ions and neutral particles are at a lower temperature. When a fluorescent lighting tube is switched on, cold plasma (at room temperature) is set up within the tube.

1.3.3 Uses

Artificially generated plasma is used in plasma television, fluorescent lightening, environmental control – abating pollutant gas emissions, plasma ball toys, material processing techniques (explained latter) etc.

1.4 Plasma torch

Plasma torch refers to a device used for directing plasma generated from whatever source to a specific area or have its directional flow. It has numerous applications in materials processing techniques. We need to design it specifically to have a directed flow according to the requirement

1.4.1 Significance

Plasma jet is significant because:

- It has flexible design and can easily be used for numerous applications
- It is adoptable at every level
- It is highly cost effective for numerous costly techniques.

Chapter 2: Literature Review

2.1 Applications

We are determined to develop a flexible design for plasma torch so it can be used for numerous material processing techniques.

Al_shamma's et al have proposed a solution for designing of low cost and efficient method for generating microwave plasma jet in atmospheric pressure using 2.45 GHz and simple waveguide design. Their solution suggests using magnetron power supply, circulator equipped with water load, and the design of transmission line according to the application. They used stub tuning applicator for matching the reflected and transmitted waves. These microwaves were directed from the source magnetron to the sink of microwaves energy by transmission line. The sink of energy they are using is numerous gases medium e.g. Nitrogen, Argon and Helium. Using above described equipment they constructed Microwave Plasma Jet (MPJ) for materials processing like cutting, welding, glass vitrification, quartz processing. They proposed adjusting flame by gas type, its flow, power of source and nozzle design. [2]

M Mosian gives a detail report of theoretical as well as practical use of atmospheric pressure plasma generation torch with axial flow in a waveguide based design. They detailed the method of impedance matching and wave mode conversion and power transfer. This gives a way to optimize the performance. [5]

"Efficient modular microwave plasma torch for thermal treatment" proposed design for coupling foe waveguides in series for nitrogen and atmospheric based plasma to improve the efficiency of plasma jet. They succeeded to develop 25 cm long flame by axial flow using total of 4 kW at 140 l/min in the 2.5 cm diametric discharge tube. Their design has major limitations like modular stages and high volumetric gas flow but have a significant potential of being scale up for commercial proposes for various material processing techniques. One of the major advantages is to have an electrode free setup of the techniques using replacement of the electrodes frequently. The cost estimation is as low as one dollar per watt for the design proposed by them. [3]

Another research by Wilson Lai et-al shows a portable microwave plasma torch running stable with air flow hence used for decontamination of biological warfare agents. The plasma jet produced by microwave source produces reactive atomic oxygen by the flow of air. They tested and concluded that at about 0.393 l/ sec flow of air they have the best concentration of reactive oxygen and observed a relation between time and distance of the nozzle from the specimen. This relation can easily be understood in the table illustrating killing of required spores by the time altering the distance. [17]

Table 2: Relation between MPJ and Time

Time (sec)	**Distance of MPJ nozzle (cm)**
8	3
12	4
16	5

Al Shamma'a et al also reported in his report "low pressure microwave plasma ultraviolet lamp for purification of water and ozone applications" about UV light lamp. He introduced a new technique for generation and controlling of intense UV up to 185nm. This paper shows the comparison between conventional lamps through spectral analysis under temperature and power input variants. [18]

Spencer P. Kuo and Daniel Bivolaru explained torch characteristics used in scram jet engines used in 2.5 mach wind tunnel. It was operating under pulsed mode delivering up to 100 joules per pulse. [19]

Alan Hynes Castgna Walter Carr of Dow Corning Plasma Solutions introduce new coatings approach in which atmospheric plasma technology is combined with precursor delivery system named as Atmospheric Liquid Deposition. Patented APPLD enables deposition of plasma i.e. coating on a wider surface up to 1.6m width in true reel to reel conditions at industrial line speed up to 30m/min. [6]

2.1.1 Sputtering

One of the applications of Microwave Generated Plasma is that of sputtering. Sputtering or sputter deposition is a method through which thin films of material are deposited from a ‘target’ onto a surface called the ‘substrate’. Sputtering is done by means of using gaseous plasma. Plasma also known as the fourth state of matter, and is a condition where all the particles exist in a balanced state at the same time, such as atoms, ions and electrons. Once the gaseous plasma is created, the ions are accelerated into the target, which is then eroded by the incoming transfer of energy. These particles will keep travelling in a straight line, unless something such as a substrate comes into their path of travel, which will result in the substrate being coated. It must also be noted that while the plasma is losing energy to its surrounding, a source of energy is required for upkeep [18]. There are a number of ways to do this such as bringing a live electrode into the environment by a vacuum feed through or by introducing a gas into a pre-pumped vacuum chamber and allowing the pressure levels to reach a certain point. This specific type of sputtering is also known as High Target Utilization Sputtering [20]

What happens in sputtering is that the target material and substrate both are placed in a vacuum chamber, and a voltage is applied due to which the target becomes the cathode and the substrate the anode. A sputtering gas such as Argon is ionized to create plasma and the gas then hits the target and sputters the material, which is supposed to be deposited. The plasma is likely to die if there are not sufficient collisions, which is why every electron has to individually generate sufficient secondary emission. As a result, the pressure also has to be sufficient, but not too high.

There are a number of things that can happen if an ion is to bombard a surface, but for sputtering to occur, the ion beam energy should be between 10 and 3 KeVs. The main principle that is involved when ions sputter atoms is that of energy and momentum being conserved. The collisions that occur as a result of sputtering are said to be elastic since the energy required are higher than lattice or vibrational energies. During the process, there are some parameters such as voltages and temperatures that need to be taken into account. [20]

2.1.2 Decontamination of Chemical and Biological Warfare Agents

The Bacillus anthracis assaults of 2001 have expanded stresses that "weapons review" natural operators can be acquired or created and spread by psychological oppressors or fear monger gatherings. These occasions prompted the acknowledgment of the issues encompassing the ponder arrival of organic fighting operators (BWA) into sharp focus. BWA comprise of various infections, for example, Ebola, yellow fever, extreme intense respiratory disorder (SARS), smallpox, spore forming microorganisms (e.g., anthrax), and vegetative microbes. Because of the exceedingly lethal nature of aspiratory Bacillus anthraces (80%–90%), the simplicity of generation and capacity of the spores of Bacillus and their survival in the earth after bioattack, this creature (Bacillus anthraces) has turned into the essential bacterial specialist in biowarfare and bioterrorism. To counter the risk of fear monger assaults, a successful disinfecting guard is required to limit the outcomes of natural assaults.

A perfect disinfecting innovation that is able to do specifically and adequately annihilating BWA, likes to be all dry, effectively transported, quick working, no mass stockpiling prerequisite, safe to faculty, and latent to delicate gear. Subsequently, elective cleaning strategies are being produced. These incorporate the utilization of ionizing and non-ionizing radiations, warm vitality, and responsive gasses, for example, those created by plasmas.

Plasma can viably change over electromagnetic vitality into warm vitality; for example, it has been exhibited that high temperature microwave plasma torch can burnout sewage muck powders and break down toluene gas going through the torch. Besides, plasma or gas in an exceptionally invigorated state, containing energized ions and particles, ionized gasses, radicals, and free electrons, is profoundly receptive. It can wreck pretty much a wide range of natural contaminants by methods for a non-thermal technique. The non-thermal devastation instrument essentially includes the separation of sub-atomic oxygen prompting the arrangement of very oxidizing species or responsive species, for example, nuclear oxygen, sub-atomic singlet oxygen and ozone. These receptive oxygen species (ROS) respond with nucleic acids, lipids, proteins, and sugars. The oxidation of lipids, lessening sugars and amino acids prompts the development of carbonyls and carbonyl adducts, for example, 4-hydroxy-2-nonenal (HNE). Notwithstanding shaping carbonyl gatherings, ROS are in charge of de-amidation, racemization, and isomerization of protein deposits. These substance alterations result in protein cleavage, accumulation, and loss of reactant and auxiliary capacity by misshaping optional and tertiary protein structures. These irreversibly oxidatively adjusted proteins can't be repaired. This event is known as protein degradation. Through these concoction responses most contaminants are changed over by ROS to carbon dioxide and water.

The investigation of the microwave plasma torch for cleaning of compound and organic fighting specialists is separated into two sections; the reenacted try for wellbeing utilizing toluene, sewage ooze power and residue released from a diesel motor and the sterilization of phosgene (COCl2) as a real operator. The disposal examinations of any concoction and organic fighting operators are practically inconceivable in a common research facility inferable from security issues. In this way, stimulant is utilized.

The recreated trial framework for disposal of CBW operators comprises of three microwave plasma torches. The plasma torches are associated in arrangement so that the gas stream to be sanitized enters the following plasma torch instantly subsequent to leaving the past torch, in this way adequately expanding the required habitation time. Each microwave plasma torch is associated with tube shaped tubes made of metal or stainless steel. Each whirl gas is infused through a metal pipeline, entering the release tubes sideways, making vortices inside the release tubes and balancing out the torch flares. The blower fan connected to the primary plasma torch sucks up air and toluene gasses from the toluene vaporization gadget and moves the contaminants into the plasma torches. The tube shaped tube was warmed to keep toluene vapors from gathering on the internal mass of the tube, between the blower fan and the main torch. The blower fan unit may act like a vacuum cleaner, notwithstanding swiping surfaces and gathering contaminants settled on surfaces. Bolts show the stream course of gas stream. Igniters made of tungsten turn on the plasma torches. The three plasma torches in this test are utilized for toluene gas separation, where 1 kW microwave torches refine 1000 lpm of sullied air. In spite of the fact that the plasma temperature at the focal point of the flares is high (around 5500 °C), 3 kW of microwave power is utilized to warm the wind current of 1000 lpm. Along these lines, the general air temperature at the exit is around 100 °C or less, which does not cause any trouble in inspecting the air in the cushion load and does not cause any unsafe impacts on the human body on account of brisk blending of the hot gas with the cool surrounding air.

2.1.3 Atomic Spectroscopy

Microwave-Induced Plasmas (MIP) has indicated significant potential as spectro chemical sources in analytical science. As an excitation source, the MIP can energize atomic and ionic species with high effectiveness [l-4]. The subsequent emanation spectra are typically straightforward, comprising for the most part of reverberation moves of nonpartisan species superimposed on a moderately feeble continuum foundation. Likewise, the power and stream rate prerequisites for stable plasma operation are moderately low, and microwave generators are promptly accessible and more affordable than are radio-recurrence generators of the kind utilized for inductively coupled plasmas. [3]

2.1.4 Production of carbon nano tubes

Analysis of the many investigations of carbon nano tube arrangement in high temperature instruments obviously demonstrates that the key prerequisites of nanotube development are a nuclear carbon source and a wellspring of nanometal particles. In this specific situation, the microwave plasma-burn creation of CNTs at climatic weight is examined in this area. CNTs were blended by all the while sustaining acetylene (carbon source) and iron pentacarbonyl (wellspring of metal impetus particles) through a twirl settled plasma flame. Besides, so as to enhance the yield of CNTs, a high temperature heater was utilized. As the heater temperature increments from 700^{o}C to 1000^{o}C, the development rate and the normal distance across increment. [4]

The carbon nanotubes are becoming inside the quartz tube, which was peeled off utilizing a brush keeping in mind the end goal to gather the CNTs.

2.1.5 Nano powder synthesis of various materials

As said prior, the microwave plasma burn gives an exceptionally irregular and receptive synthetic condition in which a few plasma–molecular responses happen. In this unique situation, different oxide and nitride mixes were set up by the microwave plasma burn. In this area, exploratory outcomes for amalgamation of TiO2 and TiN are introduced. In any case, a high temperature heater was not utilized as a part of the planning of TiO2 and TiN. A beginning material is titanium tetrachloride (TiCl4). O2 for TiO2 and N2 for TiN as twirl gasses were infused into the microwave plasma burn. A blend of H2 gas and gas-stage TiCl4 raised by 0.1 lpm argon gas was pivotally brought into the microwave plasma burn fire balanced out by the twirl gas. [5]

Every one of the specimens were taken from the internal mass of the quartz tube after operation. As H2 stream rate increments from 0.03 to 0.5 lpm, the portion of rutile stage in TiO2 increments from 56% to 64.8% inferable from diminishment in oxygen-rich particles. The weight part of anatase and rutile in the specimens was computed by utilizing the notable recipe fA = [1 + 1.26 (IR/IA)]−1, where fA is the division of anatase in the blend and IR and IA are the forces of reflection (110) of rutile and reflection (101) of anatase, separately. Likewise, as the H2 stream rate increments from 0.03 to 0.3 lpm, the half-power breadths of the (200) reflections increment, which suggests littler mean precious stone size of the mass TiN items. In such manner, precious stone sizes were figured from XRD line-widening by utilizing the Scherrer equation with a shape variable of 0.9. It is resolved that the gem sizes at H2 stream rates of 0.03 lpm and 0.3 lpm are 15.5 nm and 11.6 nm, individually.

2.1.6 Nitriding

Nitriding is a heat treatment process that diffuses nitrogen into the surface of a metal to make a hardened surface. These procedures are most ordinarily utilized on low-carbon, low-composite steels. The technique utilized for our process is Plasma Nitridation.

In plasma nitriding, the reactivity of the nitriding media is not because of the temperature but rather to the gas ionized state. In this method extraordinary electric fields are utilized to create ionized particles of the gas around the surface to be nitrided. Such exceptionally dynamic gas with ionized particles is called plasma, naming the strategy. The gas utilized for plasma nitriding is typically immaculate nitrogen, since no unconstrained deterioration is required. There are hot plasmas epitomized by plasma planes utilized for metal cutting, welding, cladding or showering. There are additionally cool plasmas, at low weight administrations.

Since nitrogen particles are made accessible by ionization, plasma nitriding proficiency does not rely on upon the temperature. Plasma nitriding can along these lines be performed in a wide temperature go, from 260 °C to more than 600 °C. For case, at direct temperatures (like 420 °C), stainless steels can be nitrided without the arrangement of chromium nitride precipitates and consequently keeping up their erosion resistance properties. [4]

A gleam release with a high ionization level (plasma) is created around the parts. At first glance region that is specifically charged by the particles, nitrogen-rich nitrides are shaped and decay, discharging dynamic nitrogen into the surface. Because of this component protecting is effectively done by covering the concerning regions with a metal cover. Plasma nitriding permits adjustment of the surface as per the coveted properties. Tailor made layers and hardness profiles can be accomplished by adjusting the gas blend: from a compound without layer surface with low nitrogen substance up to 20 microns thick, to a compound layer with high nitrogen substance and an extra of carbonic gas (plasma nitro-carburation). The wide appropriate temperature goes empowers a huge number of utilizations, past the potential outcomes of gas or salt shower forms.

Other applications discussed in literature are:

- Material processing:

  Deposition, cutting, cleaning surface modification, etching and welding are discussed in [7]. It includes amorphous silicon [8] and similar to diamond coating [9].

- Ion production:

  For example for bombarding ions produced in plasma according to the requirement [14]

- Waste Treatment:

  Including detoxification of detrimental gases [13]

- Light Source:

  Fusion lightening in solar lamps is usually induced discharge of sulpher operated under 2.45 GHz. [16]

- Excitation source:

  Usually used in Analytical chemistry [17, 18]

2.2 Microwave Parts and some useful terms

2.2.1 Microwave Transmission Lines

Wires are used to connect components like transistors and capacitors that work at relatively lower frequency range than microwaves. The electrical signal is carried from one part to the other by the electron flow. Microwaves however cannot be transported through wires. The microwaves travel with their wave-like characteristics from one part to another. Even if the parts are only a fraction of an inch apart, the microwaves travel as waves and the power for the microwaves must be provided for each part. The guiding device is called a transmission line. Although there are a lot of microwave transmission lines, there exist only three basic types of transmission lines: waveguides, coaxial cable and micro-strips [1].

2.2.1.1 Waveguide

A waveguide can be referred to a hollow metal pipe. Usually the waveguide has a rectangular cross section, but can also have a circular or an oval cross section as well. The waveguides used to guide the microwaves in the same aspect that a water pipe guides water. The microwaves travel as waves from one component to the next through the waveguide. Their advantages include high power handling capability and also their very low attenuation but limitations are the large size and limited bandwidth.

2.2.1.2 Coaxial Cable

These consist of an outer conductor encapsulating an inner conductor. The word coaxial means the inner conductor and outer conductor share the same axis. To achieve this alignment, there must be some sort of insulating material present to support the inner conductor. In the space between the inner and outer conductors an insulator is inserted, and the microwaves are conducted through the insulator. In contrast, the inside of waveguide, where microwaves travel, is empty because the waveguide walls are self-supportive. Their advantages are large bandwidth available and small size but disadvantages include: high attenuation and low power [1].

2.2.1.3 Micro strip

“To solve the problem of making many connections in a complex microwave circuit, micro-strip transmission lines are preferred. Micro-strip consists of a conductor, an insulator, and a flat plate called the ground plane. It can be compared to a coaxial cable that’s been cut and laid out flat so that the ground plane on the bottom behaves like the outer conductor. The strip on the top is like the inner conductor, and the space in between is the insulator. Most of the microwave is carried inside the insulation.

The advantages of micro-strips include: several microwave transmission lines can be easily connected together. The disadvantages are high attenuation and low power”[1]

2.2.2 Waveguide terminations

A waveguide without causing reflection, the termination impedance must be equal to the incident wave impedance. Consider a thin sheet of resistive material that closes the end of the waveguide. Between the top and bottom of the waveguide, the resistive material has a length of resistance path and AB Cross section, where "t" is the thickness of the sheet; "A" and "B" are the dimensions of the waveguide. Sheet strength up and down only should be considered as the direction of the current is perpendicular to the H field in the sheet. The transmitted wave can be eliminated by extending the waveguide of a quarter of the wavelength over the blade and ending short-term end. The extended section and gives infinite short impedance so no waves can be transmitted through it. Then, the sheet resistivity is equal to the impedance of the incoming wave. This ensures that the sheet absorbs the incident wave as if proceeding for an infinitely long way. So the reflected wave is completely minimized. The sheet resistivity and a short fourth wave stroke to isolate the external impedance load. Two important principles are discussed: The arrangement is not entirely satisfactory in practice mainly because it uses the use of a short stretch of adjustable large which is quite difficult to adjust. Adjusting the strip in the maximum electric field area reduces microwave reflections to a negligible level. A carbon coated ribbon or using a glass cover strip with a thin metal film, which in turn has a slim dielectric coating for protection is also possible. The surface resistivity of about 500 ohms per square is typical in these cases.[20]

2.2.3 Skin depth

If walls of waveguide are made up of perfect conductors then there would be no penetration of the microwaves into the walls. However, the walls are not perfect so the microwaves penetrate slightly into the walls of the waveguide. The depth to which they extend is called skin depth. The relation between frequency and skin depth is given as:

$$\text{Skin Depth} = \delta_s = \sqrt{\frac{2\rho}{2\pi f \mu_0 \mu_R}}$$

where :

ρ = bulk resitivity (ohm − meters)

f = frequency (Hertz)

μ_0 = permeability constant (Henries / meter) $= 4\pi \times 10^{-7}$

μ_r = relative permeability (usually ~ 1)

We conclude that for higher frequencies skin depth will be less. For WR 340 waveguide at 2.45 GHz skin depth will be approximately equal to 0.2mm [1].

2.2.4 Cutoff Frequencies

Waveguides can support many modes of transmission. The usual mode of transmission in rectangular waveguide is called TE10. The lower cutoff wavelength and frequency is simply:

$\lambda_{lowercutoff} = 2 \text{ x } a$

$F_{lowercutoff} = \frac{c}{ax2}$ (GHz)

a= dimension of the broad wall

c=speed of light=29.979 cm/ns

The upper cutoff frequency is exactly one octave above the lower [21].

2.2.5 Waveguide operating band

The accepted limits of operation for rectangular waveguides are between 125% and 189% of the lower cutoff frequency. For WR 90 waveguide the lower cutoff frequency is 6.557GHz and the accepted band of operation is 8.2 to 12.4 GHz. At the lower cutoff frequency, the guide simply stops working [21].

2.2.6 Guide wavelength

Defined as the distance between two equal phase planes along the waveguide. The guide wavelength is a function of operating wavelength and the lower cutoff wavelength and is always longer than the wavelength would be in free space. Here's the equation for guide wavelength [20]:

$$\lambda_{guide} = \frac{\lambda_{freespace}}{\sqrt{1 - \left(\frac{\lambda_{freespace}}{\lambda_{cuttoff}}\right)^2}}$$

$$\lambda_{guide} = \frac{c}{f} \times \frac{1}{\sqrt{1 - \left(\frac{c}{2a \cdot f}\right)^2}}$$

Guide wavelength is used when designing distributed structures in a waveguide. For example, excitation of a particular mode in a waveguide, the distance of antenna from the short circuit plate would be ¼ of the guide impedance [21].

2.2.7 Characteristic impedance:

Characteristic impedance of a transmission line is the ratio of the electric field to the magnetic field of the microwaves. It depends not only on the height to width ratio but also on the guide wavelength as well, and thus it varies with the frequency across the band of the waveguide [1].

Chapter 3: Design and Fabrication of Parts

3.1 Fabrication of WR-340 Waveguide

Our frequency of operation in microwave band is 2.45 GHz. At 2.45GHz TE10 mode can be established in two standard rectangular waveguides, WR-340 and WR-284. So we have selected WR-340 waveguide. Inner dimensions of this waveguide are 3.4 x 1.7 inches. We have chosen aluminum for the construction of the waveguide. Thickness of the aluminum sheet was 1mm as the skin depth for TE10 mode was 0.2mm and also to impart additional strength into the structure.

3.2 Fabrication of WR-340 Tapered Waveguide

We have also fabricated WR-340 single tapered waveguide. The purpose of tapering is to concentrate the microwave power in a smaller region, for minimum reflection we have chosen the taper length as the guide wavelength. For double tapered waveguide the length of the taper must be twice of the guide wavelength.

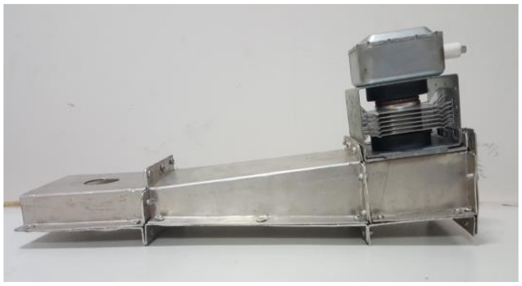

Figure 3.1: Fabricated WR-340 Waveguide

3.3Termination of waveguide

Termination of waveguides at both ends is done by short circuit plates. At the antenna side short circuited plate is placed at one quarter of guide wavelength from the magnetron antenna to establish desired TE10 mode in the waveguide. Also at the load side distance of short circuited plate from nozzle is one quarter of guide wavelength so that standing waves are produced, having maximum amplitude at the tip. To minimize reflected power, position of short circuit plate can also be varied.

3.4 Construction and working

The MPT system requires electrical current in the magnetron and the waveguide. The power of microwave power and the magnetron have the output capacity of 800 W of microwave to 2.45 GHz. The use of this frequency maintains the low cost of MPT, due to the mass production of magnetrons that produce 2.45 GHz for consumer products. During experiments, the MPT operates at 800W forward.

Typically, the MPT system operates with less than 1% of the reflected power. A cavity of 3.5 cm in diameter is a quarter of a wavelength shorter than 4.3 cm from the end of the waveguide. An empty quartz tube sits inside the cavity. You can also use a boron nitride (BN) cylinder. Quartz and BN are both dielectric materials and are nearly transparent at the microwave frequency of 2.45 GHz. However, the hollow cylinder must also be transparent at both visible and ultraviolet wavelengths. The BBN prevents the transmission of these wavelengths, while the quartz transmits all these wavelengths that facilitate the study of the atomic emissions in the plasma. Therefore, a quartz cylinder is used to contain the plasma in these experiments.

Sometimes plasma forms within the waveguide due to debris or roughness within the waveguide. Each rough surface provides a point for the plasma to form. In fact, plasma starting point formation involves the addition of a metal wire in the hollow cylinder. For a quarter of a shorter wavelength from the end of the waveguide, the electric field reaches its maximum value. At1.5kV / cm. Even at this maximum, the field does not reach the value required for ionization. The inclusion of a tungsten W wire in the waveguide, however, focuses the electric field sufficient to decompose the air. Microwave energy is fully compatible with plasma.

3.4.1 Electric Field Concentration

As we have mentioned that inserting Tungsten W, wire into the waveguide ignites the microwave plasma. The W wire serves two vital purposes for starting the plasma. First, the W provides a source of electrons needed for ionizing the air. The E-field accelerates the electrons which then collide with the air molecules leading to ionization. Secondly the W wire concentrates the E-Field. Applying Gauss's theorem to Coulumb's law yields:

$$\boldsymbol{E = Q/4\pi\varepsilon r^2}$$

E=Electric Field

Q=Charge

r= radius of the W wire

ε=vacuum permittivity constant

The above expression shows that the electric field is inversely proportional to the radius of the W wire. Therefore a small diameter wire would cause a larger E-field to concentrate. To ignite the MPT, a 0.25 mm diameter W wire is used. This wire effectively concentrates the E-field to breakdown the Argon gas.

3.5 Coupling of Multiple Plasma Torches:

For few applications we need very high power MPT. This problem can be solved by using a high power magnetron or by coupling multiple plasma torches together. Coupling is done by using a single Quartz channel, passing through many torches to attain very high temperatures in the plasma.

3.6 Procedure for starting the MPT:

1. Open the argon cylinder valve
2. Using the needle valve set the axial gas flow rate to 5 lit/min
3. Turn on the Microwave Oven power supply
4. Set the Microwave Oven power to high that is continuous mod
5. Insert a Tungsten Wire into the Waveguide Cavity until the Plasma forms

Chapter 4: Experiments and Results

4.1TM-10 Mode in Waveguide

As our first prototype of the furnace was developed, we joined the magnetron with the waveguide in such a way that the magnetron gun was parallel with the surface of waveguide. The magnetron was attached with the first section of the waveguide from the back known as TM-10 mode. In this mode, the magnetic field is transverse to transporting medium, which is the waveguide. But the electric field needed to generate the plasma is much less in this mode. Most of the energy is lost as heat. We observed that the tapered section of the waveguide much hotter than the last section, where quartz tube is inserted. This led to poor efficiency and power transmission to the quartz tube and only sparks of plasma were produced.

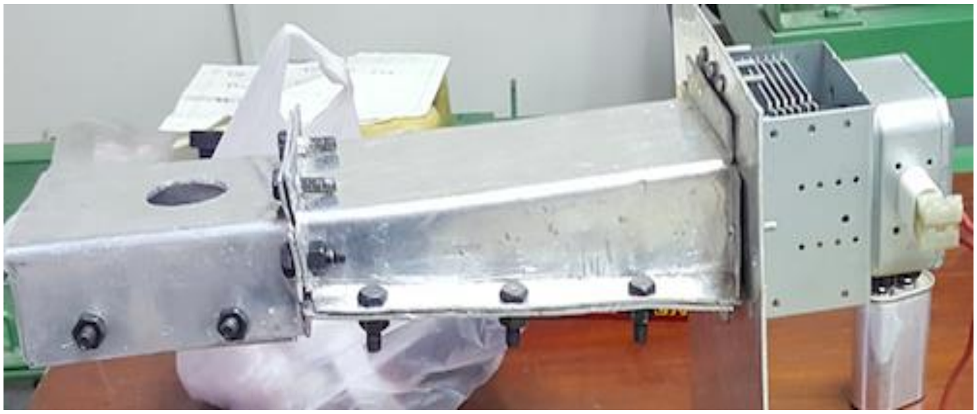

Figure 4.1: TM-10 mode in WR-340 waveguide

4.2 TE-10 Mode in Waveguide

In this mode, the magnetron is inserted perpendicularly through the broad side of waveguide at one quarter of wavelength from the short circuit plate. By doing this we establish the desired TE-10 mode. In this mode instead of a single wave being targeted at quartz tube, multiple waves are concentrated there. As magnetic field and electric field are always perpendicular to each other, they travel altogether as electromagnetic waves. Now the heat loss is reduced and the efficiency of magnetron is improved as most of the energy is transmitted to the quartz tube. Tapered section and all other sections were not heated even after several minutes of operation. Figure on the next shows the magnetron in TE-10 mode.

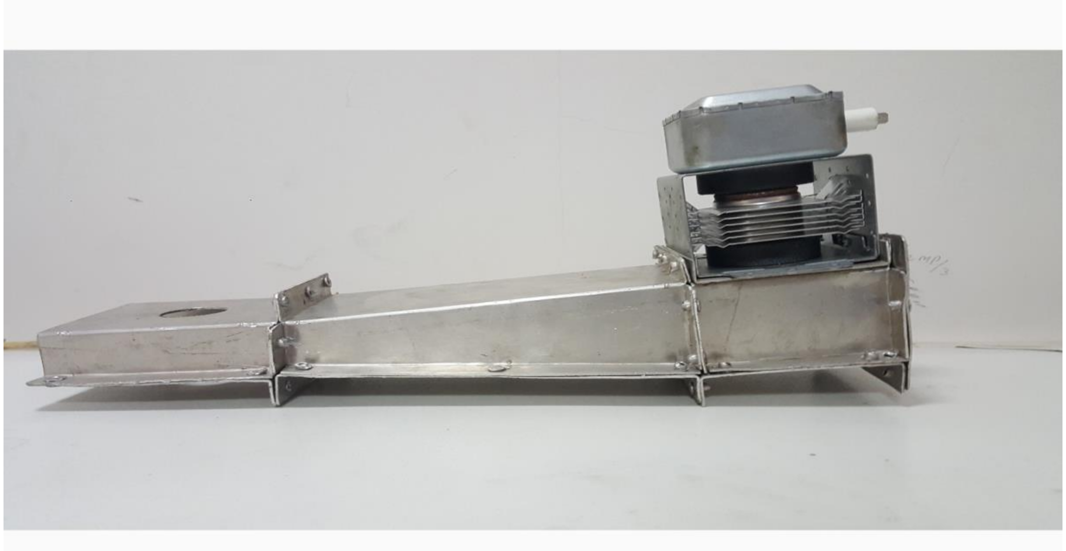

Figure 4.2: TE-10 mode in WR-340 waveguide

The diagram below shows the propagation of waves in both the TE and TM modes.

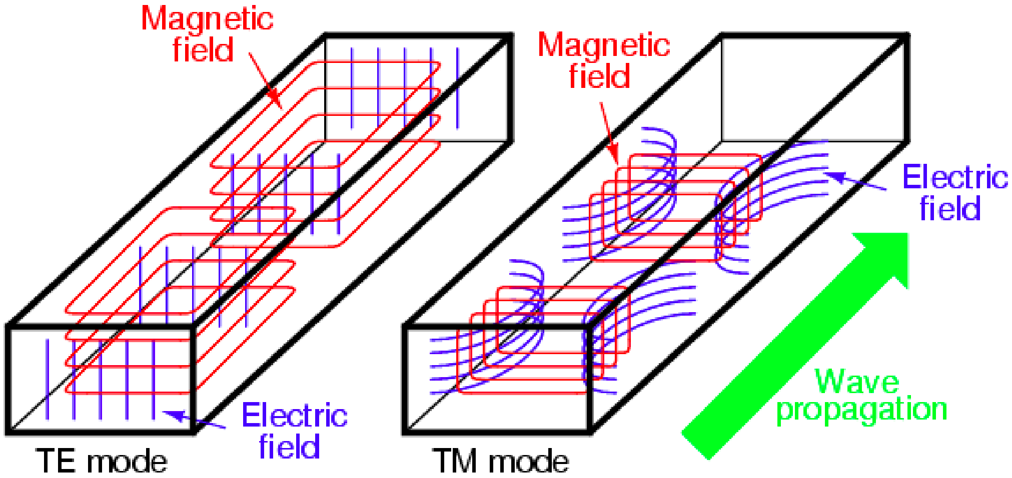

Figure 4.3: Microwaves Propagation in TE-10 and TM-10 modes respectively

4.3 Sustainability

Initially, our experiments with copper resulted in a short term Plasma Torch due to its early melting. A high melting temperature material was required instead. So we opted for Tungsten to be used in our experiments. This increased the time of operation exponentially and we were able to have a sustainable plasma jet.

4.4 Coupling of Multiple Sources

In the beginning the setup was used with a single power source which gives a single heat zone and the effect of heating was observed to be inefficient. This was concluded as the presence of unionized gas in the quartz tube. It was proposed and tested that use of multiple sources in series can help in proper ionization of gases and indirectly an exponential increase in temperature. The sources were coupled in series to avoid any constructive and destructive interference of microwaves which may give uncontrollable and ineffective results respectively. Properly coupled three sources, give very effective completely ionized sustained plasma jet in the presence of tungsten rods.

4.5 Heat treatment

Melting of Copper was achieved within seven seconds using only a single source for the experiment. The sample used was of one millimeter thickness. This experiment proved our setup as having high heating rates and having ability to achieve high temperatures (>1000^{o}C) and hence can be used for Heat treatment applications.

A B

Figure 4.4: Melting of Copper (A), Coupling of Multiple Sources (B)

4.6 Nitriding

Nitridation was performed using all three magnetron sources on an industrial sample of 1020 mild steel with diameter of 1cm. Using all three magnetron sources, Plasma was generated and the sample was placed beneath it. Two experiments were performed for two and six minutes. The results obtained are shown in the table below.

Table 3: Effects of Nitridation time on Hardness of sample

Treatment	**Highest Hardness Value (HRB)**	**Average Hardness Value (HRB)**	**Standard deviation of Hardness**
Original Sample	58	56.6	1.527
Two minutes Nitriding	58 (no effect)	57	1.60
Six minutes Nitriding	64	60.6	3.05

The results show an increase in Hardness value with increase in treatment time. A considerable increase in hardness was observed with treatment of six minutes whereas no significant change was observed with the two minutes treatment.

Due to shortage of time and resources, a detailed experiment could not be performed outlining the depth of the case hardening. These results from our setup may contain anomalies but the setup can be optimized further to cater specifically to nitridation and to achieve even more controlled results.

Conclusion

An efficient Microwave Plasma Torch was designed and developed using standard household microwave oven magnetron sources. Temperatures greater than 1000^{o}C were achieved within seven seconds. Multiple sources were coupled resulting in an increase in flame length and hence temperature. The Optimum flow rate for the generation of Plasma was found to be 5 liters per minute. Change of modes and ignition source also helped us to sustain the plasma for longer. Nitridation and heat treatment applications were also performed using the device. Considering the cost and the flexibility of our device, the MPT can be employed effectively for materials processing, heat treatment and several other applications.

Future Recommendations

1. Integrating minor modifications to the design to achieve Sputtering using the MPT.
2. Further optimization to achieve greater flame length and temperatures.
3. Employing the device to be applicable for multiple materials processing techniques.

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