

**ON THE EFFECT OF ENVIRONMENTAL PRESSURE ON GAS
TUNGSTEN ARC WELDING PROCESS**

by

Gökhan Göktuğ

B.Sc. in Civil Engineering, İstanbul Technical University
İstanbul, 1986

S.M. in Civil Engineering, MIT
Cambridge, 1990

**SUBMITTED TO THE DEPARTMENT OF
OCEAN ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREES**

OF

**OCEAN ENGINEER
and
MASTER OF SCIENCE IN NAVAL ARCHITECTURE AND MARINE ENGINEERING**

**at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June 1994**

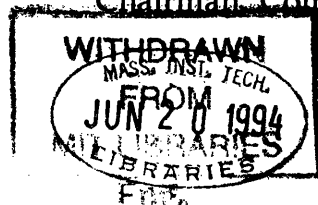
© 1994 Gökhan Göktuğ
All rights reserved

The author hereby grants to MIT
permission to reproduce and to
distribute publicly paper and
electronic copies of this thesis
document in whole or in part.

Signature of Author _____
Department of Ocean Engineering
June, 1994

Certified by _____
Koichi Masubuchi
Thesis Supervisor

Accepted by _____
A. Douglas Carmicheal
Chairman, Committee for Graduate Studies



ON THE EFFECT OF ENVIRONMENTAL PRESSURE ON GAS TUNGSTEN ARC WELDING PROCESS

by

Gökhan Göktuğ

Submitted to the Department of Ocean Engineering in June, 1994 in partial fulfillment of the requirements for the degrees of Ocean Engineer and Master of Science in Naval Architecture and Marine Engineering.

Abstract

With the increasing need for methods that will assist the construction and repair of space structures, gas tungsten arc welding (GTAW) is considered to be a possible process. This thesis reviews the experimental work performed in Welding Systems Laboratory (WSL) at MIT and Takamatsu National College of Technology (TNCI), Japan. To study the basic relation between pressure and the arc behaviour of GTAW, a pressure vessel installed at WSL was used to simulate high pressure (hyperbaric) and low pressure (vacuum) conditions. The arc shape of the GTAW was monitored by a 35 mm camera installed outside the vessel as welding was conducted at different levels of pressure. Another series of experiments were carried out under the vacuum condition at THCI, at a later date. A hollow tungsten electrode was designed to use in GTAW on stainless steel (SUS304) specimens. The effect of the flow quantity of inert gas and the height of electrode on penetration, bead width, arc voltage, and transient arc discharge were studied. It was determined that a small amount of inert gas flow fed through the hollow electrode, made it possible to initiate and maintain a stable arc even under very low environmental pressure.

Thesis Supervisor: Koichi Masubuchi
Title: Kawasaki Professor of Ocean Engineering and
Materials Science

Acknowledgements

I would like to express my gratitude to my advisor Prof. Koichi Masubuchi, for his invaluable guidance and financial and emotional support when I needed it the most.

Special thanks to Dr. Y. Suita, Mr. Koga and Dr. A. Hirose for their involvement and help throughout this thesis. I am also grateful to Mr. S. Koga for his friendship and help in my work. Without him, I would have to work twice as much to finish. Thanks to Mr. Hijigate, Mr. Umekuni, Mr. Ichikawa, Mr. Meada, Mr. Kaito, Mr. Mukai, and Mr. Tanizawa for their friendship and the fun we shared.

Deep thanks to Ms. Ipek Ilter for proof-reading the text, helping me with some of the drawings and text.

Finally, I would like to thank to my friends here at MIT, İpekus, Hıbız, Ufaklık, Gupta, Dayucuğum, my dear Hispanik Cillop and Çınoş, for sticking with me in good and bad times.

Table of Contents

Abstract.....	2
Acknowledgements.....	3
Table of Contents	4
List of Figures.....	6
List of Tables.....	8
1. Introduction.....	9
1.1 Objectives and Scopes	10
1.2 Organization and Outline of theThesis	11
1.3 Review of Previous Work.....	11
2. On Different Joining Processes.....	13
2.1 Advanced Welding Processes Pertinent to Space Applications.....	16
2.1.1 Electron Beam Welding	17
2.1.2 Laser Beam Welding.....	21
3. Gas Tungsten Arc Welding Process.....	25
3.1 Introduction.....	25
3.2 Principals of Process	26
3.2.1 Types of Welding Torches	28
3.2.1.1 Gas Cooled Torches	28
3.2.1.2 Water-Cooled Torches.....	28
3.2.1.3 Parts of Welding Torches.....	28
3.2.2 Electrodes.....	29
3.2.2.1 Electrode Classification.....	29
3.2.2.2 Electrode Sizes	30

3.2.2.3 Electrode Tip Configurations	30
3.2.2.4 Electrode Contamination.....	31
3.2.3 Power Supply	32
3.2.3.1 Direct Current.....	32
3.2.3.1.1 Pulsed Dc Welding	34
3.2.3.2 Alternating Current	35
3.2.4 Shielding gases	36
3.2.4.1 Argon.....	37
3.2.4.2 Characteristics	38
3.2.4.3 Recommended Gas Flow Rates	38
4. Experimental Study	40
4.1 Introduction.....	40
4.2 Study at MIT.....	40
4.2.1 The Pressure Vessel.....	42
4.2.2 High Pressure Welding Process.....	44
4.2.3 Low Pressure Welding Process	51
4.2.4 Discussion and Results.....	55
4.3 Study at Takamatsu Institute of Technology, Japan.....	57
4.3.1 Experimental Apparatus	57
4.3.1.1 Hollow Tungsten Electrode.....	58
4.3.2 Discussion and Results.....	60
4.3.2.1 Arc Phenomenon in Vacuum by GHTA.....	61
4.3.2.2 Flow Quantity of Argon	63
4.3.2.3 Melting of the Base Metal	66
5. Conclusion	72
6. References.....	74

List of Figures

Figure 2.1 Schematic illustration of electron gun.....	18
Figure 2.2 Schematic illustration of electron beam welding process.....	18
Figure 2.3 Comparison of cross-sectional shape of penetration between arc welding and electron beam welding.....	19
Figure 2.4 Schematic illustration of CO ₂ laser resonator and processing equipment.....	22
Figure 3.1 Gas tungsten arc welding equipment.....	26
Figure 3.2 Gas tungsten arc welding operation and torch assembly.....	27
Figure 3.3 The variation of arc shape and fusion zone at different tip geometries of electrode[3].....	31
Figure 3.4 Characteristic of current types for GTAW [3].....	33
Figure 3.5 Waveform of pulsed direct current [3].....	34
Figure 3.6 Characteristic of variable square wave AC[3].....	36
Figure 3.7 The relationship of voltage-current with argon and helium shileding[3].....	37
Figure 4.1 The pressure vessel.....	42
Figure 4.2 Inside the pressure vessel.....	43
Figure 4.3 Shape of arc under 0.1 MPa pressure.....	45
Figure 4.4 Shape of arc under 0.17 MPa pressure.....	46
Figure 4.5 Shape of arc under 0.27 MPa pressure.....	47
Figure 4.6 Shape of the arc under 0.38 MPa pressure.....	48
Figure 4.7 Shape of the arc under 0.48 MPa pressure.....	49
Figure 4.8 Effect of the high pressure on arc length.....	50
Figure 4.9 Shape of the arc under 0.013 MPa pressure.....	52

Figure 4.10	Shape of the arc under 0.0067 MPa pressure.....	53
Figure 4.11	Shape of the arc under 0.013 MPa pressure.....	54
Figure 4.12	Effect of low pressure on arc length.....	55
Figure 4.13	Experimental apparatus.....	58
Figure 4.14	Hollow tungsten electrode and welding torch.....	59
Figure 4.15	Arc discharge in a low pressure condition.....	62
Figure 4.16	Effect of the flow quantity of argon on arc voltage.....	63
Figure 4.17	Effect of the flow quantity of argon on period of transient arc discharge.....	64
Figure 4.18	Effect of the height of the electrode on arc voltage.....	65
Figure 4.19	Effect of the flow rate of argon on bead shape and penetration.....	67
Figure 4.20	Effect of the flow quantity of argon on penetration depth.....	68
Figure 4.21	Effect of the flow quantity of argon on bead width.....	69
Figure 4.22	Effect of the height of electrode on bead width and penetration depth.....	70

List of Tables

Table 4.1 Welding condition for the high pressure experiment.....44
Table 4.2 Welding conditions for the vacuum experiment51
Table 4.3 Welding conditions for gas hollow tungsten arc welding60

Chapter 1

1. Introduction

In the last decade, space structures became increasingly popular with the development of technology and the increasingly available information about the previously unknown. The welding process is vital in joining metals, construction, and manufacture which has a very large application field including, car industry, ship yards, aircraft manufacturers, etc. Its importance is due to the inherent advantages of welding over mechanical fastening and bonding techniques.

Almost any reliable high accuracy system requires welding as a joining process. Moreover, welding constitutes the main part of repair and maintenance work on existing structures. Man has performed welding process in nuclear power plants, underwater in oceans, in pipe line constructions under very severe environmental conditions. Now, it is time for scientists to extend their knowledge and experience and be able to implement welding in space to repair, construct and maintain future space stations and space vehicles. There is no doubt that NASA's space exploration program in the next years, including a permanently manned space station, a lunar base and a manned mission to Mars, will extensively benefit from on-orbit welding endowment.

As an alternatives to each other in terrestrial welding conditions, Gas Tungsten Arc Welding (GTAW) and Gas Hollow Tungsten Arc Welding (GHTAW) processes have been selected. When GTAW and GHTAW are compared with their opponent, Electron Beam Welding (EBW), they confirm to have superior potential in manual operations, adaptability to joint mismatch problems and less harmful to the welder in manual operation. Furthermore, GTAW can be easily operated by a rechargeable and relatively small battery-pack.

1.1 Objectives and Scopes

The purpose of this study is to understand the behavior of the arc characteristic of GTAW under different environmental conditions other than Earth and to develop a system of GTAW which may result in a stable arc, required weld quality and penetration. One of the conditions is vacuum, while the others are weightlessness; extreme temperatures and ionizing; and hard ultraviolet radiation, all of which scientists define space with. In this work, the application of GTAW in high pressure (dry underwater condition) and low pressure environment (vacuum) were considered. Based on the results of the work carried out at Welding Systems Laboratory of MIT, a hollow tungsten electrode, which is a modified tungsten electrode, was introduced and a series of experiments were conducted at Takamatsu National College of Technology, Japan.

1.2 Organization and Outline of the Thesis

In Chapter 2, a review of joining processes is given. Alternative advanced joining methods namely Electron Beam Welding and Laser Beam Welding, are presented with the basic and application fields[12].

In Chapter 3, GTAW is reviewed generally. The components and application procedure are outlined. The parts used in the GTAW are schematically shown.

In Chapter 4, the experiments are discussed. The details of the experiments performed both at WSL at MIT and TNCI, Japan are given. In order to contribute to a clearer understanding, the results are graphically presented. At the end of the chapter, a discussion of the experiments is summarized.

In Chapter 5, the results of the discussion are given.

1.3 Review of Previous Work

Researchers under the direction Prof. Koichi Masubuchi have conducted systematic research on under water welding at MIT since the beginning of 1968. On this subject, Prof. K. Masubuchi has supervised eighteen theses for B.S., M.S, Engineer's and PhD degrees¹.

¹ These theses are available at Barker Engineering Library of MIT

Underwater welding as the name implies, is 'welding produced underwater'. Difficulties associated with the underwater welding have been experienced since early 1900's. Underwater welds are plagued by a rapid quenching effect from surrounding water and a susceptibility to hydrogen embrittlement. It is reported that, in the application of gas-metal-arc welding, controlling speed of travel, amperage and arc voltage are the primary problems[15].

Tamir[31] has carried out a tremendous amount of work on space welding application of GTAW and introduced the Hollow Tungsten Electrode for the first time. At Paton-Institute of Welding, Kiev, Ukraine, a handheld portable electron beam welding machine was designed and it was actually used in space by a Russian astronaut. The result was very successful. However, the astronaut had some burns and injured from the machine[23].

In Japan, many researchers have worked on the effect of the pressure on the arc. Matsunawa and Nishiguchi [22] have found that arc voltage is very sensitive to pressure changes. These results coincide with ours as well. Comments similar to ours were made by Yamamoto and Shimida[29].

Chapter 2

2. On Different Joining Processes

Today, more than 50 different processes used in various applications, are commercially available to join metals. Among those joining methods, the term "welding" is used for processes in which thermal energy is used to produce coalescence. When heated, the metal melts, increases its ability of plastic flow, or is activated for self- and mutual-diffusions. There are several ways of heating the joint and welding processes can be classified in terms of the method of heating employed.

- (1) *Gas flame* is the most traditional heat source for welding. Before electricity became widely available, gas flame was used to heat up the metals to be joined. Oxyacetylene flame welding process, which uses gas torch and bare welding wire, is the representative process to this heat source.
- (2) *Arc*, which is a kind of electric discharge, is now the most commonly used heat source for welding. After the development of metal arc, arc welding rapidly replaced oxyacetylene flame welding. The most important characteristic of the arc is its high current up to several hundreds of amperes. By this high energy, the arc can heat up most kinds of metals to their melting point quickly. To maintain the arc steadily and shield it from the atmosphere, various kinds of processes

such as shielded metal arc welding, gas shielded arc welding, plasma arc welding, and submerged arc welding have been developed. These welding processes are widely used in almost all types of manufacturing industries.

- (3) *Electric Resistance Heating* is also a popular heat source for welding. Metals to be welded are heated by resistance with the passage of an electric current through the metal. In most cases, pressure is applied to a joint after the joining area is melted by the heat. The representative process by this heat source is spot welding. It is exclusively used in the manufacture of the body structures of automobiles and trains.
- (4) *Electron beam* became available as a heat source for welding about 40 years ago. By the development of an electron gun which has an electron accelerator and a focusing system of the electron beam, this new heat source of an extremely high energy density has become available to welding. Electron beam welding is done in vacuum atmosphere in most cases, and is mainly used for welding precise machinery components with electron beam welding, welding deformation is limited to a quite small area.
- (5) *Laser light* is generated by a laser resonator. In the resonator, a laser source is energized by electric power, and laser light is generated when the energy of laser source goes down to its original level. CO₂ gas and artificial YAG crystal are commonly used as laser sources. A well focused laser beam of 10 kW can penetrate through a steel plate of half an inch in a moment, and welding process using this quite attractive

heat source has unlimited possibilities to various kinds of manufacture.

(6) *Heating by mechanical friction* is a simple and efficient method of welding materials. Today, friction welding process is mainly applied to components of cylindrical shape, including shafts and tubes. Here, surfaces of the work pieces to be joined are placed touching each other, then one of the work pieces rotates and both pieces are heated by friction. Finally, pressure is applied to the joining surface and coalescence is completed. In this process, the metal in the joined area does not melt and coalescence is achieved by a plastic flow of the material. Therefore, this friction welding is also called solid-phase welding.

(7) *Heating from atmosphere using a furnace* is mainly applied to diffusion bonding and blazing. In diffusion bonding, work pieces that mechanically touch each other are set in a furnace which provides a vacuum atmosphere. The pieces are then heated and a compression is applied to the touched surface to be joined. Coalescence is produced by the mutual diffusion of atoms in work pieces through the touched surfaces of works. Here, heating is needed to increase the diffusion speed of atoms, and to promote a sufficient mechanical touch between works. In blazing process, an additional material is inserted between work pieces to be joined. The inserted material is melted by furnace heating, and work pieces are bridged by the inserted material. Coalescence is produced when the inserted material is solidified during cooling.

- (8) *Ultrasonic Vibration* is a unique source of energy. By applying ultrasonic vibration, heat is generated at the boundary surface of materials. The ultrasonic welding process is applied to relatively small components of plastics and polymers.

- (9) *Chemical reaction* also can be a heat source for welding, although it is not so popular. For welding rails, for example, an exothermic reaction between aluminum and iron oxide is used. This process is termed thermit welding.

2.1 Advanced Welding Processes Pertinent to Space Applications

In the late 1950's, a couple of brand-new welding processes using completely different heat sources from the conventional electric arc were introduced. These sources employed power beams including electron and laser beams. Because of their extraordinary energy density, those heat sources were first used for welding special works such as the components of nuclear reactors and some precise machinery parts. However, as their output power increased by the recent developments of highly efficient beam generators, those processes also started to be used in steel fabrication industries. Although those processes have not been widely used in shipbuilding yet, it is useful to have a brief overview about them, considering the possibility of their future use. In this section, outlines of these advanced welding methods will be mentioned.

2.1.1 Electron Beam Welding

Electron beam welding (EBW) process was introduced for the first time by Stohr, a French scientist, for joining metals that have a high melting point and are used for the core components of a nuclear reactor. The feature that distinguishes this process from other welding methods is its heat source, highly focused electron beam generated by an electron gun. The process is fully automatic, and usually welding is performed in the vacuum atmosphere to prevent the scattering of electrons due to collisions to gas molecules.

Figure 2.1 shows the schematic structure of a typical electron gun. Electrons are extracted from a heated filament, and accelerated by a high voltage between the filament and an anode electrode. The accelerating voltage is usually up to 150 kilovolts, and the velocity of electron at the anode electrode reaches to near the speed of light. The number of electrons, called the beam current, is variable from zero to up to 1 ampere by adjusting a bias voltage between the filament and a grid cup. The maximum power output of electron guns varies from 3 to 100 kilowatts according to the usage of each gun. The electron beam is finally focused by a magnetic field generated by a focusing coil equipped near the outlet. This focusing system makes EBW a distinctive welding process.

Figure 2.2 shows the schematic illustration of EBW process. When electrons reach the surface of the work, kinetic energy of the electrons is transformed to heat.

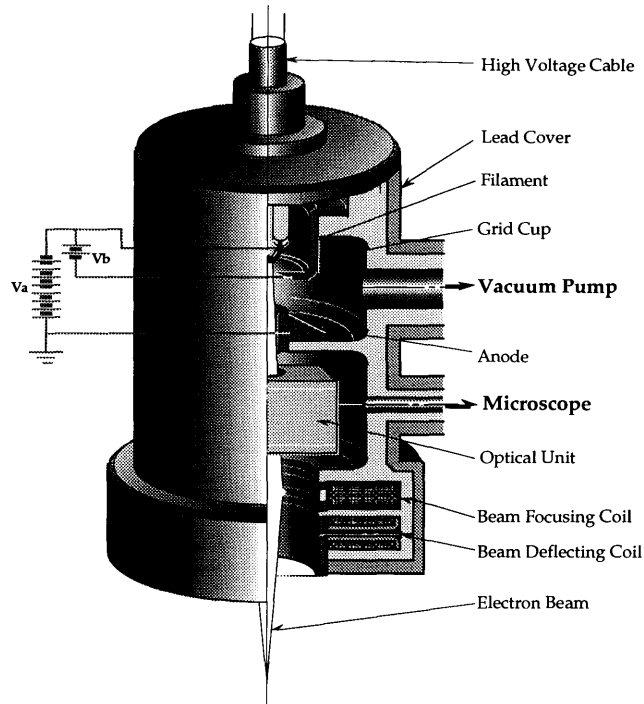


Figure 2.1 Schematic illustration of electron gun

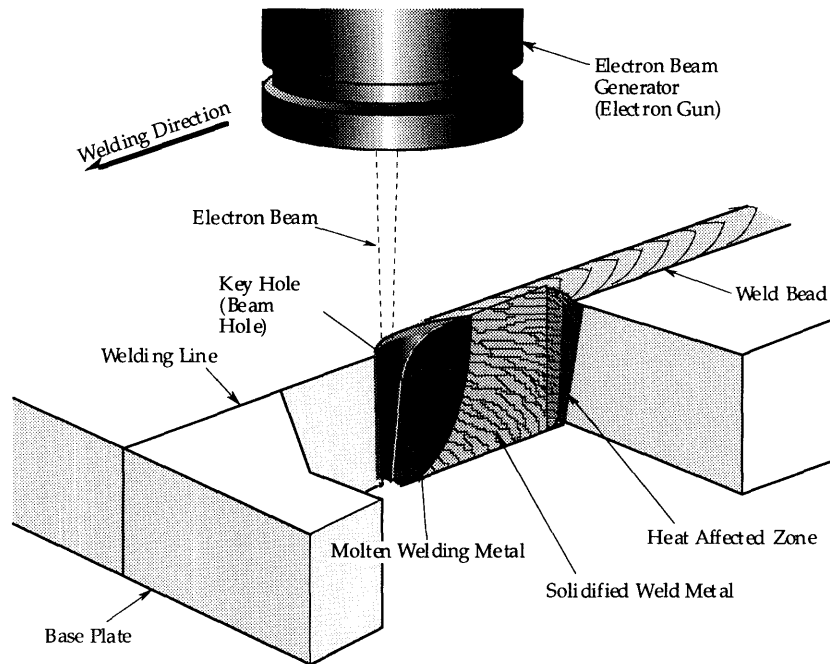


Figure 2.2 Schematic illustration of electron beam welding process

When the electron beam is highly focused at the work surface, the diameter of the area irradiated by the beam is approximately 0.5 mm. In that case, the energy density in the heated area becomes up to 100,000 times of the tungsten arc. By this tremendously high energy density, the base metal facing the beam evaporates immediately, and a deep keyhole is created as shown in the figure. A region of molten metal is formed around the keyhole. By moving the electron gun so that the beam tracks the welding line, coalescence is produced continuously. Edges of the works to be welded are planed and positioned so that they touch each other. Usually the filler material is not applied in an EBW process.

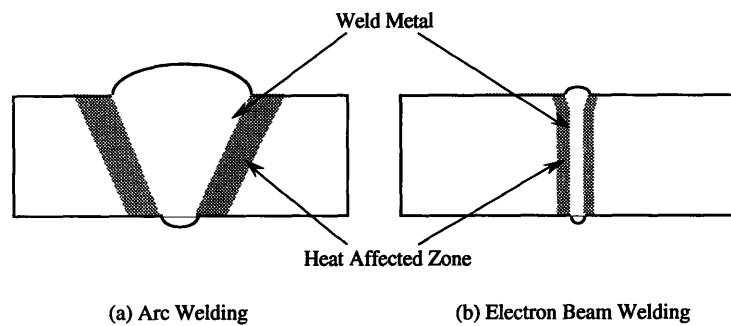


Figure 2.3 Comparison of cross-sectional shape of penetration between arc welding and electron beam welding

Most advantages of the EBW process are brought by the high energy density of EBW. The cross sectional shape of the penetration is narrow and parallel in comparison with the ones created by arc welding processes, as shown in Figure 2.3. This penetration shape results in a small contraction and distortion of the welded joint. The width of a heat affected zone, that usually has inferior properties to the base metal, is also narrower than that produced

by arc welding processes. Furthermore, the EBW process has an outstanding advantage concerning productivity. For example, steel plates of up to 200 mm thick can be welded in the single pass by using a high power electron gun in 100 kilowatts class.

Since its introduction in the late 50's, EBW has been adopted in various industries. In the aerospace industry, EBW is a suitable process for welding light metals including titanium and aluminum because of the small welding deformation and the vacuum atmosphere, which together create an ideal condition to protect those active metals from atmospheric contamination during welding. The automobile industry has applied EBW process widely for welding transmission gear components because of the great productivity obtained by high welding speed.

In spite of its superiority to conventional arc welding processes, EBW has not been widely used in the manufacturing industries of heavy steel structures including ships and bridges. The biggest factor that has obstructed the application of EBW is the necessity of the vacuum atmosphere for this welding process. Usually, in the EBW process, works to be welded are put in a vacuum chamber. The size of the vacuum chamber, therefore, determines the dimensional limit of the work to be welded. Recently, however, attempts have been made to apply EBW to some highly value-added products in steel fabrication industries. Some Japanese heavy industries constructed large vacuum chambers for EBW of more than 100 m³ capacity (the biggest one is more than 300 m³). They have been used for the welding components of heavy sections including pressure vessels for a nuclear reactor system, inner hull structures of submarines, and nozzle diaphragms of steam turbines.

2.1.2 Laser Beam Welding

Laser (Light Amplification by Stimulated Emission of Radiation) light was discovered for the first time in the late 1950's by Maiman, an American scientist. He found that a crystal of ruby generates a special kind of light when an internal energy transition occurs within its molecule. Unlike other lights which already exist, such as sun light and lamplight, laser light had unique features such as a single wave length and an electromagnetic coherency. Those features gave a focused laser beam an extremely high energy density that could be applied for material processing including cutting, drilling and welding. Since Maiman's historic discovery, numbers of materials that can generate the laser light have been studied. As the result, today, a couple of laser sources, CO₂ gas and YAG crystal, are commercially and widely used for industrial applications.

Figure 2.4 shows a schematic illustration of an axial flow type CO₂ laser resonator and processing equipment. Primarily, a CO₂ laser resonator has a glass tube which contains CO₂ and other auxiliary gases, a couple of mirrors, and electrodes for a glow discharge. To promote the energy transition in the CO₂ molecule, the gas is first energized by using a glow discharge. Immediately after energized, CO₂ molecules lose their internal energy by an internal energy transition, and at this time, generate the laser light of 10.6 μm wavelength. Laser light generated by a CO₂ molecule stimulates the other molecule to breed the laser beam. By this manner, laser light is amplified in the tube to a certain strength that is determined by a volume of the tube and energizing efficiency by the glow discharge.

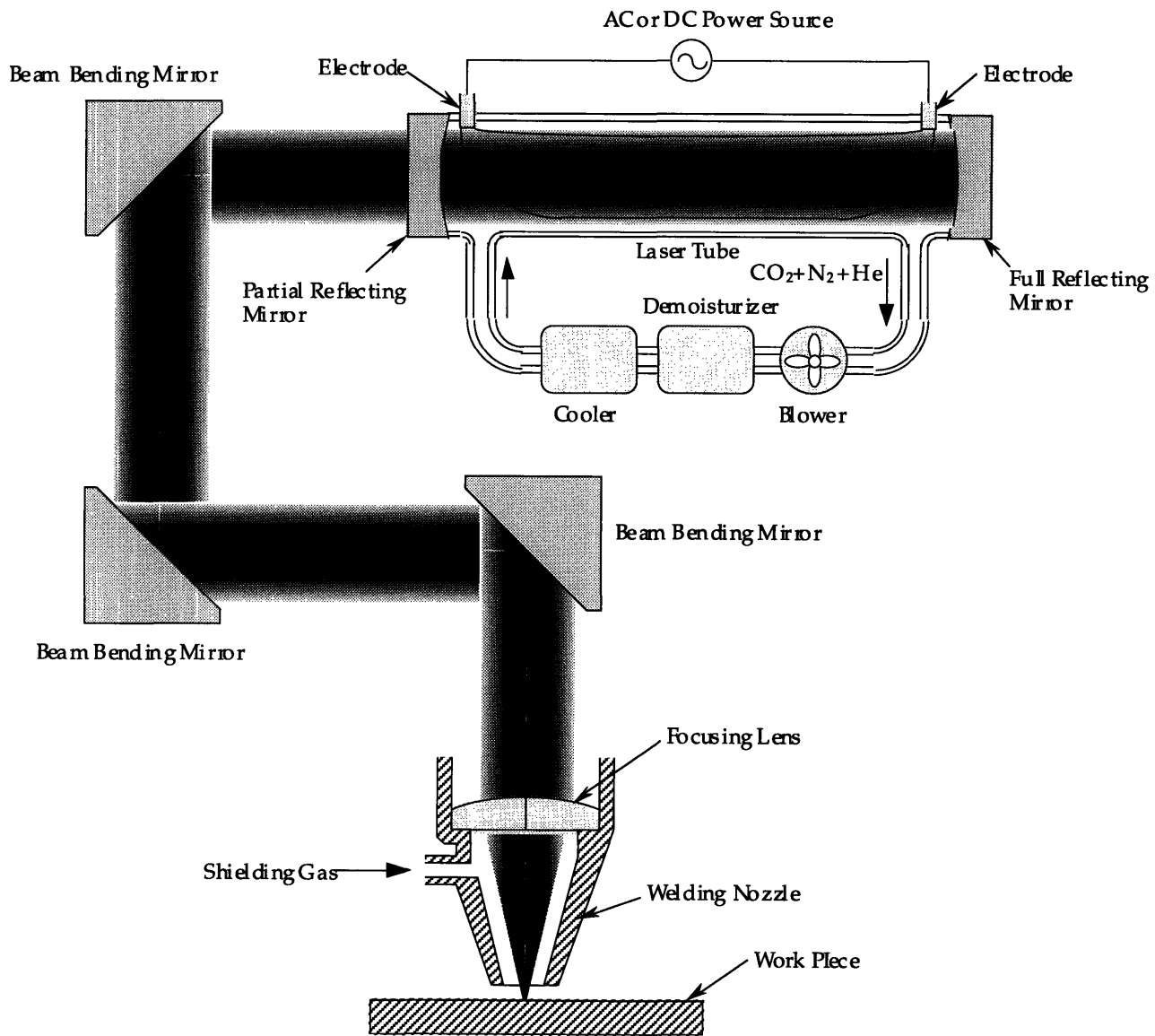


Figure 2.4 Schematic illustration of CO₂ laser resonator and processing equipment

Today (in 1994), the maximum output of a commercially available CO₂ laser resonator is up to approximately 50 kilowatts. A couple of mirrors equipped in the generator limit the direction of laser light so that only the light in the direction parallel to the tube is efficiently amplified. Laser light goes out of the tube through one of those mirrors that partially transmits the light, and is guided to the work station by a reflecting mirrors system. Finally, the laser beam is focused by a lens or a parabolic mirror, and reaches to the surface of the workpieces to be welded. Like the GTAW process, the shielding gas which is usually an inert gas is supplied to the welding region through a nozzle equipped in a welding head.

In the case of YAG laser resonator, a cylindrical bar of YAG crystal (YAG rod) acts as the tube, and energizing is done by a xenon lamp instead of the glow discharge in the CO₂ laser resonator. Because of the high transmission rate in the crystal caused by the short wavelength (1.06 μm), YAG laser beam can be guided to the work station through a crystal fiber, which a CO₂ laser beam cannot do. This fiber guiding gives YAG laser a great flexibility in actual applications. However, due to the limitation of the size of a commercially available YAG rod, the maximum output of a single rod YAG laser resonator is up to only 400 watts (kilowatts-class YAG laser generators that have some combined YAG rods were released to the market in the late 80's). YAG laser has been mainly used for welding precise machinery parts and computer chips.

The energy density of the focused laser beam is almost equal to that of the focused electron beam as long as the power of those beams are the same. Therefore, the process of laser beam welding (LBW) is similar to that of EBW

shown in Figure 2.2, except for the welding atmosphere which is a vacuum in EBW process. In LBW, however, the efficiency of the energy transfer from the laser beam to the work piece is usually not as high as that of the EBW process. This is caused by the reflection of the laser light on the surface of the work, and the absorption of the laser beam by a plasma that is generated over the keyhole by the intensive heat in the welding region.

Since its introduction to industrial fields, LBW process has been applied mainly for high speed welding operations of relatively thin plates and small machinery components. Concerning this kind of usage, the automobile industry is a representative user of the LBW process. In assembly lines of car bodies, automatic LBW systems are widely used for welding blank panels before they are press-formed. By using 5 kilowatts LBW equipment, blank panels of approximately 1 mm thickness can be welded by a welding speed of up to 4 inches per second without a harmful welding deformation. Machinery parts in the mass-production line such as transmission gears and torque converter casings are also suitable targets for applying LBW process.

In addition to the application to welding, the laser beam is today widely applied to various material processing including cutting, drilling and different surface modifications. For steel fabrication industries, especially, laser beam cutting has recently become a very important technique. By using the CO₂ laser beam of several kilowatts with the oxygen assist gas, steel plates of up to one inch thickness can be precisely cut with a speed twice as high as that of oxy-fuel gas flame cutting. In some Japanese shipyards, fully automated CO₂ laser cutting systems have already been installed and used for cutting plates for structural components of the ship hull.

Chapter 3

3. Gas Tungsten Arc Welding Process

3.1 Introduction

The aim of this chapter is to illustrate the Gas Tungsten Arc Welding Process (GTAW), which is an arc welding process that uses an inert gas to protect the weld zone from the atmosphere. The necessary heat for welding is provided by a very intense electric arc, struck between a virtually nonconsumable tungsten electrode and the metal workpiece. For the joints where filler wire is required, a welding rod is fed into the weld zone and melted with the base metal.

In any type of welding, the best obtainable weld is one that has the same chemical, metallurgical and mechanical properties as the base metal itself. To obtain such conditions, the molten weld puddle has to be protected from the atmosphere during the welding operations; otherwise atmospheric oxygen and nitrogen will combine readily with the molten weld metal and result in a weak, porous weld. In gas tungsten-arc welding, the weld zone is shielded from the atmosphere by an inert gas. For this purpose, either argon or helium may be used. Argon is generally recommended because of its general suitability for a wide variety of metals, and the considerably lower flow rates required. Another important factor is its low cost compared to helium.

No flux is required with the gas tungsten-arc process. This makes welding applicable to a wider variety of joint types, Corrosion due to flux entrapment can not occur, and postweld cleaning operations are eliminated. The entire welding action takes place without spatter, sparks or fumes. Welds can be made in almost all metals used in industrially. These include aluminum alloys, stainless steel, cast iron, magnesium alloys, silver, nickel and nickel-base alloys, copper, silicon-copper, copper-nickel, brasses, phosphor bronze, plain carbon and low-alloy steels, cast iron and others. It is also widely used for joining dissimilar metals.

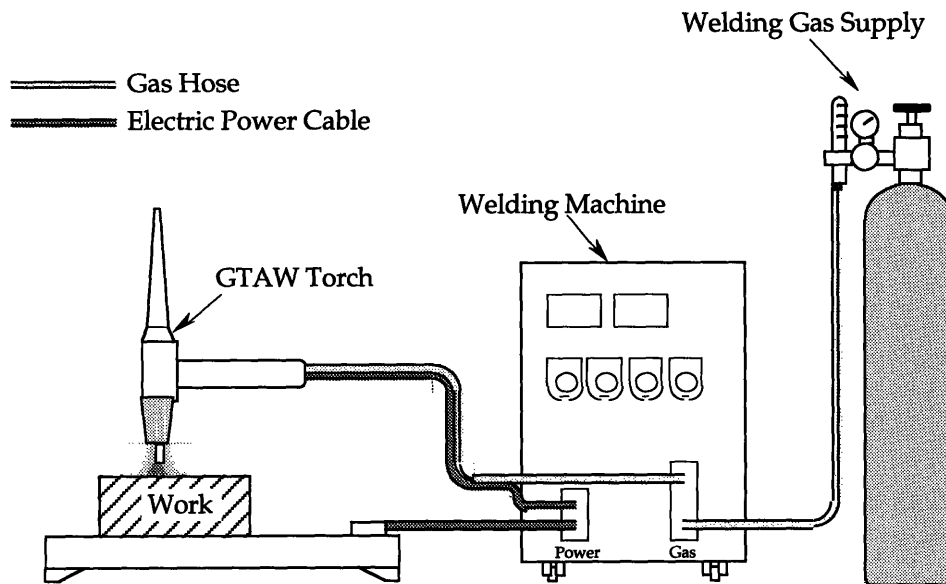


Figure 3.1 Gas tungsten arc welding equipment

3.2 Principals of Process

The gas tungsten-arc welding equipment is shown schematically in Figure 3.1. The process uses a nonconsumable tungsten electrode held in torch. Shielding gas is fed through the torch to protect the electrode, molten weld pool, and solidifying weld metal from contamination by the atmosphere. The

electric arc is produced by the passage of current through the conductive, ionized shielding gas. The arc is established between the tip of the electrode and the work piece. Heat generated by the arc melts the base metal. Once the arc and weld pool are established, the torch is moved along the joint and the arc progressively melts the surface.

GTAW torches one of which is shown in Figure 3.2 hold the tungsten electrode which conducts welding current to the arc, and provide a means of conveying shielding gas to the arc zone. Thorches are rated in accordance with the maximum welding current that can be used without overheating.

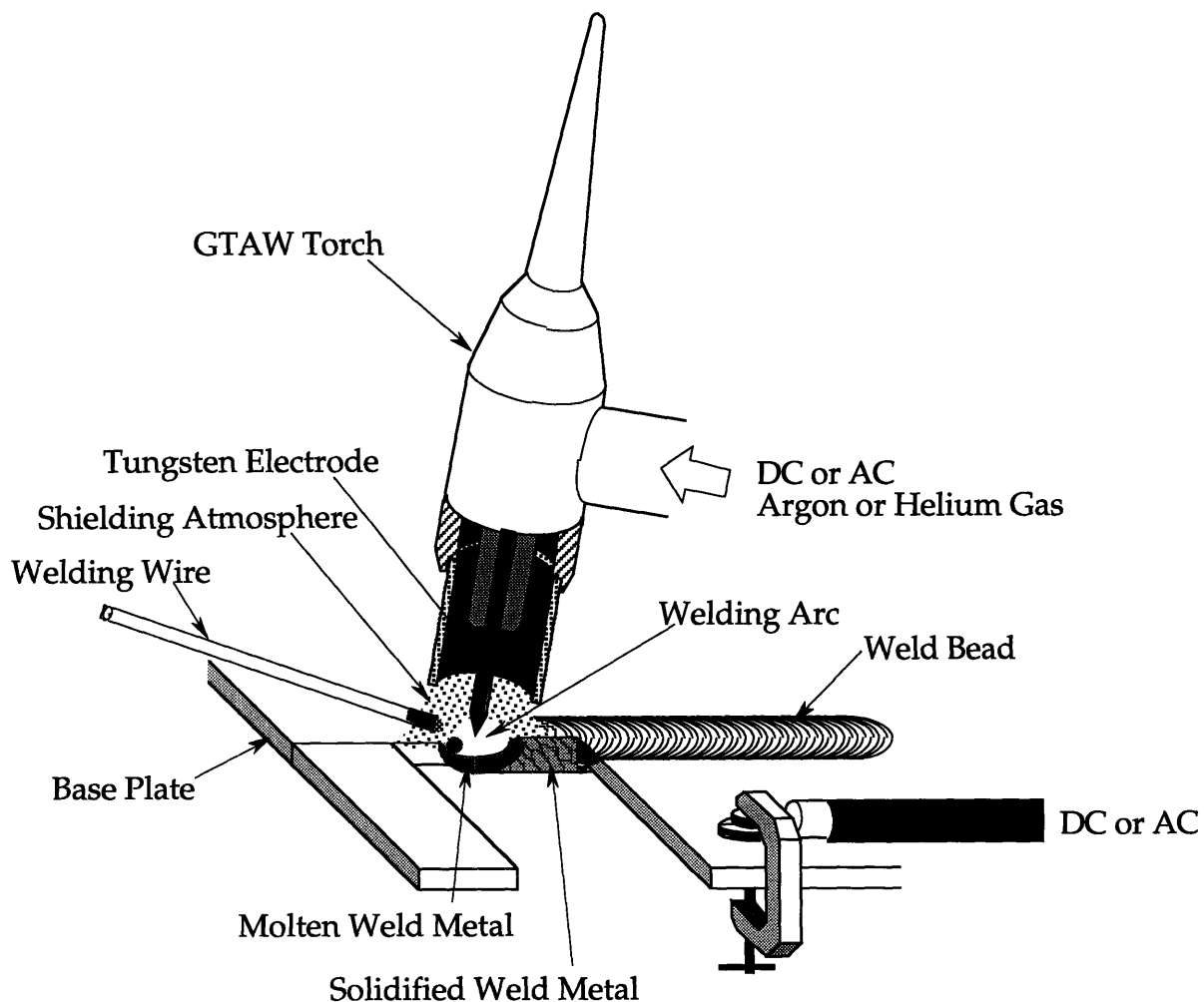


Figure 3.2 Gas tungsten arc welding operation and torch assembly

The function of the tungsten electrode is to serve as one of the electrical terminals of the arc which supplies the heat required for welding. Its melting point is 6170° F.

3.2.1 Types of Welding Torches

3.2.1.1 Gas Cooled Torches

The heat generated by the torch is either cooled by gas or water. Gas or air-cooled torches use a relatively cool shielding gas which pass through the equipment.

3.2.1.2 Water-Cooled Torches

A water-cooled torch uses water passing through its passageways in its holder to cool the torch. This type torches were designed to work at higher welding currents and to operate continuously. Although gas-cooled torches are limited to a maximum welding current of only 200 amperes, water-cooled torches can typically withstand 300 to 500 amperes. These torches use ordinary tap water as a coolant. Also, to prevent freezing and corrosion automotive antifreeze can be added.

3.2.1.3 Parts of Welding Torches

Collets and nozzles are two important components of GTAW torches. While the collets hold the electrode, nozzles direct shielding gas to the weld zone. In

the torch body there are also parts called diffusers which feed the shield gas into the nozzle. The reason for these diffusers are to produce a laminar flow of the existing gas shield. Nozzles are usually made out of ceramic, metal, metal jacketed ceramic, fused quartz or other materials. Among these nozzle materials water-cooled metal nozzles have a longer life and are used widely where welding currents exceed 250 amps. Another device to assure a laminar flow of shielding gas is an addition called a gas lens. They fit around the electrode or collet and contain a porous barrier diffuser. They not only produce a longer undisturbed flow of shielding gas but also enable the operator to come closer to the welding area and see weld pool better.

3.2.2 Electrodes

The T in the word GTAW refers to tungsten. It is a pure element and its alloys are used as electrodes. These electrodes are nonconsumable because they do not melt or transfer to the weld. The purpose of the tungsten electrode is to act as an electrical terminal of the arc that provides the heat.

3.2.2.1 Electrode Classification

Tungsten electrodes can either be produced by a clean finish or a ground finish. They are classified according to their chemical compositions. There are six tungsten electrode classifications: EWP - Pure Tungsten Electrodes; EWTh - Thoriated Tungsten Electrode; EWCe - Ceriated Tungsten Electrode; EWLa - Lanthana Electrodes; EWZr - Zirconiated Tungsten Electrodes; EWG -

Electrodes produced by the nonspecified addition of a non-specified oxide or oxides.

3.2.2.2 Electrode Sizes

Tungsten electrode sizes and current ranges are listed in Welding Hand Book [3]. Levels short of these recommended will result in arc stability while those in excess will cause the tungsten to erode or melt.

3.2.2.3 Electrode Tip Configurations

During their preparation tungsten tips are either balled, ground or chemically sharpened. On all but the smallest electrodes a tapered electrode tip is usually manufactured.

In balling, a hemispherical tip is produced by striking an arc on a water-cooled copper block and increasing the arc current until the end of the electrode turns white, tungsten starts to melt and causes a small ball to form at the tip.

When grinding atungsten electrode, grinding should be performed with the axis of the electrode perpendicular to the axis of the grinding wheel. The wheel should only be used to grind tungsten to prevent contamination.

In chemical sharpening the red-hot end of the electrode is submerged in sodium nitrate. The resulting chemical reaction causes the tungsten to erode at a uniform rate all around the circumference and the tip. For different

types of tip geometry of the tungsten electrode, the variation of arc shape and fusion zone is shown in Figure 3.3 [3].

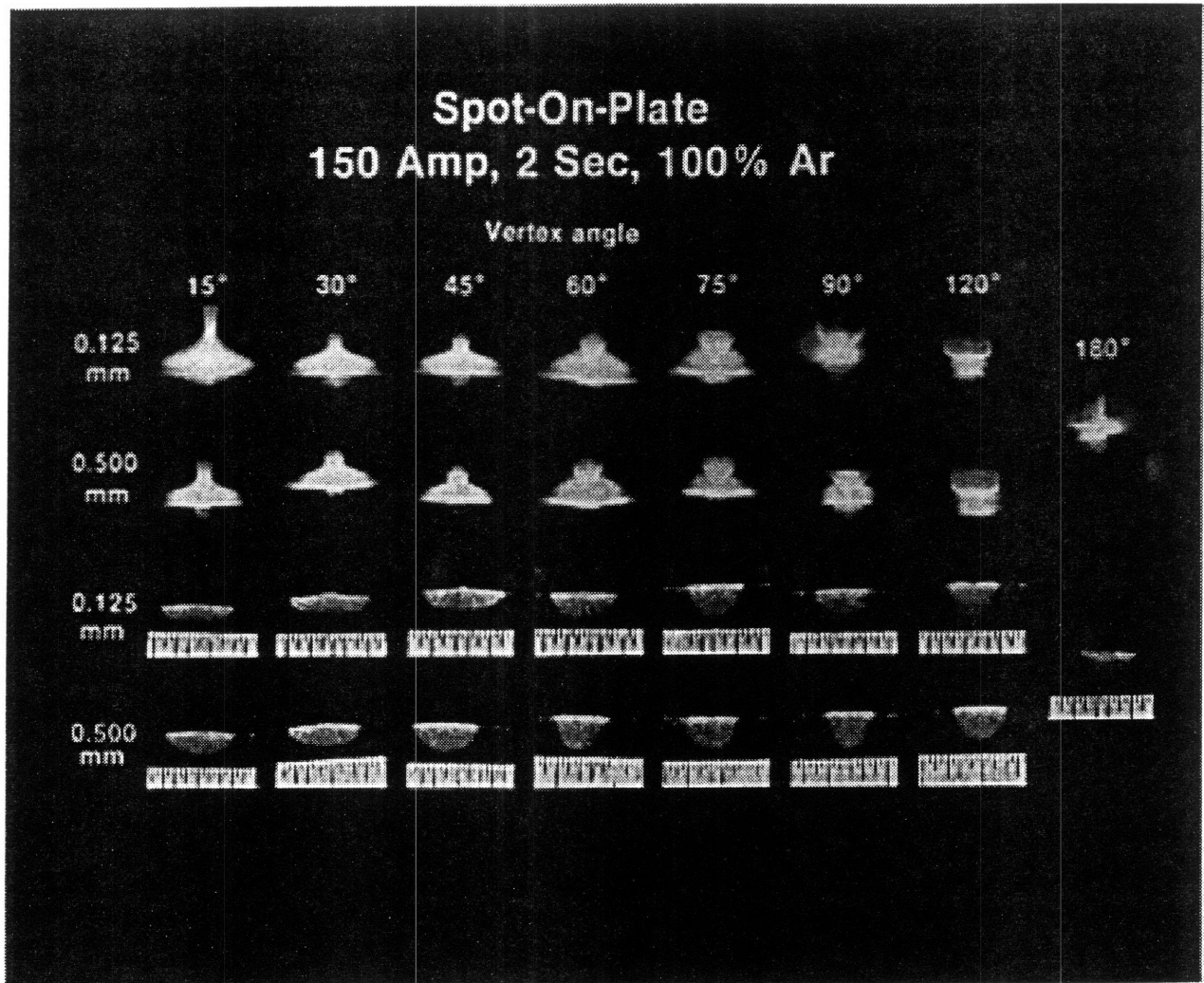


Figure 3.3 The variation of arc shape and fusion zone at different tip geometries of electrode[3]

3.2.2.4 Electrode Contamination

The two main causes of contamination are the accidental dipping of the electrode tip into the molten weld pool or touching the tungsten with the

filler metal. Also the electrode may become oxidized by an improper shielding gas or insufficient gas flow during or right after welding. Other causes are metal vapors from the welding arc, weld pool eruptions or spatter and evaporated surface impurities. If contamination occurs, arc characteristics will be adversely affected. Moreover, tungsten inclusions in the weld metal will also follow. If contamination takes place, welding should be stopped and the contaminated portion of the electrode should be removed.

3.2.3 Power Supply

The power supply for gas tungsten-arc process welding may be either a-c or d-c. However, certain distinctive weld characteristics obtained with each type often make one or the other better suited to a specific application¹.

In the direct-current process, either straight polarity² or reverse polarity³ can be used.

3.2.3.1 Direct Current

Connecting the tungsten electrode to the negative or positive terminal of the power supply have different effects. If the electrode negative is chosen,

¹ Welding Handbook, eight edition, volume 2

²Electrode negative, base plate positive

³Electrode positive, base plate negative

straight polarity takes place and electrons flow from the electrode to the work and positive ions are transferred from the work to the electrode. If the positive electrode is chosen, this process is reversed and reverse polarity takes place.

With straight polarity, the resulting weld penetration is deeper because of the greater amount of heat generated. Therefore straight polarity is more commonly used and is utilized with argon, or helium or a mixture of the two.

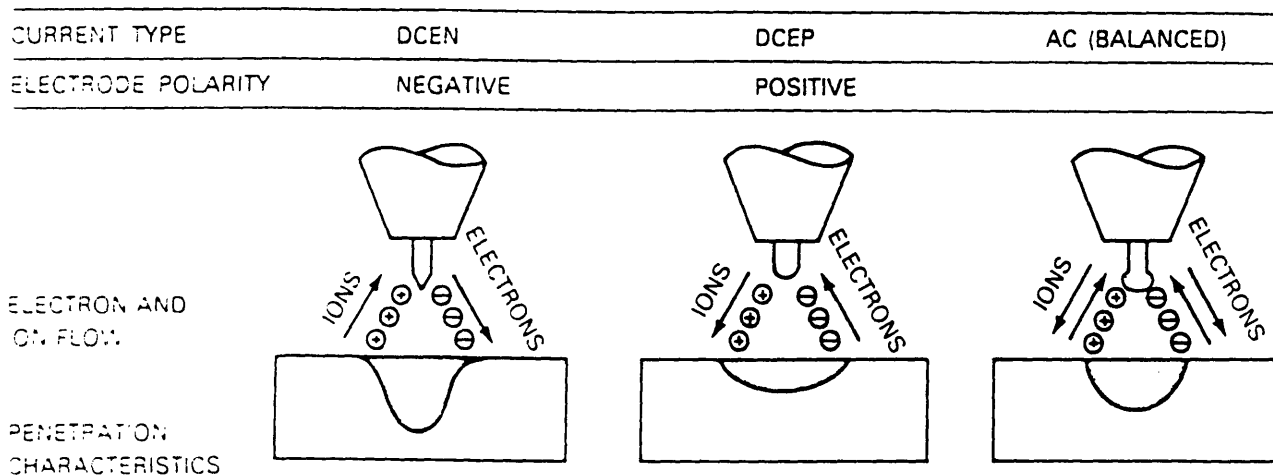


Figure 3.4 Characteristic of current types for GTAW [3]

Reverse polarity is preferred for welding aluminum or magnesium because the generated cathodic cleaning action removes the refractory oxide surface that inhibits wetting of the weldment. However, unlike straight polarity, when reverse polarity is used, the tip of the electrode is heated by the bombardment of electrons as well as by its resistance to the passing of the electrons through the electrode. This limits reverse polarity to the welding of sheet metal. The resulting weld is not as deep but wider.

3.2.3.1.1 Pulsed Dc Welding

In pulsed dc welding, the arc current is alternated repeatedly between a low and a high value. Generally this alternation rate is adjustable. This type of source makes it possible to adjust the pulse current time, background current time, peak current level and and background current level. The high current obtains good fusion and penetration while the low current maintains the arc and allows the weld area to cool.

Pulsed current is better than a steady current when used on heat input sensitive metals as it minimizes distortion. It is also effective for bridging gaps in open root joints.

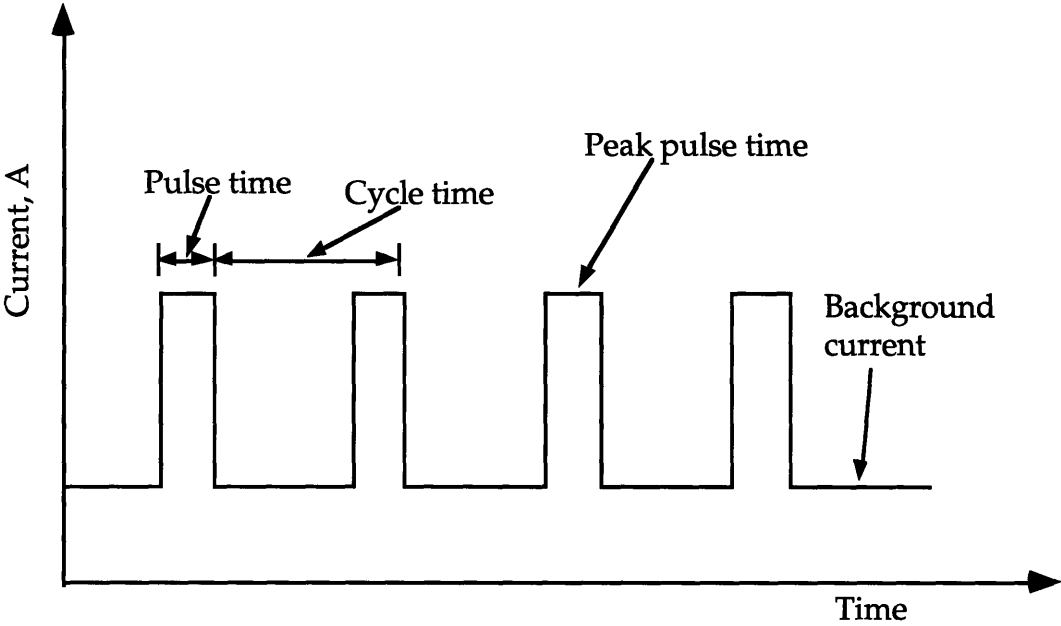


Figure 3.5 Waveform of pulsed direct current [3]

3.2.3.1.2 High-Frequency Pulsed Welding

Here direct current is applied by switching from a low to a high-current level at a rapid, fixed frequency of about 20 kHz. This high frequency switching produces a "stiff" welding arc. This arc is useful in precision machine and automatic applications. It is also useful at very low-average currents. However, this kind of high-frequency switched dc is quite costly.

3.2.3.2 Alternating Current

Alternating current welding power can be considered to be a combination of dc straight and reverse polarity. Ac is specified with the periodic reversal in the polarity of the welding current from the positive to the negative electrode. In this way, alternating current can combine the work cleaning action of reverse polarity with the deep penetration characteristic of straight polarity. For example, in the welding of Aluminum, moisture, oxides and the surface of the plate tend to partially or completely prevent the flow of current in the reverse polarity direction. This is called rectification. To prevent this event from taking place, an additional high voltage, high frequency low power current is introduced into the welding current. This current jumps the gap between the electrode and the work, pierces the oxide film, thus forming a path for the welding current to follow.

Unfortunately, the ac arc is not very stable and several measures are taken to guarantee stability. The methods used to ensure stability are the utilization of high open circuit power supplies; the discharging of capacitors at the appropriate time in the cycle; the application of high-voltage, high-frequency

sparks in parallel with the arc; and the usage of power supplies with a square wave output.

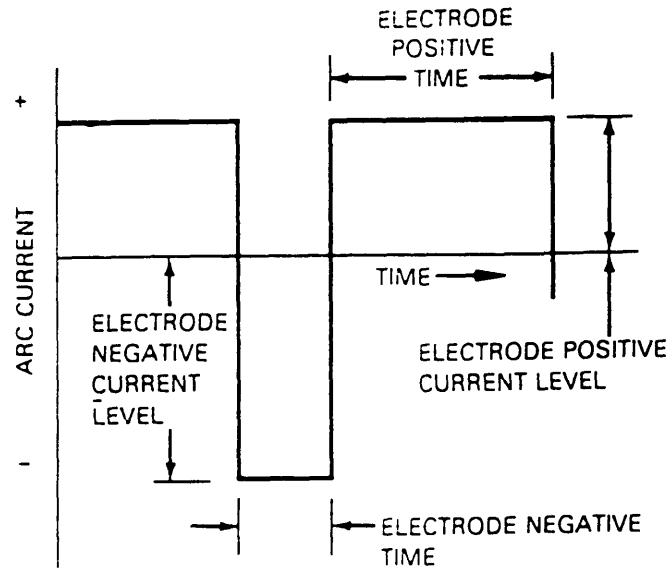


Figure 3.6 Characteristic of variable square wave AC[3]

3.2.4 Shielding gases

The purpose of a shielding gas is to protect the electrode and the molten weld metal from atmospheric contamination. Also, backup purge gas can also be used to protect the underside of the weld and the neighboring base metal surfaces from oxidation during welding. When gas backup is used under controlled conditions, uniformity of the root bead contour, freedom from undercutting, and the desired amount of root bead reinforcement are liable to be accomplished. In some materials, gas backup also reduces root cracking and porosity in the weld.

3.2.4.1 Argon

Argon (Ar) is an inert monoatomic gas. Argon used in welding is purified to 99.95% minimum. Although this value is acceptable for GTAW of most metals, for reactive and refractory metals, a purification of 99.997% is required. Although it is possible to use helium as a shielding gas instead of argon, argon is preferred because it has many advantages over helium. It has a smoother, quieter arc action and has reduced penetration. With materials such as aluminum and magnesium, it has a cleaning action. It is more widely available than helium, it also costs less. It has lower flow rates for good shielding and also has better cross-draft resistance. Moreover, its arc is easier to start.

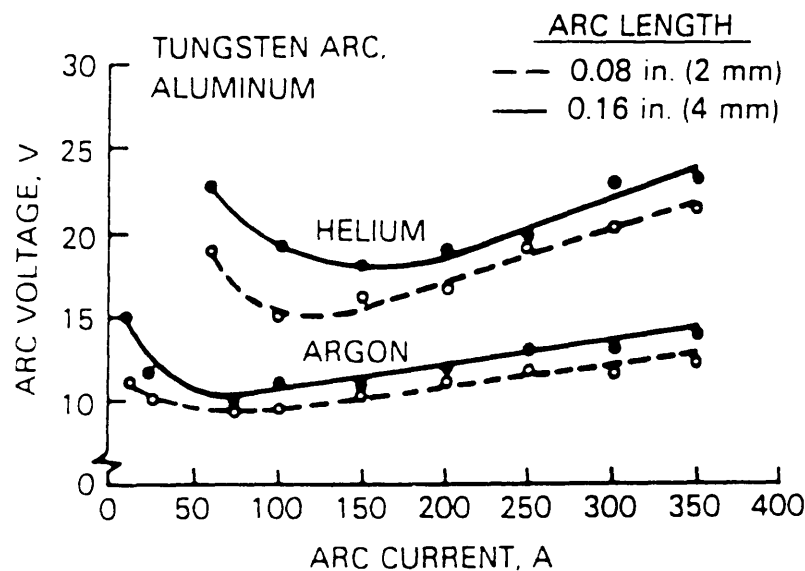


Figure 3.7 The relationship of voltage-current with argon and helium shielding[3]

3.2.4.2 Characteristics

The main factor influencing the effectiveness of shielding is the density of the gas. Argon is an effective shield because it is 1.33 times heavier than air and ten times heavier than helium. It can be supplied and stored as a liquid or compressed gas in cylinders. The cylinders used in transportation or storage are specially cleaned and dried to prevent contaminants and moisture. However, moisture is eliminated when it is delivered in liquid form because argon cannot exist as a vapor at such low temperatures (-300° F). After it leaves the nozzle of the torch, it forms a blanket over the torch area. However, compared to an arc created by helium, an argon arc must use a determinedly higher current to equal the arc power of helium. Argon provides excellent stability with direct current power. The arc stability is even better with alternating current power. That is the reason why argon is used extensively for welding aluminum and magnesium where argon also has the highly desirable cleaning action.

3.2.4.3 Recommended Gas Flow Rates

The required shielding gas flow are determined by cup or nozzle size, weld pool size and air movement. In general, the flow rate increases in proportion to the cross-sectional area at the nozzle. The minimum flow rate is determined because it is necessary to overcome the heating effects of the arc and cross drafts by a stiff stream. Excessive flow rates result in turbulence in the gas stream which in turn may aspirate atmospheric contamination into the weld pool.

Similarly, a cross wind or draft of five or more miles/hr. can disrupt the shielding gas coverage. To block such an occurrence, protective screens are preferred to increase shielding gas flow.

Chapter 4

4. Experimental Study

4.1 Introduction

In GTAW processes performed under extreme conditions, special attention should be paid to certain variables such as arc current, the height of electrode, arc voltage, the flow quantity of inert gas, surrounding pressure, type of the tungsten electrode etc. In this thesis, the effects of these parameters are studied individually and the results are presented with the corresponding graphics. Since the equipment available at MIT has limited capabilities to perform this study, the experiment was performed in two parts at two locations. The first study was carried out at the WSL, Welding Systems Laboratory, in Department of Ocean Engineering at MIT. The second set which used a new type GTAW process using a hollow tungsten electrode was conducted at Takamatsu National College of Technology, Japan.

4.2 Study at MIT

In this experiment, a basic study was carried out to understand the fundamentals of arc behavior under hyperbaric and vacuum condition. In

order to simulate the extreme environmental conditions, the pressure vessel located in the WSL was modified for the GTAW process by installing a semi-automatic welding torch and a moving cart inside. A control panel enabled us to control the welding machine remotely from the outside of the vessel. The power supply available at WSL is a Miller Syncrowave 350. This is a multipurpose welding machine of constant potential type with maximum rated output of 385 Ampere.

The material used was 304 stainless steel (SUS304). Fifty 1"X10" Strips with 0.125" thickness were machined for the experiment. The surface was cleaned with chemicals in order to maximize arc initiation and to avoid fumes. Each strip was placed on the moving cart in the pressure vessel and the vessel was closed securely and the bolts were fastened with a heavy duty wrench for the possible fluctuation of pressure and air tightness.

All welding was performed in the pressure vessel. For the hyperbaric environmental condition, an air compressor was used to supply the pressure in the vessel. The arc was obtained at a maximum of 0.48 MPa pressure. For the vacuum condition, a minimum of 0.0027 MPa was reached. Under higher vacuum, we were not able to either initiate the arc or have a stable arc any more. As welding was performed, the shape of the arc was observed. Moreover, by using a 35 mm camera located outside the vessel, the pictures of the arc were taken.

4.2.1 The Pressure Vessel

The pressure vessel has a maximum of 350 psi pressure level. It has a steel structure and is pressurized with an external air pump. The door of the vessel is tightened with 30 3/4" bolts. There are two observation windows which allow the welder to see the inside of the pressure vessel. The windows are covered with 1" thick pressure resistant glass. However, due to distortion caused by the thickness of the glass, vision was not very clear. If a better view is desired, one has to replace the glass with a similar material which causes less visual distortion.

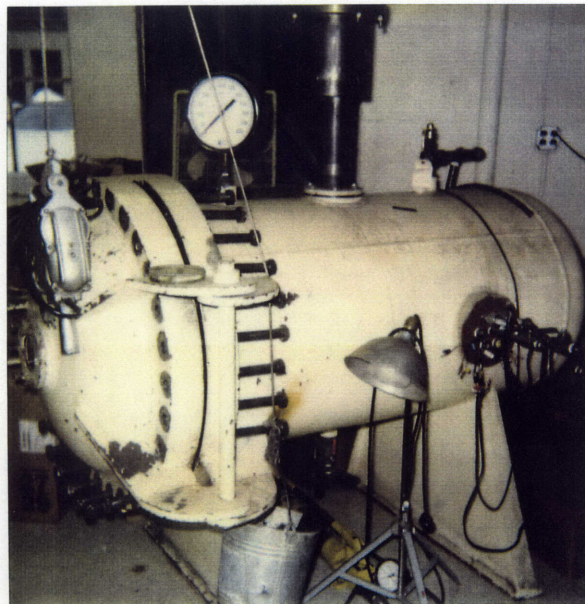


Figure 4.1 The pressure vessel

The geometry of vessel is shown in Figure 4.1. The vessel is big enough to have large pieces, up to 1' by 2' to be welded. The moving cart in the chamber makes it possible to have welding process remotely controlled through a control panel outside the vessel. Sealing is performed to keep the air steady in the chamber. In case of GTAW process, the inert gas argon, was fed by tube from an external gas storage tank. The vessel has an emergency valve to control the over pressurization in the chamber. If a certain value of pressure is exceeded, the valve automatically goes off.

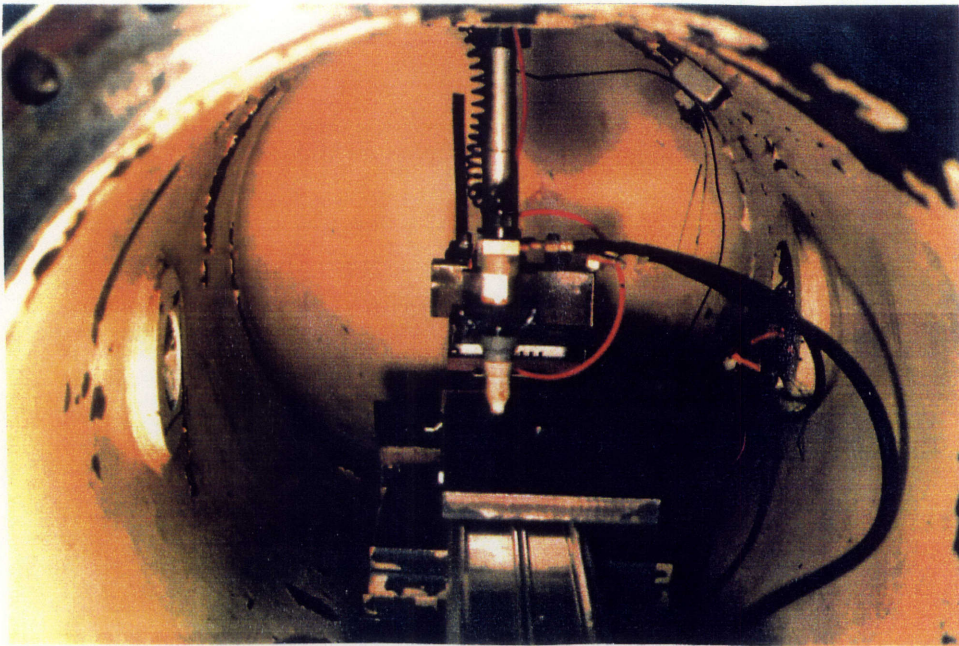


Figure 4.2 Inside the pressure vessel

The torch is fixed in the horizontal plane. However, it has a degree of freedom in a vertical plane. The movement in the horizontal plane is supplied by the cart in the vessel which travels on rails. The speed of welding or the arc can be adjusted easily with control buttons on the cart. The torch is remotely controlled by the control panel outside the vessel.

4.2.2 High Pressure Welding Process

The shape of arc was observed at five different levels of pressure, namely 0.1, 0.17, 0.27, 0.38 and 0.48 MPa. Experiment conditions are summarized in Table 4.1.

Pressure	0.1, 0.17, 0.27, 0.38, and 0.48 MPa
Voltage	12 Volts
Current	130 Amperes
Polarity	Direct-Current Straight Polarity
Electrode	2 % Th-W
Material	304 Stainless Steel
Arc speed	5 mm/sec
Inert gas	Argon

Table 4.1 Welding condition for the high pressure experiment

The experiment shown in Figure 4.3, was carried out at atmospheric pressure. As seen in the picture, the arc is stable and the arc is symmetric around the tip of the tungsten electrode. Moreover, the arc starts at the tip of the electrode and has a bright and strong color.

In Figure 4.4, the pressure was increased to 0.17 MPa. The arc as can be observed is still stable. However, the shape of the arc has become smaller and the arc length has shortened a little. The same behavior was observed at higher pressure levels. At the end of the experiment, a maximum of 0.48 MPa of pressure was reached. Beyond this level, the arc was not stable and it was impossible to initiate a stable arc. As seen in Figure 4.7, the arc length is very short and the arc has lost its symmetrical shape at higher pressure. However, arc intensity is very high.

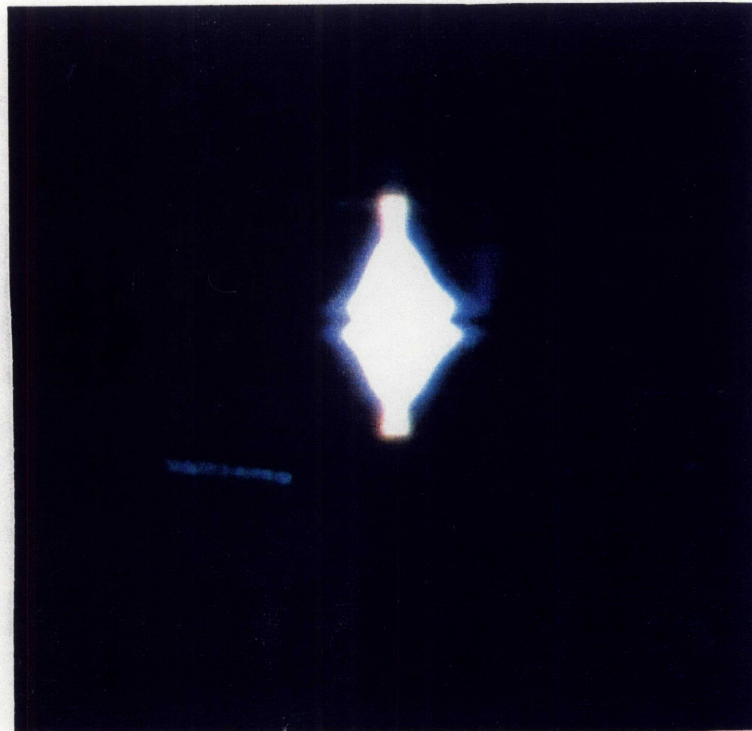


Figure 4.3 Shape of arc under 0.1 MPa pressure

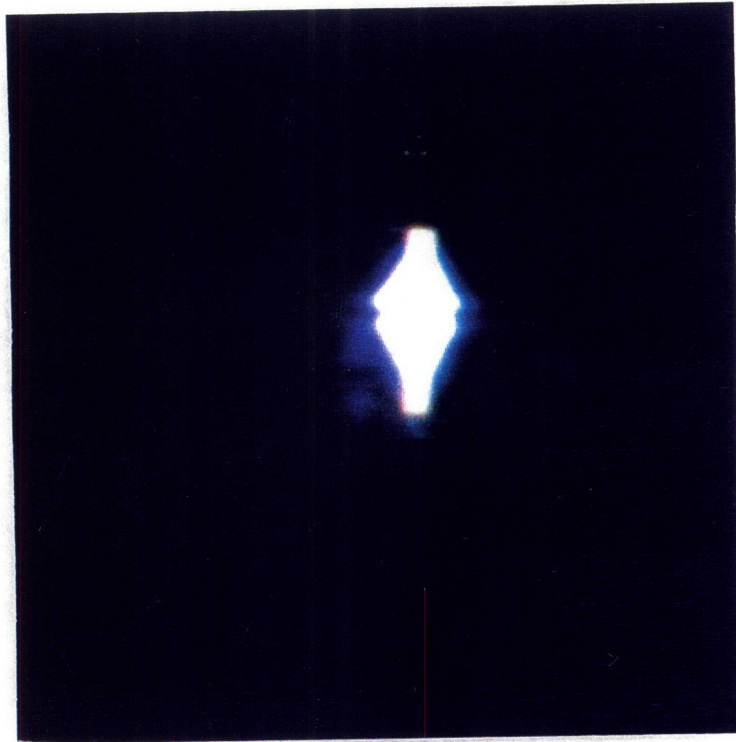


Figure 4.4 Shape of arc under 0.17 MPa pressure

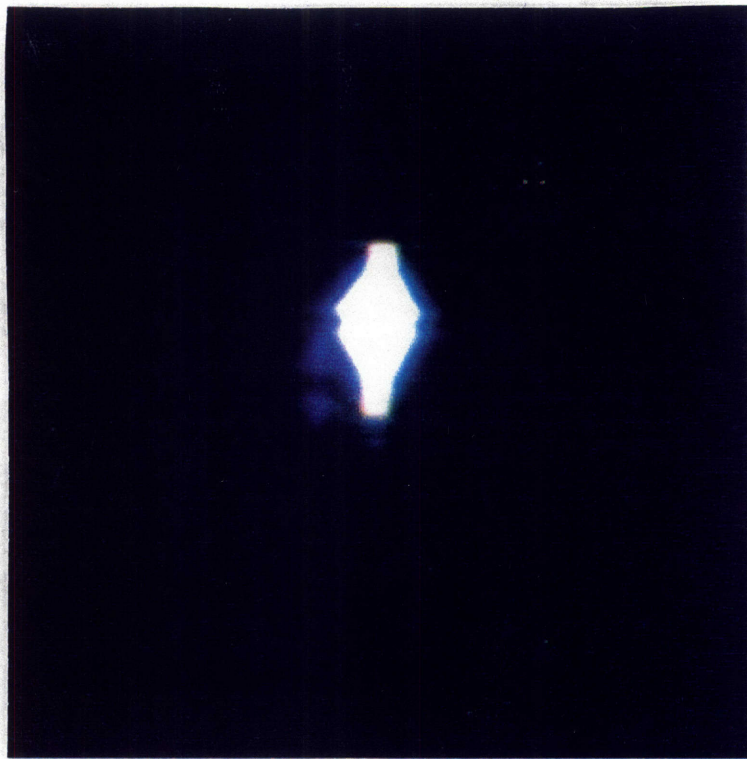


Figure 4.5 Shape of arc under 0.27 MPa pressure



Figure 4.6 Shape of the arc under 0.38 MPa pressure

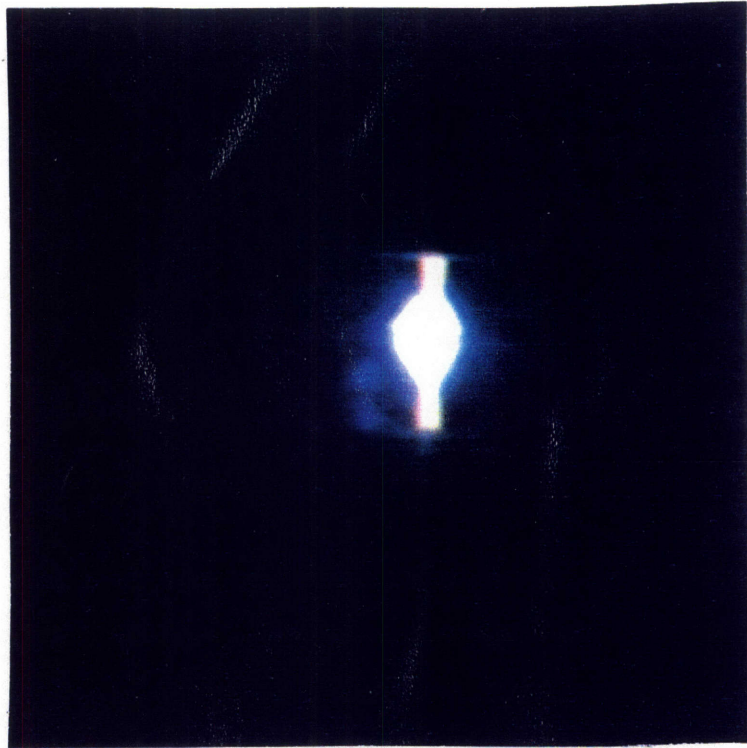


Figure 4.7 Shape of the arc under 0.48 MPa pressure

Experimental results were compared with the empirical formula given by Allum[2] as

$$l = \frac{V - 8}{0.8\sqrt{P}} \quad (4.1)$$

where l is the arc length in mm, V is the arc voltage in volt, and P is the pressure in bars.

Figure 4.6 shows that there is some agreement between the formula and the results of the experiments. However, the difference could be from the reference point of the measurements and the inert gas flow rate.

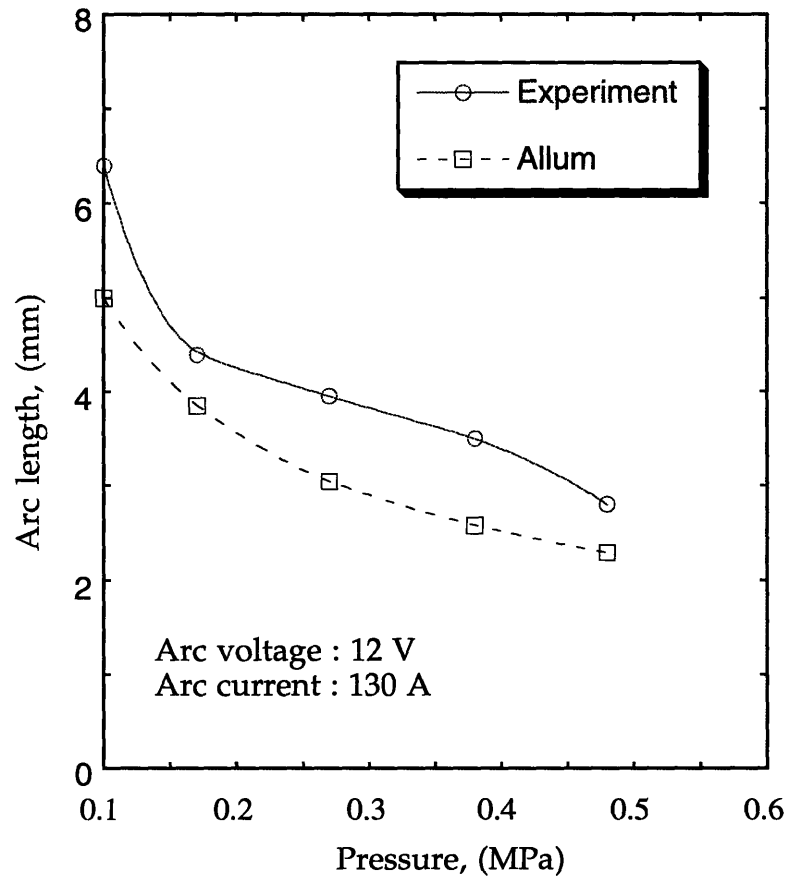


Figure 4.8 Effect of the high pressure on arc length

4.2.3 Low Pressure Welding Process

The experiment was carried out at three pressure levels in vacuum condition. The conditions of the welding process are given in Table 4.2. The shape of the arc, at these three pressure levels, was determined by pictures taken during the experiment. In Figures 4.9, 4.10, and 4.11, it was observed that the arc becomes unstable and less bright in vacuum. As the arc length gets shorter, the spread of the arc gets larger. Moreover, controlling the current and voltage became very difficult and the high frequency start caused electric jumps between the power cord and the ground. In order to avoid this, the high frequency start up was turned off and the distance between the electrode and base metal was adjusted to have arc initiation without high frequency.

Pressure	0.013, 0.0067, and 0027 MPa
Voltage	12 Volts
Current	130 Amperes
Polarity	Direct-Current Straight Polarity
Electrode	2 % Th-W
Material	304 Stainless Steel
Arc speed	5 mm/sec
Inert gas	Argon

Table 4.2 Welding conditions for the vacuum experiment

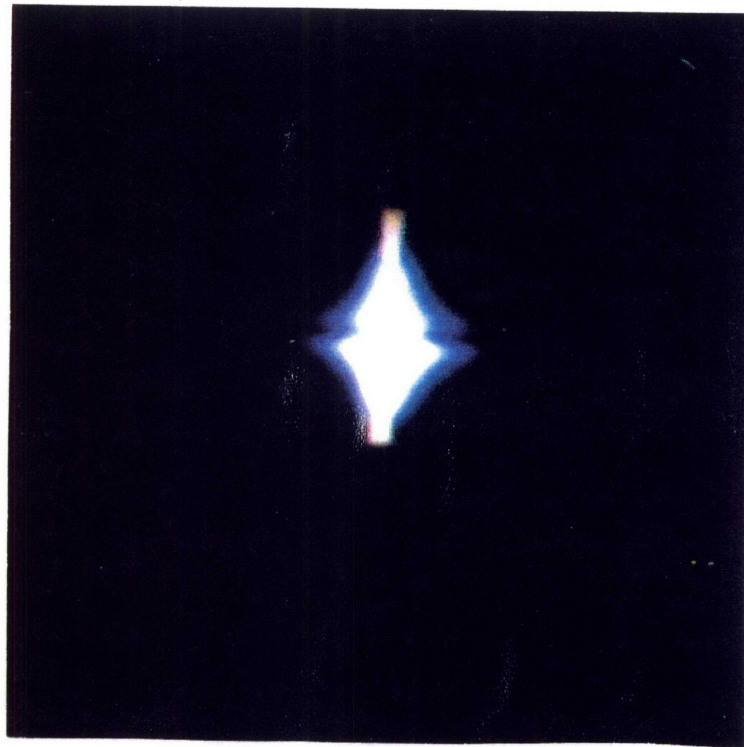


Figure 4.9 Shape of the arc under 0.013 MPa pressure

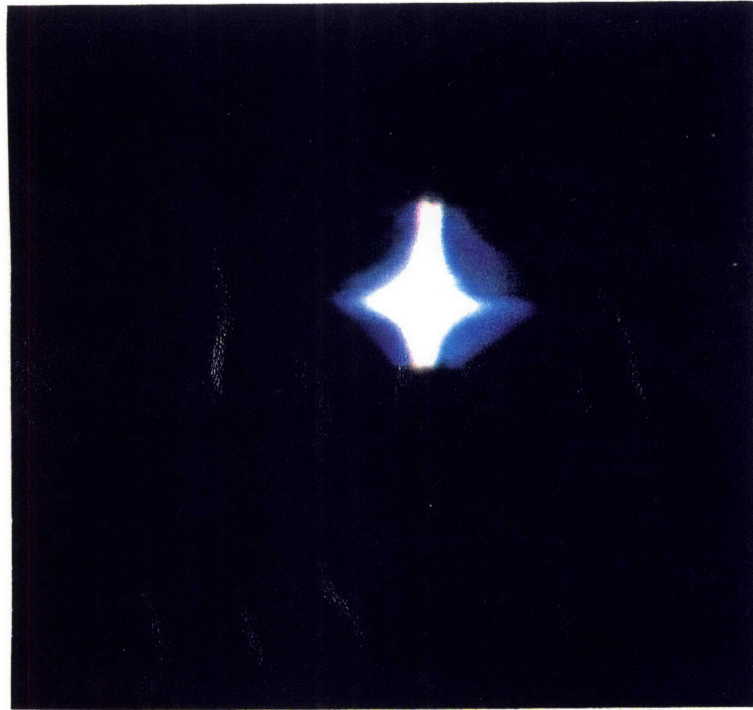


Figure 4.10 Shape of the arc under 0.0067 MPa pressure



Figure 4.11 Shape of the arc under 0.013 MPa pressure

4.2.4 Discussion and Results

In the high pressure welding experiment, the shape of the arc was influenced greatly as pressure went higher. Figure 4. 6 summarizes the results. Arc stability did not seem to be very sensitive to high pressure. However, increasing the pressure above the atmospheric condition produced a shorter arc length, a more intense arc and a smaller diameter arc. At 0.48 MPa pressure, we lost control of the arc initiation and beyond this point we were unable to have a stable arc. At this pressure, the arc had its smallest volume. However, there was no distortion or spread on the arc shape. The shape of the arc at different pressure levels is shown in Figures 4.3, 4.4, 4.5, 4.6, and 4.7.

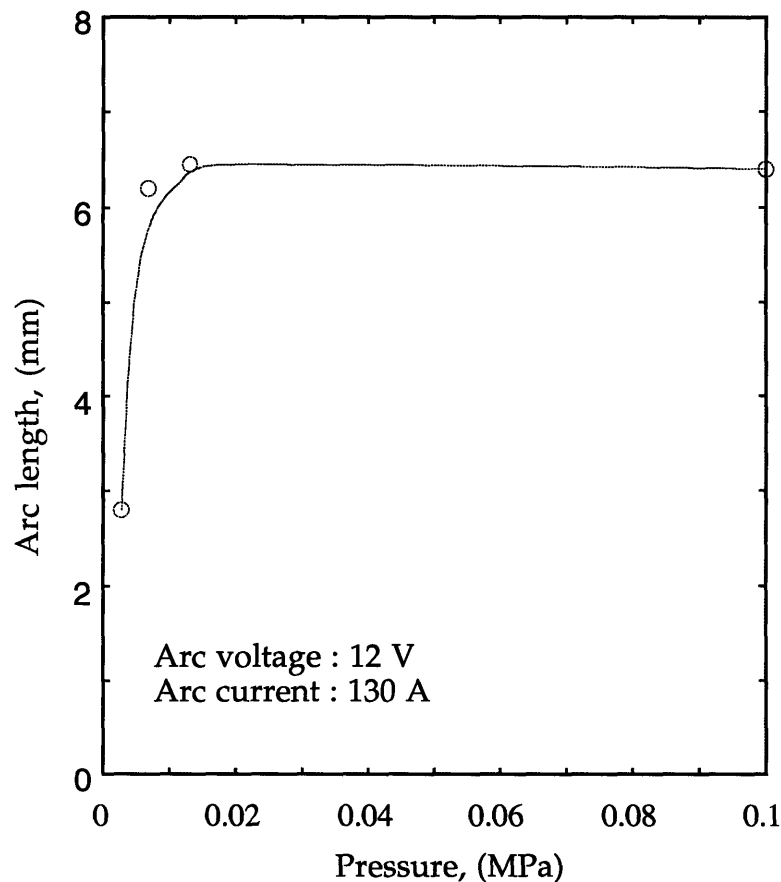


Figure 4.12 Effect of low pressure on arc length

In the low pressure experiment (vacuum condition) arc stability is a serious problem. Vacuum drains the inert gas fed through the nozzle. Therefore, the tungsten electrode is not entirely covered by the flow of the inert gas. The arc column becomes more diffuse and assumes a rounded shape. Moreover, it loses its bright color and the tip of the tungsten electrode is bared in this cloudy and fuzzy arc. The starting point of the arc column is shifted from the tip of the electrode to a higher point above the tip. The arc covers the electrode inside. At the minimum pressure point reached in this experiment (0.0027 MPa), a larger spherical region, blue in color and highly ionized, appears at the cathode, while at the anode area the discharge resembles glowing. This spherical region, designated as cathode plasma zone, appears to be an extended form of the blue cone that appears close to the cathode at atmospheric pressure.

An increase of heat in the anode was noticed as pressure was decreased. This is directly related with the size of plasma zone. The ionized environment in the pressure vessel caused short circuits and electrical jumps. Therefore, it is a good idea to consider a proper isolation of the cables and the cords carrying power to the welding torch and to other devices.

The penetration of the weld was also investigated in this study. In high pressure welding, penetration increased with increasing pressure. In vacuum, some undercuts and uneven weld beads were observed with increasing vacuum. The appearance of the arc at various pressures is shown in Figure 4.9, 4.10, and 4.11. Figure 4.12 shows the effect of low pressure on arc length.

4.3 Study at Takamatsu Institute of Technology, Japan

Under the supervision of Prof. K. Masubuchi, a study on space welding was initiated by a group of students and visiting scientists including Prof. Y. Suita while was a visiting researcher in the Department of Ocean Engineering at MIT between 1989 and 1990. After Prof. Suita left MIT, a second set of experiments was performed at his institute in Japan. These series of experiments were the continuation of the research started at MIT during his stay. A joint effort between MIT and TNCI was made to finish the experiments. This part of the thesis covers the experimental procedure and the results obtained from these experiments.

4.3.1 Experimental Apparatus

Since the size of the pressure vessel used in the first part of this research at WLS was too large to control the vacuum condition, a small scale special chamber was designed. The chamber had a cylindrical shape. Its height was 0.55 m. and radius 0.48 m. Hence, its internal volume was 0.1 m³. The body of the chamber was constructed of heat resistant glass in order to observe arc formation. A vacuum pump was attached to lower the pressure. While keeping the torch fixed, the base metal was moved on a rotational table. A copper tube was connected to the welding torch to run the shielding gas from tank to the nozzle. The torch was modified in order to accommodate the gas flow through the hollow tungsten arc. Later in this chapter there will be more detailed information on the torch and hollow tungsten electrode. A

schematic representation of the experimental apparatus is shown in Figure 4.13.

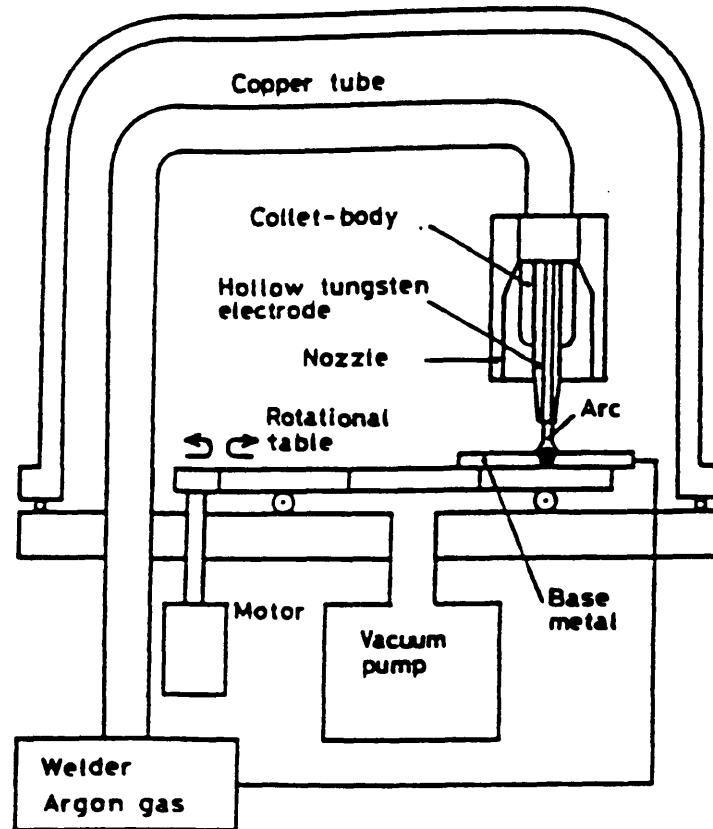


Figure 4.13 Experimental apparatus

4.3.1.1 Hollow Tungsten Electrode

As mentioned earlier, the vacuum in the chamber causes the inert gas to diffuse from the nozzle. Therefore, it was necessary to keep the gas flow running around the tip of the electrode in order to strike the arc within an inert environment. Considering these facts, a hollow tungsten electrode was used in this study. By using electron discharge method, a hole was drilled

through the tungsten electrode's axis. While the diameter of the solid tungsten is kept constant at 3.2 mm, two hollow electrodes with two different diameters of 0.5 mm and 1.00 mm were prepared. The configuration of nozzle and electrode attachment including their dimensions is shown in Figure 4.14.

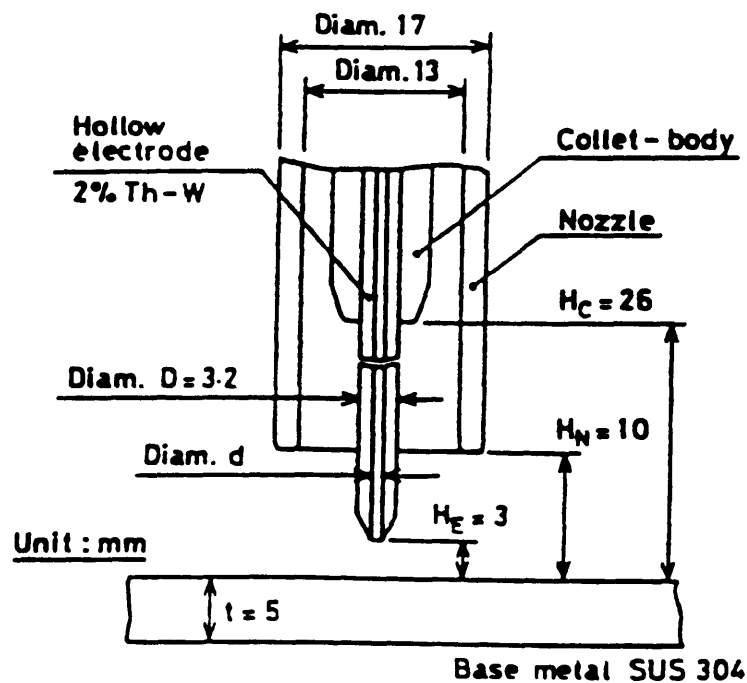


Figure 4.14 Hollow tungsten electrode and welding torch

In this part of the study, the material used was again 304 Stainless Steel. The specimens were machined to have a thickness of 5 mm, a width of 50 mm and a length of 90 mm. Arc speed was set at 2.4 mm/sec. The details of the welding conditions are given in Table 4.3. The rate of the gas flow was

controlled in order to see the effects of the flow rate on arc shape and weld quality.

Pressure	0.013 Pa
Flow rate of argon	0.012 ~ 0.086 Pa.m ³ /sec
Current	50 Amperes
Polarity	Direct-Current Straight Polarity
Electrode	2 % Th-W, hollow with 0.05 and 0.1 mm
Material	304 Stainless Steel
Arc speed	0.24 cm/sec
Inert gas	Argon

Table 4.3 Welding conditions for gas hollow tungsten arc welding

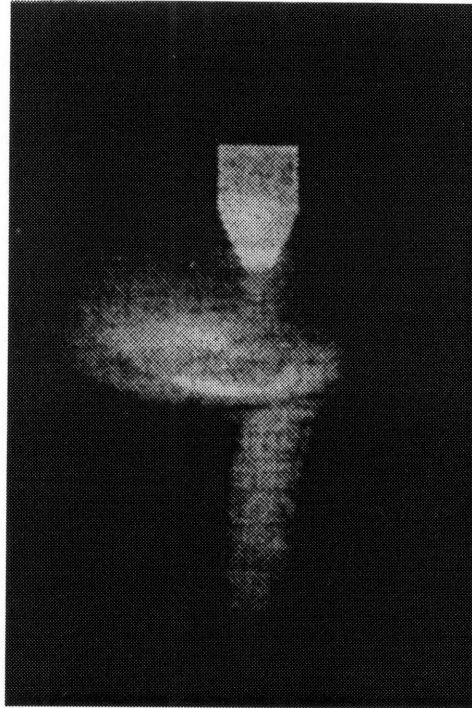
4.3.2 Discussion and Results

The hollow tungsten electrode enabled us to initiate and maintain a stable arc under a very high vacuum condition even with a little flow quantity of argon. In order to compare the effectiveness of the hole size on the hollow tungsten arc, the results of the experiments using electrodes with different hole sizes were illustrated together on the same graphics. The effect of the flow quantity of argon and arc length on penetration depth, arc voltage, bead width and period of transient arc charge were also observed and individual graphs were drawn to show the results clearly.

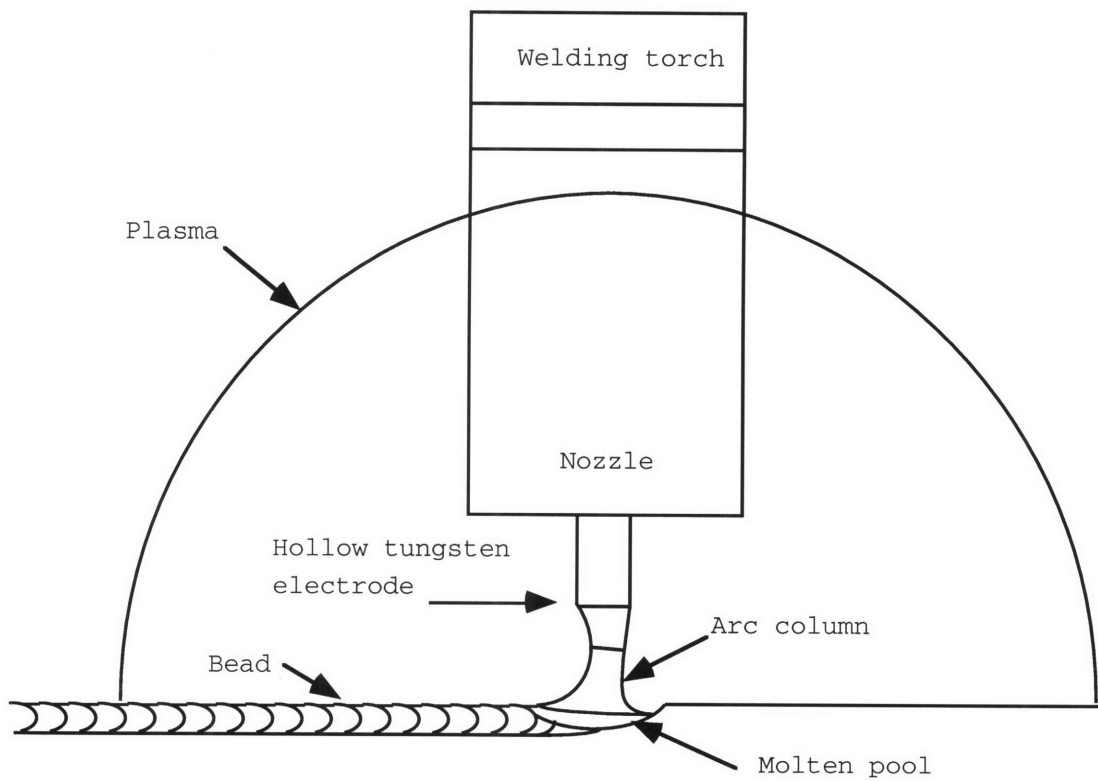
4.3.2.1 Arc Phenomenon in Vacuum by GHTA

When the arc is started by flowing a very small amount of Ar gas from the hole at the tip of the tungsten electrode, first a discharge of light blue color is generated. That discharge looks like it is blowing out of the welding nozzle. We call this discharge a transition arc. Transition arc is generated between the collet body of the welding torch and the base plate, and was also found in the experiments carried out by Yamamoto and Shimada. The reason for the generation of transition arc generation is considered to be a lack of emission of electrons from the electrode due to the cold temperature at the start of the arc. During the transition arc time, the current stays almost constant at 50A with an arc voltage of 30V.

A few seconds after the transition arc is generated, the electrode is red-hot and a steady state arc is formed between the tip of the electrode and the base metal. Weld bead is formed by this steady state arc. If the base metal is not melted by the arc, the arc is orange. Once the base metal is melted, the color of the arc changes from orange to blue. A spherical plasma is observed around the arc as shown in Figure 4.15 (a and b). The diameter of the plasma is from 40 to 80 mm, and the its color is light blue or light green. The size of the plasma increases as the welding current increases and the pressure decreases.



(a) Arc column



(b) Plasma ball around arc

Figure 4.15 Arc discharge in a low pressure condition

4.3.2.2 Flow Quantity of Argon

Figure 4.16 shows the effect of the flow quantity of argon on arc voltage. Increasing flow rate results in decreasing arc voltage and increasing equilibrium pressure.

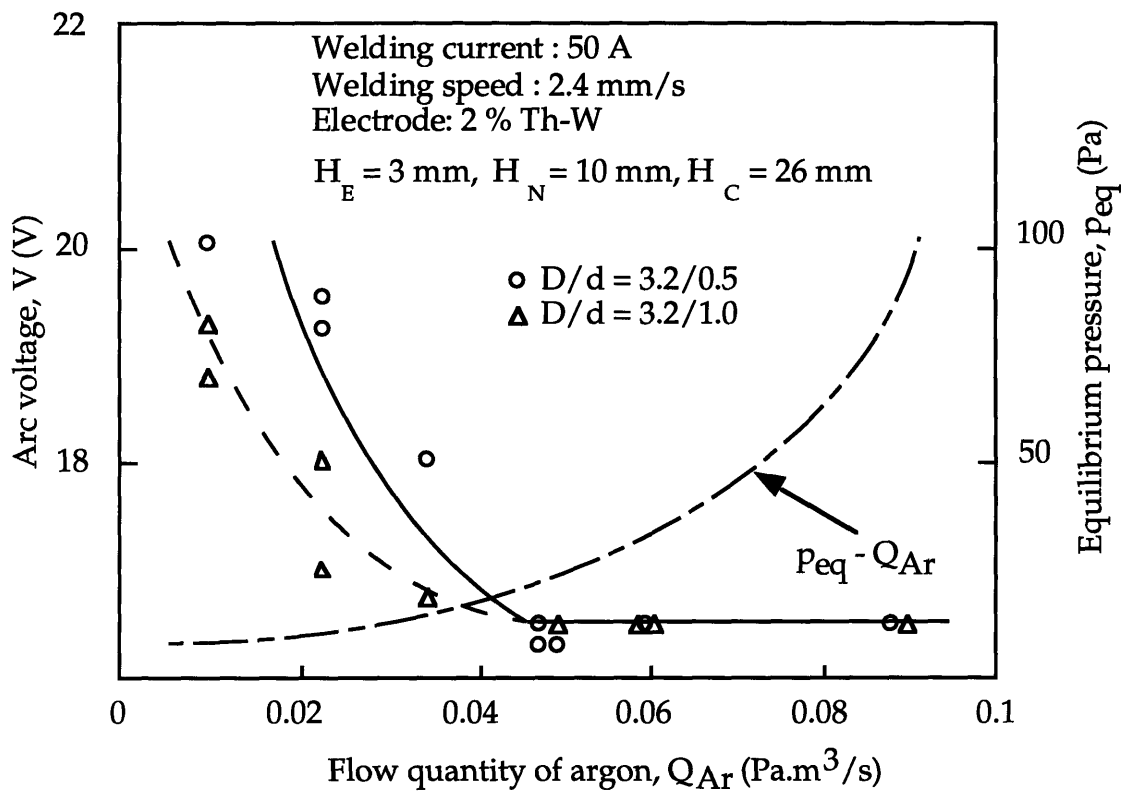


Figure 4.16 Effect of the flow quantity of argon on arc voltage

In Figure 4.17, the period of transient arc discharge decreased dramatically with increasing flow rate. At around 0.08 Pa.m³/sec, the value of the period of transient arc discharge approached to zero. When a hollow electrode with a smaller diameter was used, the decrease in these values was smaller than those observed with a larger diameter electrode. Moreover, the equilibrium pressure also increased with the increase in the flow rate.

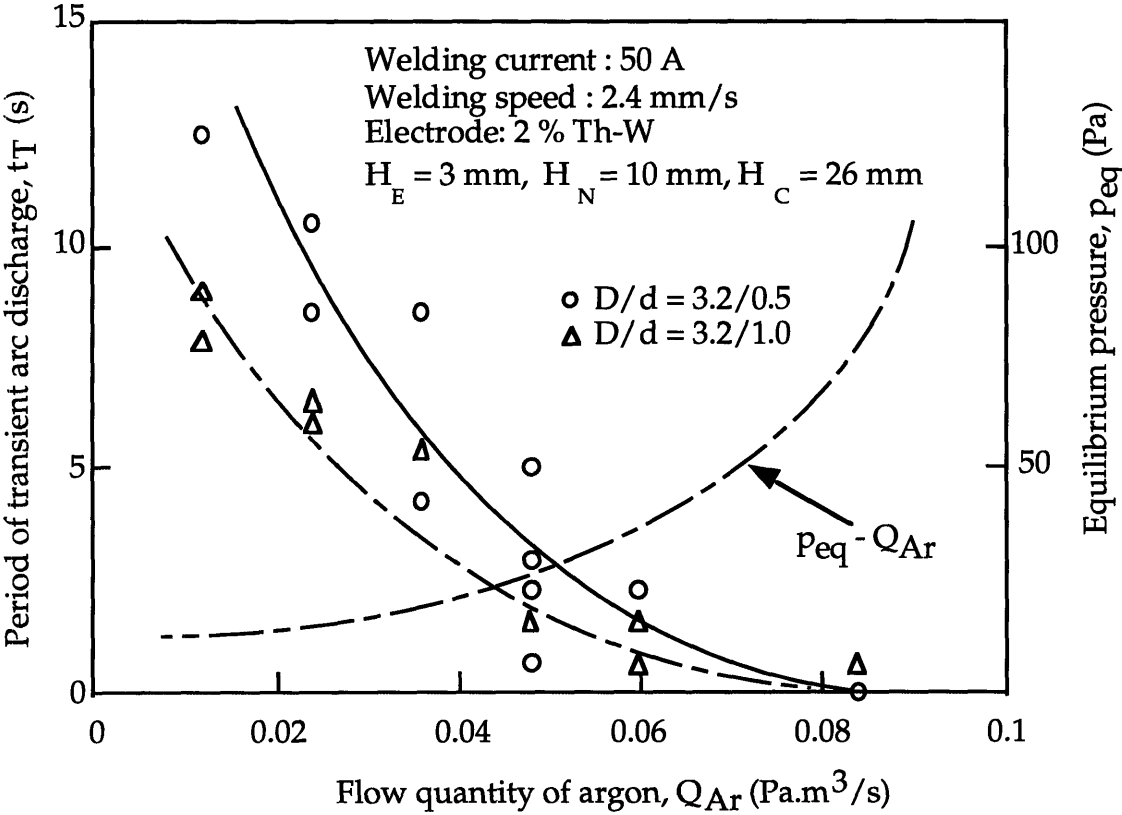


Figure 4.17 Effect of the flow quantity of argon on period of transient arc discharge

Figure 4.18 shows the relationship between the voltage of the steady state arc and the arc length, H_E . As shown in the figure, unlike the arc in the air atmosphere when the arc length is longer than 4 mm, the arc voltage remains constant. In this region, the potential gradient in the arc column is very small and it is similar to the arc property in the low pressure atmosphere (a few KPa) mentioned by Yamamoto and Shimada [29].

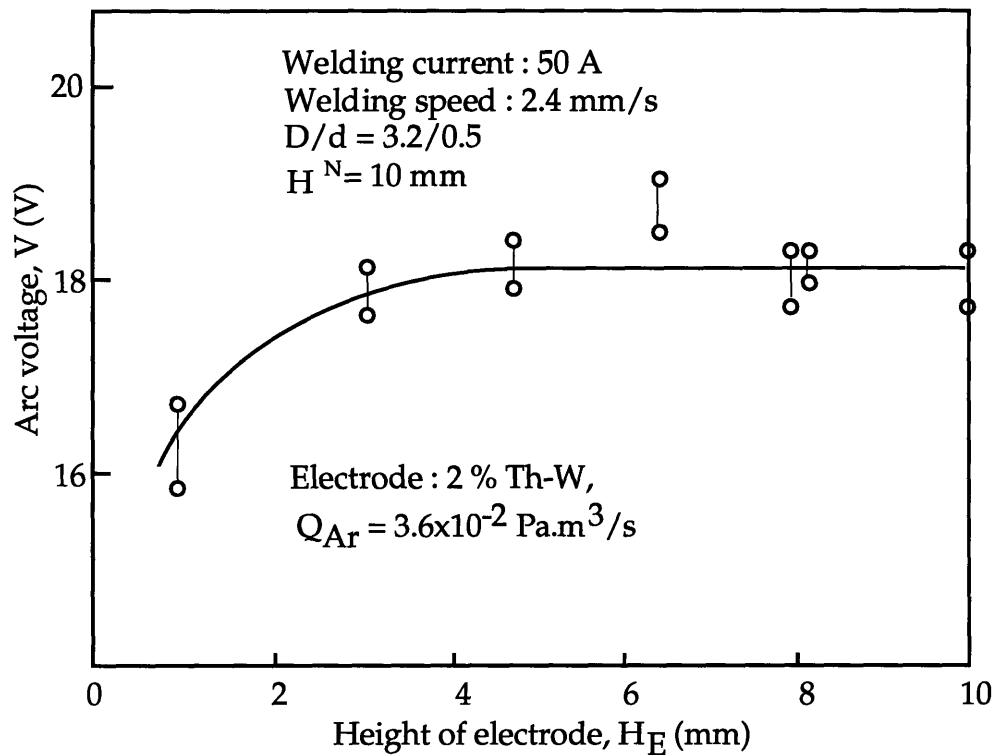


Figure 4.18 Effect of the height of the electrode on arc voltage

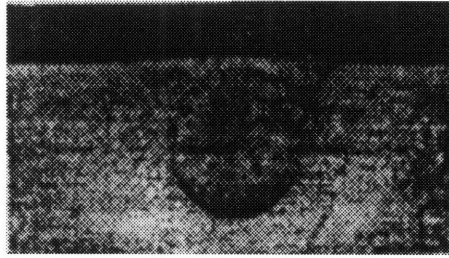
On the other hand, arc voltage decreases as the arc becomes shorter. Although the reason of this is not clearly understood yet, H_E should be taken into account because it affects the gas density at the arc region.

The GHTA welding phenomenon in the low pressure atmosphere with a hollow electrode are summarized as follows:

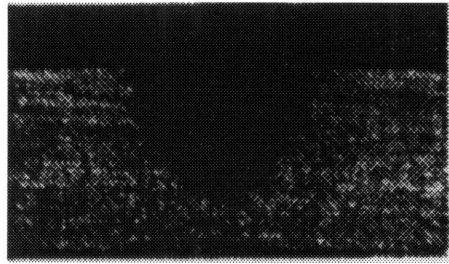
- a) In the very beginning, transition arc of high voltage is generated.
- b) Then, after a certain time, the electrodes are heated and a steady state arc is formed with a clear arc column which melts the base metal .
- c) While the transition arc is maintained, the collet body on the welding torch and the hollow electrode are heavily damaged.
- d) Base metal evaporates greatly and vacuum deposition occurs.
- e) These behaviors are influenced strongly by Ar flow rate.
- f) In low pressure, parts of the welding torch are heated rapidly because the heat loss to the atmosphere is very low.

4.3.2.3 Melting of the Base Metal

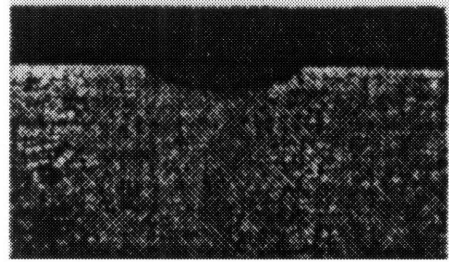
Figures 4.19, 4.20 and 4.21 show the influence of the Ar flow rate on weld bead formation. With the welding condition used here (50A, 2.4mm/s, $H_E = 3$ mm) it was impossible to form a weld bead in the air atmosphere. As shown in the figures, when the Ar flow rate goes below 5×10^2 Pa m³/sec, penetration depth and bead width increase significantly. The higher arc voltage, or the higher heat input, caused by lower equilibrium pressure is considered to be one of the reasons of this result.



(a) Q_{Ar} (Pa.m³/sec) = 1.2×10^{-2}



(b) Q_{Ar} (Pa.m³/sec) = 3.6×10^{-2}



(c) Q_{Ar} (Pa.m³/sec) = 4.8×10^{-2}

Figure 4.19 Effect of the flow rate of argon on bead shape and penetration¹

¹Welding current = 50A, Welding speed = 2.4 mm/sec, H_E = 3mm, H_N = 10mm, H_C = 26mm

As seen in Figures 4.20 and 4.21, when the Ar flow rate is low, the penetration depth and bead width decrease as the inner diameter of the electrode becomes larger. The lower arc voltage caused by the larger hole and the lower energy density caused by a dispersed arc are considered to be the reason for this event.

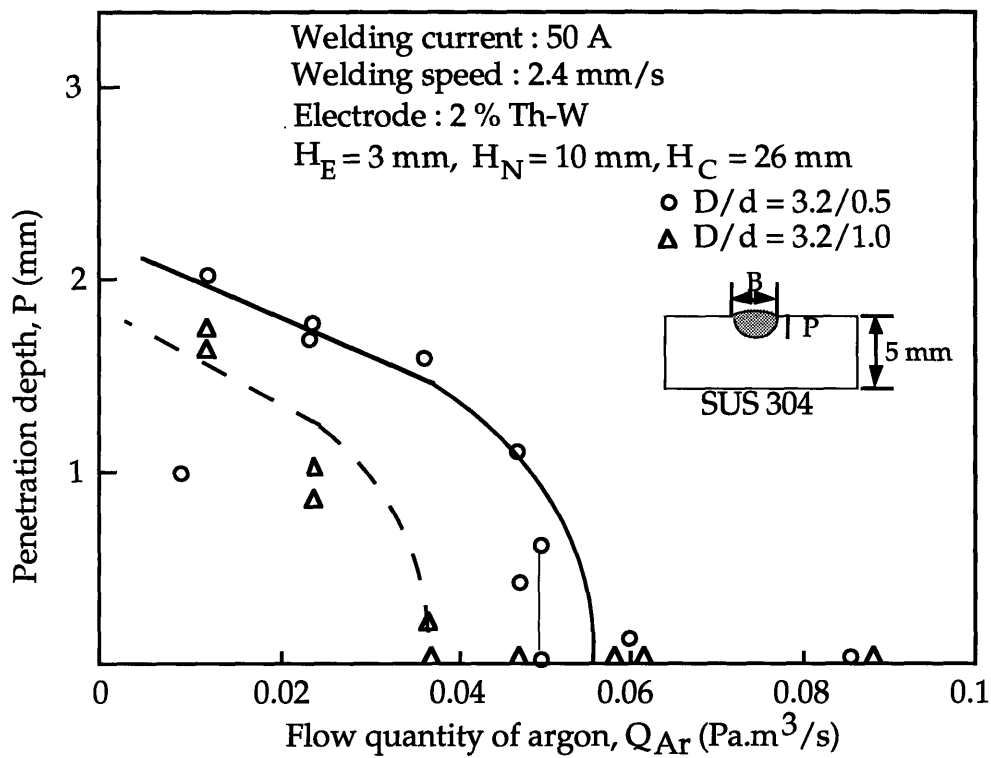


Figure 4.20 Effect of the flow quantity of argon on penetration depth

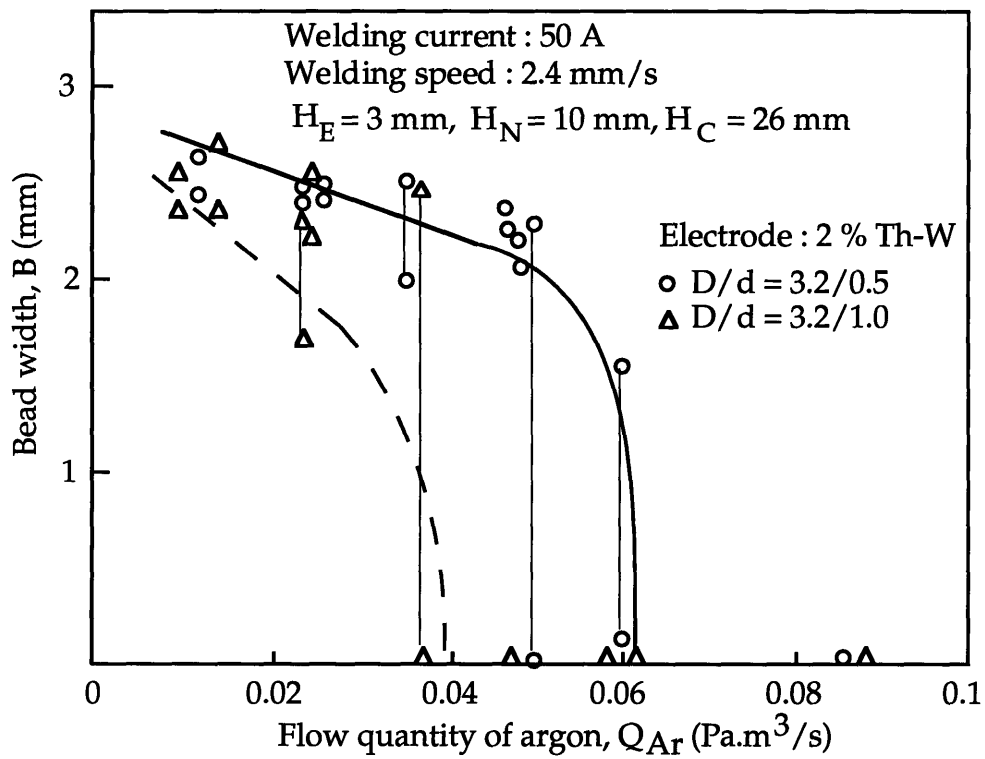


Figure 4.21 Effect of the flow quantity of argon on bead width

Figure 4.22 shows the effect of the arc length on the bead shape. In the welding condition indicated in the figure, the penetration depth shows maximum value when the arc length is about 5 mm. When the arc length is longer than 5 mm, though the arc voltage increases the penetration depth decreases as the arc length increases. When the arc length reaches 10 mm, the energy of the arc is dispersed too much so the base metal is not melted by the arc any more. On the other hand, a shorter arc length (< 4 mm) generates a wider and shallower weld bead. The reason of this result is not known yet.

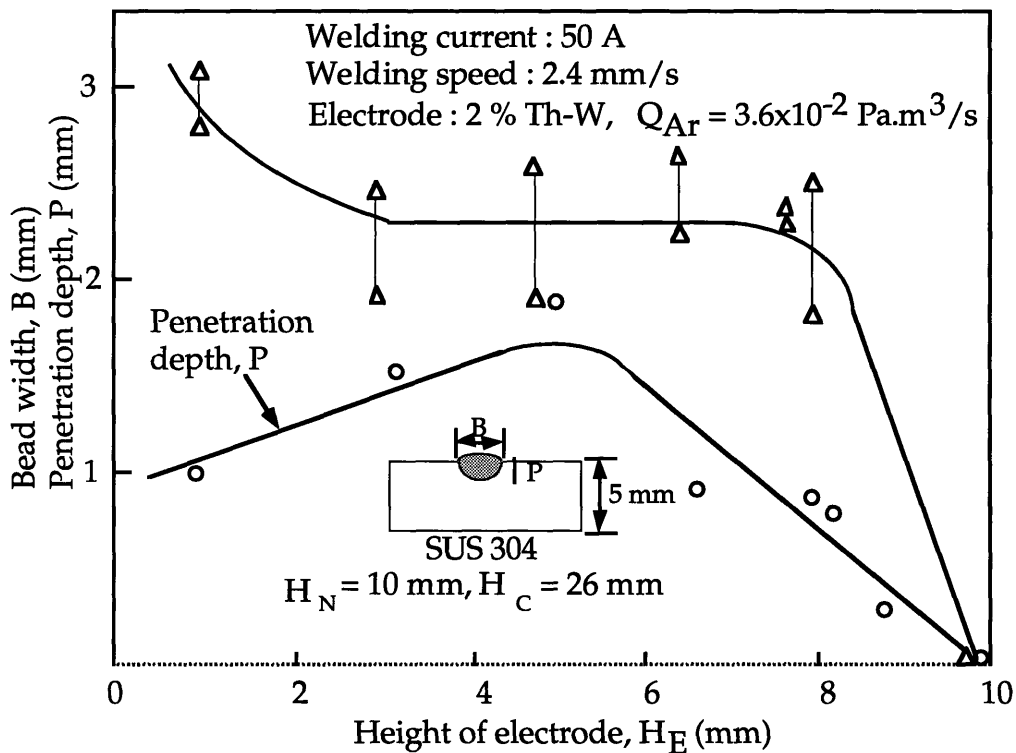


Figure 4.22 Effect of the height of electrode on bead width and penetration depth

As mentioned above, the welding phenomena seen in the Gas Hollow Tungsten Arc Welding process is much different from one in the ordinary Gas Tungsten Arc Welding process in the air atmosphere.

Chapter 5

5. Conclusion

It has been shown that when applied to GTAW process, it is impossible to go below a certain pressure using a regular tungsten electrode. The minimum pressure where the stable arc can be initiated is 0.023 MPa. However, the hollow tungsten electrode has a larger spectrum of pressure and a better weld quality.

1. The work conducted in Welding Systems Laboratory at MIT can be summarized as follows:

- A stable arc can be initiated and maintained at very light vacuum and hyperbaric pressure conditions.
- High pressure produces more constricted arc
- Increasing vacuum diminishes the brightness of the arc and enlarges the spread. With other words, more diffused and rounded arc column.
- With the start of the arc, the pressure in the pressure vessel changes and the environment becomes ionized.
- Due to cathode plasma zone, a heat increase is observed at the anode.
- At vacuum, the arc start point moves from the tip to a point above the tip.
- Increasing vacuum decreases arc length, therefore, penetration becomes deeper.
- Ionization requires good isolation to avoid electrical short circuits.

2. The work performed at TNCI, Japan can be summarized as follows:

- A small amount of argon gas flow from the tip of the hollow electrode can ignite and sustain arc discharge even in a low pressure atmosphere.
- In gas hollow tungsten arc method, welding can be performed with the $1/100 \sim 1/1000$ gas flow rate of the flow used in regular GTAW process at atmospheric condition.
- While the transient arc time becomes longer with a decrease in argon gas flow rate, it becomes shorter with a larger hole diameter of hollow tungsten electrode.
- The arc voltage increases with a decrease of argon gas flow rate. In equal earth welding current conditions, therefore, higher heat input can be obtained by gas hollow tungsten welding than an ordinary gas tungsten arc welding process at atmosphere condition. Accordingly, penetration depth increases when gas tungsten hollow arc process is used at a low argon gas flow rate.
- In low pressure conditions, a stationary arc follows a transient arc.

As a result of the facts mentioned above, if gas hollow tungsten welding (GHWA) is used, welding process can last for a long time with a relatively small size argon gas cylinder in a vacuum atmosphere. Moreover, a good quality weld can be performed for repairs and/or construction purposes.

Chapter 6

6. References

- [1] **Agapakis, J. E., Masubuchi, K., and Alt, C.**, 'Fundamentals and Advances in the Development of Remote Welding Fabrication Systems', *Welding Journal*, Vol. 65, No. 9, September, 1986
- [2] **Allum, C. J.**, Ph.D. Thesis Cranfield Institute of Technology
- [3] **American Welding Society**, 'Welding Hand Book', Volume 2
- [4] **American Welding Society**, 'Welding Technology', Welding Hand Book, Vol. 1, 1987
- [5] **Ando, K. and Nishikawa, J.**, 'Studies on anode and cathode energy of TIG arc', IIW Document 212-158-83
- [6] **Brandi, Newton-Montiel**, 'Workshop Launches Welding in Space Research', *Welding Journal*, Vol. 69, No. 3 (1990), p. 45-47.
- [7] **Dzhanibekow, V. A.**, 'Welding Equipment for Space Application', p. 49-58
- [8] **Evans, J. H., and Adamchak, J. C.**, 'Ocean Engineering Structures', M. I. T. Press, 1969
- [9] **Froese, F. H.**, 'Aerospace Materials for the Twenty-First Century,' Material Design
- [10] **International Institute of Welding**, 'The Physics of Welding', Pergamon Press Inc, Headington Hill Hall, Oxford OX3 OBW, England
- [11] **Irving, Bob.** 'Electron Beam Welding , Soviet Style', *Welding Journal*, Vol. 70, No. 7 (1991), p. 55-59.
- [12] **Koga. S.**, 'Lecture notes of 13.39 Analysis of Welded Structures', MIT
- [13] **Koga, S.**, Personal communications

- [14] **Kou, S.**, 'Welding Metallurgy', JohnWiley & Sons, 1987
- [15] **Masubuchi, K.** 'Analysis of Welded Structures', Pergamon Press Inc, Headington Hill Hall, Oxford OX3 OBW, England
- [16] **Masubuchi, K.** 'Lecture notes of 13.17 Welding Engineering', MIT
- [17] **Masubuchi, K.** 'Lecture notes of 13.15 Materials Science for Ocean Engineering', MIT
- [18] **Masubuchi, K., and Miyake, M.**, 'An Initial Study of Remotely Manipulated stud Welding for Space Application', *Welding Journal*, Vol. 67, No. 4, April, 1988
- [19] **Masubuchi, K.**, 'Materials for Ocean Engineering', M.I.T. Press, 1970
- [20] **Masubuchi, K., and Terai, K.**, 'Future Trends of Materials and Welding Technology for Marine Structures', Proceedings of the 1976 Spring Meeting of the Society of Naval Architects and Marine Engineers, p. 5.1 - 5.21
- [21] **Masubuchi, K.**, Personal commucunations
- [22] **Matsunawa, A. and Nishiguchi, K.**, 'Arc characteristics in high pressure argon atmosphere', *Arc Physics and Weld Pool Behavior*, The Welding Institute, Cambridge.
- [23] **Paton, B. E.**, 'Welding in Space', *Welding Engineer*, Vol. 57, No. 1 (1972), p. 25-29 2
- [24] **SEA-Japan**, No. 209, April 1988 published by
- [25] **Shen-D'Ge, N. J.**, 'Structures/Materials Synthesis for Safety of Oceanic Deep-Submergence Bottom-Fixed Manned Habitat', *Journal of Hydronautics*, Vol. 2, No. 3, pp. 120-139, July 1968
- [26] **Suga, Y.**, 'On the Arc Welding under High Pressure Argon and Helium Atmosphere', International Conference on Welding Under Extreme Conditions, International Institute of Welding, Helsinki, Finland, 1989

- [27] **Stanford, P.**, 'Steam and Speed'. *Sea History*, National Maritime Historical Society, No. 64, pp. 12-19, Winter 1992-93
- [28] **Yamamoto and Shimada**, *Japanese Welding Journal*, Vol. 38, No.1 (1969), p.72-78.
- [29] **Yamamoto and Shimada**, *Japanase Welding Journal*, Vol59, No.6 (1990), p.421-427.
- [30] **Yamamoto and Shimada**, 'Cathode zone and its effect on the penetration of the TIG arc at low pressure atmosphere', IIW Document 212-157-68
- [31] **Tamir, D.**, 'A path to In-Space Welding', 1992 Shuttle Small Payloads Symposium, October 20-23